A Multi-Objective Genetic Allocation Method for Comprehensively Planned Projects

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Abstract. In the current complex and dynamic project management environment, the allocation of reserve resources for comprehensive planning projects often faces challenges such as multi constraint coupling, strong resource heterogeneity, and goal conflicts. Traditional methods rely heavily on a single fund balance constraint, resulting in low resource allocation efficiency, poor dynamic adaptability, and difficulty in achieving multi-objective collaborative optimization. Therefore, this article proposes a comprehensive planning project reserve resource allocation method based on multi-objective genetic algorithm. Firstly, a fitness assignment mechanism based on dominance strength and density information is introduced to effectively distinguish non dominant solutions and improve the convergence accuracy and diversity of the algorithm; Secondly, construct a multi-objective optimization model with the core of maximizing comprehensive income and minimizing total cost, embedding multidimensional constraints such as dynamic allocation of human resources, timeliness of material transportation, and balance of capital flow; Furthermore, by integrating the fuzzy chance constrained planning method, resources are divided into two categories: basic and elastic, and deterministic guarantee strategies and dynamic response mechanisms are adopted respectively to achieve the unity of robustness and flexibility in resource reserves. The experimental results show that the average resource utilization improvement rate of our method is 48%, and it exhibits excellent stability and adaptability in multi-objective collaborative optimization. Compared to existing mainstream methods, this method has significant innovative advantages in terms of precision, dynamism, and multi-objective balancing ability in resource allocation.

Keywords: Multi-objective genetics; Comprehensive planning project; Reserve resource allocation; Resource utilization rate;

1 Introduction

In today's complex and competitive environment, all industries face the challenge of achieving multi-objective optimization and meeting diverse needs within limited re-

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sources. Effective resource allocation can improve utilization efficiency, reduce costs, enhance the ability to cope with uncertainty, and ensure the smooth progress and sustainable development of projects. Therefore, exploring innovative methods for resource allocation in comprehensive planning projects is essential.

There have been many studies in the field of resource allocation. Albogamy et al. [1] studied the optimal resource allocation of non-orthogonal multiple access wireless networks, hoping to balance the resource requirements of different users in a complex wireless network environment and improve the overall performance of the network. However, when this method is used for the allocation of reserve resources for comprehensive planning projects, it is difficult to adapt to the diverse and dynamic characteristics of project resources, and the resource utilization efficiency is limited. Jiaming LI et al. [2] explored the application of blockchain technology in optimizing resource allocation efficiency. The decentralized and tamper-proof characteristics of blockchain provide new ideas for resource allocation, hoping to improve the transparency and fairness of resource allocation. However, in the allocation of reserve resources for comprehensive planning projects, it is difficult to optimize the allocation in a timely and flexible manner according to the actual progress of the project and changes in demand, which affects the improvement of resource utilization efficiency. Mrk Hoffbauer et al. [3] used the portfolio matrix in resource allocation in the sports field, and provided a decision-making basis for resource allocation by evaluating the risks and benefits of different projects. However, when used for the allocation of reserve resources for comprehensive planning projects, it is impossible to fully consider the complex relationships and mutual influences between projects, and the resource utilization efficiency is difficult to reach an ideal level. Shan et al. [4] studied adaptive resource allocation for workflow containerization on Kubernetes, focusing on the dynamic allocation of computing resources in related environments to improve system performance and efficiency. However, this method cannot comprehensively consider the characteristics and relationships of various resources, making it difficult to achieve collaborative optimization of multi-type resource configuration, which limits further improvement of resource utilization efficiency.

Given the limitations of existing research on resource allocation in comprehensive planning projects, a multi-objective genetics-based allocation method is proposed. This method aims to overcome the challenges of multi-objective optimization, improve resource utilization efficiency, and provide new theoretical and methodological support for the rational allocation of resource reserves in comprehensive planning projects.

2 Design of a Comprehensive Plan Project Reserve Resource Allocation Method

2.1 Fitness of Comprehensive Plan Project Reserve Resources Based on Multi-objective Genetic Calculation

In the comprehensive plan project reserve resource allocation, resource fitness is the key to measuring the efficiency of resource modules. Dynamic changes reflect resource consumption and replenishment capabilities, affecting many aspects of the project. Accurate monitoring and control can optimize efficiency and improve coordination and economy.

In order to avoid individuals dominated by the same dominant population members having the same fitness function value, in the fitness assignment of comprehensive plan project reserve resources based on multi-objective genetic calculation, all solutions that dominate the individual and the solutions dominated by the individual are considered simultaneously [5]. Let $S(j)$ be the intensity value of j, which is the total number of solutions dominated by each individual j in the evolving population and the dominant population. Its definition is as follows:

$$S(j)=\sum_{k=P\cup Q}\delta(j,k) \tag{1}$$

Where: P is the evolving population, Q is the dominant population, $\delta(j,k)$ is the judgment function, when j dominates k, $\delta(j,k)=1$, otherwise $\delta(j,k)=0$.

After calculating the individual's intensity value, the coarse fitness $R(j)$ of any individual j is the sum of the strength values of all the solutions that dominate the individual, defined as follows:

$$R(j)=\sum_{k=P\cup Q}S(j) \tag{2}$$

Where, the larger the $R(j)$ is, indicating that the individual is dominated by more solutions.

When all individuals are non-dominated, the rough fitness of different individuals $R(j)$ cannot be compared. Therefore, a multi-objective genetic algorithm [6] is introduced to distinguish individuals with the same rough fitness by density information $D(j)$, which is defined as follows:

$$D(j)=\frac{1}{\sigma_L^2(j)} \tag{3}$$

Where: $\sigma_L^2(j)$ is the square of the distance from an individual j to its L nearest neighbor.

The final fitness of an individual $F(j)$ is obtained by adding the rough fitness information $R(j)$ and the density information $D(j)$, which is defined as follows:

$$F(j) = R(j) + D(j) \tag{4}$$

The above fitness assignment method can fully consider the multi-objective characteristics of resources in the comprehensive plan project reserve allocation, avoid the same fitness value, use density information to distinguish individuals, provide precise guidance for the algorithm, and improve the rationality of resource allocation.

2.2 Constructing a Comprehensive Plan Project Reserve Resource Allocation Model

For comprehensive plan project reserve resource allocation, it is important to scientifically arrange project reserves. This study focuses on maximum benefit and minimum cost, establishes a multi-objective model based on the adaptability of reserve resources, analyzes the relationship between the two, and provides theoretical and optimization guidance for accurate resource allocation.

The quantification of overall benefits not only includes financial benefits, but also incorporates non-financial indicators such as environmental impact assessment (carbon reduction converted into economic value), social benefits (such as employment promotion index, community satisfaction score), etc., to construct a multidimensional comprehensive evaluation system for benefits. Comprehensive benefits include the benefits brought by on-time delivery, quality improvement, and efficient resource utilization [7]. Based on this, the objective function for maximizing comprehensive benefits is set as follows:

$$\max \begin{cases} F_1 = \sum_{u=1}^{m} \sum_{i \in P_u} s_{u,i} \cdot x_{u,i} \\ F_2 = -\dfrac{\sqrt{\dfrac{1}{m-1} \sum_{u=1}^{m} \left(I_u - \bar{I} \right)^2}}{\bar{I}} \\ F_3 = \dfrac{1}{T} \sum_{t=1}^{T} \left(\dfrac{1}{m} \sum_{u=1}^{m} \left(U_{\text{load},u,t} - w_u \right)^2 \right) \end{cases} \tag{5}$$

Where: n is the number of reserve resource types, $B(x_i)$ is the benefit function generated by the i th type of resource, including the conversion value of direct economic benefits and environmental and social benefits.

The total cost model includes indirect costs caused by resource heterogeneity, such as resource conversion costs, idle penalty costs, scheduling and coordination costs, in addition to direct resource procurement and usage costs. By incorporating weighted coefficients into the objective function, the total cost is minimized.

The relative differences in investment amounts among various units are minimized (to avoid "excessive tilting of top units and lack of available resources for tail units" with a coefficient of variation of 0.35 as a reasonable range).

In the comprehensive planning project reserve resource allocation model, there is a high degree of uncertainty in resource supply, and the release of reserves is influenced by multiple factors. In terms of resource dynamic balance constraints, project progress should meet construction carrying capacity constraints (dynamic), investment demand elasticity constraints, project duration matching constraints, and total investment scale constraints to ensure that resource dynamic balance is consistent with project progress requirements [8]. The specific constraints are as follows.

Construction bearing capacity constraint (dynamic): By dynamically controlling the upper limit of project construction intensity on a quarterly basis, it avoids excessive concentration of resources in specific quarters that may lead to exceeding the bearing capacity limit:

$$\sum_{i \in P_{u,t}} x_{u,i} \le C_u \times k_{u,t}, \forall u,t \tag{6}$$

The investment demand elasticity constraint sets the upper limit of head unit investment and the lower limit of tail unit protection, taking into account investment efficiency and balance:

$$0.8D_u \le I_u \le 1.5\bar{I}, \forall u \tag{7}$$

The project duration matching constraint restricts the proportion of selected projects per quarter to ensure the rationality of schedule arrangement and resource allocation:

$$\sum_{i \in P_{u,t}} x_{u,i} \le 0.3 \sum_{i \in P_u} x_{u,i}, \forall u,t \tag{8}$$

The total investment scale constraint allows for moderate overspending (5%) to enhance the model's adaptability to budget fluctuations, while controlling the overall investment scale:

$$\sum_{u=1}^{m} I_u \le B \times (1 + 0.05) \tag{9}$$

In addition to the above constraints, the following practical constraints are also included: firstly, dynamic constraints are adopted in terms of construction bearing capacity, that is, for each construction unit and time period, the total number of constructions carried out by each project under that unit at the corresponding time cannot exceed the product of its foundation construction bearing capacity and dynamic adjustment coefficient; Secondly, there is an elastic range of investment demand, and the investment amount of each project needs to be between 0.8 times and 1.5 times its basic investment demand amount; Thirdly, the project duration needs to be matched. For each project and time period, the proportion of construction carried out during the corresponding time period shall not exceed 30% of the total construction carried out during the entire planning period; Fourthly, there is a flexible limit on the total investment scale, and the total investment of all projects shall not exceed 1.05 times the basic investment budget amount.

Through the above objective function and dynamic constraints, a reserve resource allocation model for comprehensive planning projects can be constructed.

2.3 Realize the Allocation of Reserve Resources for Comprehensive Planning Projects

To scientifically allocate the reserve resources for comprehensive planning projects, improve the benefits of the entire cycle, and dynamically optimize the allocation model. Reasonable planning of the scale of key resource reserves can cope with uncertainty risks such as market demand fluctuations. Project resource reserves include multiple elements such as equipment and materials [9], and the allocation must take into account both short-term emergency response and long-term cost-effectiveness. The resource reserve optimization model introduces the fuzzy opportunity constraint planning method to meet the constraints according to controllable probability under uncertain conditions. The standard model is as follows:

$$F(x) = w_1(F_1 + F_2 + F_3) + w_2\left[C_u + I_u + x_{u,i} + B(1+0.05)\right] \tag{10}$$

Where: w_1 and w_2 are the weight coefficient.

Fuzzy chance constrained planning addresses the uncertainty of project requirements and resource constraints by introducing fuzzy set theory. Fuzzy sets are used to characterize fuzzy semantics such as "resource demand is approximately within a certain range" or "constraints can be moderately relaxed". Their membership functions are set using triangular fuzzy numbers or trapezoidal fuzzy numbers, based on the fluctuation range of historical data and expert experience. For example, resource demand Y_t can be represented as a fuzzy number, and its membership function is constructed based on the mean and standard deviation of demand data from the same period in the past three years. The confidence level α is set to 0.9, indicating that the constraint holds with at least 90% probability. This method allows for the introduction of elastic intervals in the constraint conditions, enabling the model to obtain feasible solutions even in uncertain environments, improving the robustness and adaptability of resource allocation.

Resource reserves are divided into basic and flexible types. The reserve volume of basic resources (core equipment) Q_b must be able to meet the minimum operating requirements of the project. Its allocation formula is as follows:

$$Q_b = \max\left[\frac{\sum_{t=1}^{T} Y_t \cdot F(x)}{N \cdot \eta}, Q_{\min}\right] \tag{11}$$

Where: Y_t is the resource demand forecast value for the period t, T is the resource reserve cycle, N is the reserve cycle, η is the resource utilization rate, $Q_{\min}$ is the safety stock threshold.

The configuration of elastic resources (such as spare materials) needs to consider the response speed [10] and cost balance, and its reserve volume Q_e adopts a dynamic adjustment strategy:

$$Q_e = \vartheta \int_0^t \left[\lambda(t) \cdot \Delta Y(t)\right] F(x) \tag{12}$$

Where: ϑ is the resource elasticity coefficient, $\lambda(t)$ is the demand change rate for the period t, $\Delta Y(t)$ is the deviation between actual demand and forecast. This formula reflects the timeliness of resource reserves through the exponential decay term to avoid cost waste caused by excessive reserves.

The above model and formula are synergistically optimized to enable the comprehensive plan project reserve resources to be dynamically balanced in terms of cost, risk and response capability. The basic type ensures continuity, and the elastic type improves anti-interference ability. The combination of the two reduces the full-cycle cost and provides quantitative support for resource allocation.

3 Experiments

3.1 Experimental Objects

The comprehensive plan project reserve resource configuration based on multi-objective genetic algorithm is challenging to cope with complex demands. The experimental simulation scenario covers 50 projects with an average project period of 12 months and a total of over 300 activities. The constraints include construction carrying capacity, investment elasticity, schedule matching, and total investment scale, and there is a strong coupling relationship between them (such as investment allocation affecting construction carrying capacity scheduling). The project resource demand is dynamic and uncertain, and improper allocation is easy to affect benefits. This algorithm can comprehensively consider multiple objectives such as cost, simulate evolution to find the optimal solution, and improve scientificity. A large enterprise project was selected for the experiment, and a detailed experimental model was constructed, as shown in Figure 1.

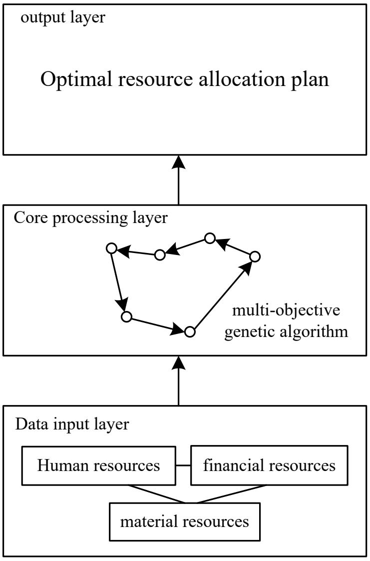

Fig. 1. Experimental Model for Comprehensive Plan Project Reserves

This model involves 50 projects across multiple business sectors of the enterprise, with a total funding requirement of 80 million yuan. The experimental area is divided into four sections based on business and numbered accordingly. On the basis of clarifying the boundaries of each project, data monitoring nodes are evenly deployed within each section to ensure the accuracy and completeness of the data. The enterprise project reserve covers four core resources corresponding to the four business sectors, with detailed records of their basic attributes and usage indicators for each type of resource.

The experiment adopts multi-objective genetic algorithm and strictly follows the four core constraints proposed earlier in resource allocation. Each allocation cycle comprehensively analyzes monitoring data, accurately calculates the resource requirements of each project, and achieves efficient allocation and maximization of comprehensive utilization benefits of limited resources based on factors such as project priority and urgency of resource requirements, while meeting the above four constraints.

3.2 Experimental Preparation

In this study of comprehensive plan project reserve resource allocation, a multi-objective genetic algorithm-based experimental framework for comprehensive plan project reserve resource allocation was constructed, integrating the enterprise's existing project scheduling and control platform. This framework serves as a critical link between the project scheduling and control platform and the external resource supplier information management system.

In dynamic adaptability testing, the simulation of demand fluctuations adopts a combination of seasonal fluctuations and random sudden fluctuations: the amplitude of quarterly fluctuations is ± 30% of the benchmark demand, and sudden fluctuations occur every 3 months with an amplitude of ± 50% and a duration of one week. The experimental framework's operational process is divided into three major modules: project scheduling and control, reserve resource allocation, and supplier resource management, along with supporting data interfaces. The reserve resource allocation host serves as the central hub, ensuring data independence for the other two hosts.

To ensure that the multi-objective genetic-based comprehensive planning project reserve resource allocation method is realistic and more instructive, it is crucial to use resource data from a real-world enterprise production environment. The data used in this experiment comes from resource usage data (RUD) collected from 1,500 work units in a production cluster of a large manufacturing enterprise over a continuous 10-hour period. Resource utilization was recorded four times at 90-second intervals, and the arithmetic mean was taken. At the beginning of the experiment, approximately 97% of the work units can be considered homogeneous, with real computing power and storage capacity normalized to the maximum storage capacity within the enterprise.

In order to test the actual effect of the reserve resource allocation method of comprehensive planning project based on multi-objective genetics, this study set this method as the experimental group. At the same time, the resource allocation strategies proposed in references [1], [2], [3], and [4] were selected as the control group to carry out comparative experiments. By comparing the differences in resource utilization improvement rate indicators between the experimental group and the control group, the feasibility and advantages of the proposed method were comprehensively evaluated.

3.3 Analysis of Experimental Results

Taking the resource utilization improvement rate as an indicator, the advantages of the proposed method for allocating reserve resources for comprehensive planning projects based on multi-objective genetics are further demonstrated. Experiments are conducted to compare five different resource allocation methods, and the results are shown in Figure 2.

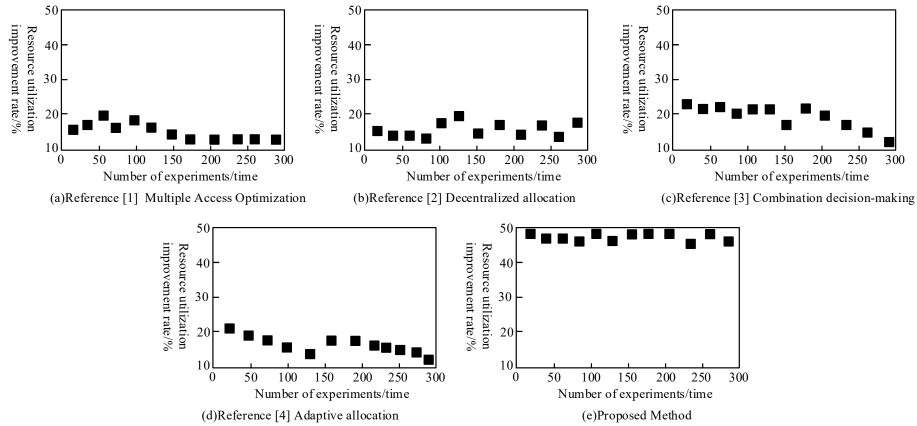

Fig. 2. Results of Resource Utilization Improvement Rate for Five Methods

From Figure 2, it can be seen that the average resource utilization improvement rate from references [1] to [4] is between 12% and 20%. The average improvement rate of this method is as high as 48%, and in multiple experiments, the fluctuation of the improvement rate is small and the stability is strong, while the fluctuations in references [1] - [4] are relatively large. This indicates that the method proposed in this article can effectively improve the efficiency of resource utilization and has good stability. Overall, the comprehensive planning project reserve resource allocation method based on multi-objective genetics has outstanding advantages in improving resource utilization efficiency and is a better choice for the rational allocation of project reserve resources, which can help the project operate efficiently and stably.

By conducting sensitivity analysis (focusing on changes in total investment scale) and comparing the actual application effects, evaluate the comprehensive benefits, investment balance, dynamic utilization rate and other indicators of the constructed model under different total investment scale settings. At the same time, compare it with the traditional plan in key indicators such as comprehensive benefits, investment balance, and construction resource utilization rate in 2023 to verify the effectiveness and superiority of the model in investment planning and resource allocation. The results are shown in Tables 1 and 2.

Table 1. Sensitivity Analysis

Total investment change	Comprehensive benefits	Investment balance	Dynamic utilization rate	Conclusion
-10%	3350	0.32	76%	Decreased balance and utilization rate
0 (Benchmark)	3680	0.28	81%	Optimal balance of three objectives
10%	3920	0.25	84%	Marginal diminishing benefit

Table 2. Actual Application Effect

Indicator	Traditional Plan for 2023	The 2024 model	Increase margin
comprehensive benefits	3250	3680	13.20%
Investment balance	0.52	0.28	-46.20%
Utilization rate of construction resources	65%	81%	24.60%

According to Table 1, based on the sensitivity analysis of changes in total investment scale, when the total investment scale decreases by 10%, the comprehensive benefit decreases to 3350, the investment balance increases to 0.32, and the dynamic utilization rate decreases to 76%. This indicates that the balance and resource utilization rate of the project have both decreased at this time; Taking the total investment scale as the benchmark, the comprehensive benefit is 3680, the investment balance is 0.28, and the dynamic utilization rate is 81%, achieving the optimal balance of the three objectives; When the total investment scale increases by 10%, although the comprehensive benefits increase to 3920, the investment balance drops to 0.25, and the dynamic utilization rate increases to 84%. However, the benefits show a marginal decreasing trend, indicating that the effect of continuing to increase investment on improving comprehensive benefits gradually weakens.

According to Table 2, comparing the actual application effects of the traditional plan in 2023 and this model in 2024, the comprehensive benefits of this model have increased from 3250 to 3680, an increase of 13.2%, indicating better economic benefits; The investment balance for investment has significantly decreased from 0.52 to 0.28, a decrease of 46.2%, indicating a more balanced and reasonable allocation of investment; The utilization rate of construction resources has increased from 65% to 81%, an increase of 24.6%, indicating that resources have been more fully utilized. Overall, this model performs significantly better than traditional solutions in practical applications.

To further demonstrate the advantages of this method in accuracy, dynamism, and multi-objective balancing ability, we conducted a set of three-dimensional comparative experiments to quantitatively compare MOGA with traditional genetic algorithm (GA) and multi-objective particle swarm optimization algorithm (MOPSO) in three dimensions. This experiment compares the performance of MOGA, GA, and MOPSO in resource allocation tasks under the same simulation environment. Accuracy is measured by the percentage deviation between the objective function value and the theoretical optimal value; Dynamicity is measured by the average response time of the algorithm from receiving demand changes to outputting new configuration solutions; Multi objective balance is measured by the coverage of the solution set obtained by the algorithm on the Pareto front. The results are shown in Table 3.

Table 3. Performance Comparison of MOGA with GA and MOPSO in Three Dimensions

Algorithm	Accuracy (target deviation%)	Dynamics (response time in seconds)	Multi objective balance (Pareto front coverage%)
MOGA	4.2	12.3	89.5
GA	15.6	45.7	62.1
MOPSO	9.8	28.4	76.3

According to Table 3, MOGA is significantly better than GA and MOPSO in accuracy, with a deviation of only 4.2%; The shortest response time in terms of dynamism indicates a stronger ability to adapt to changes; In terms of multi-objective balance, the Pareto front coverage rate reaches 89.5%, significantly higher than the comparison algorithm, indicating that it can better achieve multi-objective collaborative optimization. Overall, MOGA exhibits significant advantages in all three dimensions.

4 Conclusion

This research system proposes a comprehensive planning project reserve resource allocation method based on multi-objective genetic algorithm. By constructing a multi-objective optimization model that balances comprehensive benefits, investment balance, and resource utilization efficiency, and designing corresponding fitness calculation, constraint processing, and dynamic allocation strategies, it effectively solves the problems of single objectives and low resource utilization efficiency in traditional allocation methods. The experimental results show that this method can significantly improve resource utilization efficiency, reduce idle and loss rates, and demonstrate good stability and adaptability in multi-objective collaborative optimization, providing feasible theoretical and technical support for scientific allocation of project resources in complex environments.

4.1 Management Insights

From the perspective of management practice, this study draws the following insights:

(1) Adaptation strategies for different industries: In the power industry, emphasis should be placed on controlling investment balance (CV ≤ 0.3) and prioritizing the utilization of construction resources in the new energy sector; The construction industry needs to establish a quarterly dynamic capacity adjustment mechanism to adapt to the impact of climate and other factors; The manufacturing industry can appropriately increase the weight of comprehensive benefits (such as 0.5) and relax the balance constraint (CV ≤ 0.4) to fit its strong profit oriented characteristics.

(2) Data protection suggestion: Enterprises should establish an integrated database of "electricity consumption investment demand construction resources" to achieve monthly updates and dynamic fitting; At the same time, the investment demand forecasting model should be validated quarterly. If the deviation exceeds 15%, the industry benchmark parameters and forecasting methods should be corrected in a timely manner to ensure the accuracy and timeliness of the model input.

4.2 Research Limitations and Prospects

Although this study has made some progress in model construction and algorithm design, there are still limitations that need to be further explored

(1) Not considering project synergy effect: The model assumes that projects are independent of each other and fails to reflect the synergy gain between related projects such as "substation+line". In the future, a "synergy coefficient matrix" can be introduced to optimize the overall benefits through linkage.

(2) Insufficient dynamic adjustment mechanism: The current model is a one-time static configuration, lacking a response mechanism for personnel changes, sudden resource shortages, and other situations during project execution. In the future, a "monthly rolling optimization" model can be constructed, combined with IoT data to achieve near real-time adjustment.

(3) Intelligent decision-making and industry customization are the future directions: reinforcement learning algorithms can be introduced to enable models to autonomously learn and adjust target weights based on historical configuration data of the enterprise; At the same time, industry-specific modules such as "carbon neutrality indicators" and "safety compliance factors" will be developed and embedded based on the characteristics of different industries such as electricity, construction, and manufacturing, further enhancing the practicality and promotional value of the model.

Future research will continue to deepen in the above directions, committed to building a more flexible, accurate, and implementable project reserve resource allocation system, providing continuous support for enterprises to achieve lean resource management in complex and changing environments.

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