Application of Path Planning Algorithms in Logistics Transportation - Optimization Based on Ant Colony Algorithm and Multi-Algorithm Comparison

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Abstract. With the development of e-commerce and the upgrading of the supply chain, the traditional method has been difficult to adapt to the dynamic, multi-objective, and large-scale logistics demand. This paper takes the ant colony algorithm as the core research method, comprehensively sorts out the mainstream algorithm types in this field, and focuses on the analysis of various optimization and improvement schemes of the ant colony algorithm, the adaptation characteristics of different logistics scenarios, and the core performance advantages. Combined with typical application cases and actual empirical data, the research compares the multi-dimensional application effects of the ant colony algorithm and the traditional graph search algorithm, and clarifies the application differences of various algorithms. At the same time, the latest research results in this field from 2022 to 2025 are integrated to provide a scientific and practical reference for the selection of path planning algorithms and engineering practice in various logistics scenarios.

Keywords: Path Planning; Logistics Transportation; Ant Colony Algorithm Application

1 Introduction

As the artery system of the national economy, the efficiency improvement and cost control of modern logistics are directly related to the stable operation of the industrial chain and supply chain. According to the data of the National Bureau of Statistics, the total cost of social logistics in China will exceed 17.2 trillion yuan in 2025, accounting for about 14.1% of GDP. Although this figure is 3.6 percentage points lower than that ten years ago, it is still significantly higher than that of developed countries such as the United States (8.3%) and Japan (9.9%). Transportation costs account for 52.8% of the total cost of social logistics, which has become the core bottleneck restricting the reduction of logistics costs and the improvement of efficiency [1]. As an important decision-making link in logistics transportation, route planning directly determines the transportation mileage, fuel consumption, labor cost, and timeliness of delivery. A reasonable path planning algorithm can reduce the transportation cost of logistics enterprises by 16%~27%, improve the distribution efficiency by 22%~33%, and reduce carbon emissions by 11%~19% [2].

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With the large-scale expansion of e-commerce retail and the rise of real-time distribution, the logistics transportation scene shows the characteristics of fragmented orders, personalized demand, dynamic road network and so on. Taking community group buying, instant delivery of takeout, local fresh express delivery and other scenarios as examples, the average daily order of a single outlet can reach thousands of orders, the distribution points are scattered, the timeliness requirements are strict, and the congestion in the morning peak and evening peak sections changes in real time. The traditional path planning method relying on manual experience has exposed some disadvantages, such as low efficiency. Based on the above considerations, the intelligent optimization algorithm represented by the ant colony algorithm may become the key means to solve the vehicle routing problem under complex constraints. For example, in the urban vehicle routing scheduling with multiple vehicle types, multiple warehouses, and time windows, the ant colony algorithm can quickly converge to the route scheme with the shortest total distance or higher distribution efficiency. Therefore, the research and application of the ant colony algorithm have important theoretical value and practical significance for promoting the digital transformation of the logistics industry.

In 2011, Jianting discussed the basic principles of the ant colony algorithm and established a mathematical model, including the calculation of transition probability, various rules of pheromone update, and the range of parameter values [3]. In 2014, Yuanxianliang conducted in-depth research on three different models of the head vehicle routing problem (CVRP) [4]. In 2017, Lipengfei incorporated the uncertainty of aquatic product storage time window and road conditions into the VRP mathematical model as constraints, and established a mathematical model specifically for aquatic product transportation and logistics distribution. The global pheromone update strategy is improved, the waiting factor is introduced into the state transition rule, and the upper and lower limits of pheromone concentration on the path are set, which effectively solves the shortcomings of the ant colony algorithm [5]. In 2019, SunYutong introduced the concepts of fresh logistics loss cost, time window, and customer satisfaction, and built a bilevel programming model of the fresh logistics distribution location routing optimization problem [6]. In 2020, Shijianhua and his team optimized the traditional ant colony algorithm to solve the difficulties in the logistics transportation path planning of maritime ports. The port handling efficiency and channel traffic efficiency are brought into the evaluation dimension of the heuristic function, and the pheromone evaporation coefficient is adjusted to adapt to the characteristics of the port dynamic road network [7]. Zhang Wantong proposed an improved strategy based on the importance of logistics network nodes in order to solve the problem of search blindness of the traditional ant colony algorithm in the global path planning of logistics networks [8].

The current research is no longer limited to the individual show of a single algorithm, but multi-algorithm parallel and applied to various scenarios, special logistics scenarios, the overall planning of logistics network, and the practical application of emerging commercial formats. The application of scholars has effectively solved the shortcomings of the traditional ant colony algorithm in different logistics scenarios and significantly enhanced its practical adaptability. It is worth pondering that the existing research still faces challenges, such as insufficient response to dynamic large-scale logistics scenarios and the need to improve the convergence speed of the algorithm under multiple constraints. This paper takes the ant colony algorithm as the core research method, through theoretical analysis, case comparison, empirical analysis, and other methods, systematically discusses the optimization logic and application effect of the ant colony algorithm in multi-constraint logistics scenarios, to provide a reference for the practical application and subsequent innovation of the algorithm.

2 Theoretical foundation

2.1Model principle, advantages, and performance evaluation

The vehicle routing problem is a constrained combinatorial optimization problem, which belongs to NP hard problem. When the size of the problem is large, it is difficult to obtain the global optimal solution or a satisfactory solution, and as the size of the problem increases, the calculation time of the algorithm will increase exponentially. In recent years, scholars have made some progress in solving VRP combinatorial optimization problems with exact algorithms and heuristic algorithms. The characteristic elements of VRP mainly include time, demand, vehicles, parking lots, and objectives. Many scholars have carried out various classifications according to different standards from different angles. To sum up, we can analyze the following VRP with capacity constraints (CVRP), VRP with time windows (VRPTW), VRP with simultaneous pickup and delivery (VRPSPD), green VRP (GVRP), and dynamic VRP (DVRP) [9].

Ant colony algorithm was proposed by Italian scholar Dorigo m and others in 1996 [10]. It is derived from the simulation of ant foraging behavior: ants release pheromones on the driving path, and subsequent ants have a greater probability of selecting the path with high pheromone concentration, and gradually converge to the optimal path through the positive feedback mechanism. In logistics path planning, each ant represents a candidate distribution path, and the pheromone concentration corresponds to the pros and cons of the path. The algorithm guides the search direction through pheromone update and heuristic function.

The basic steps of ant colony algorithm are as follows: initialize, set the number of ants m, pheromone Volatilization Coefficient ρ (0<ρ), pheromone importance α, heuristic function importance β, and initialize the pheromone concentration of each path to

$$\tau_{ij}(0) = \tau_0 \text{（}constant\text{）} \quad (1)$$

Based on the above settings, the ant starts from the distribution center and selects the next customer point according to the roulette method. The selection probability is

$$p_{ij}^{k}(t) = \begin{cases} \frac{[\tau_{ij}(t)]^{\alpha} \cdot [\eta_{ij}]^{\beta}}{\sum_{l \in allowed_k} [\tau_{il}(t)]^{\alpha} \cdot [\eta_{il}]^{\beta}}, & j \in allowed_k \\ 0, & otherwise \end{cases} \quad (2)$$

Where allowedk represents the set of client points that have not been visited by ant k.

$\eta_{ij} = 1/c_{ij}$,(c_{ij} represents the transportation cost from node i to j, where the shorter the distance, the greater the heuristic value); then, pheromone updating is implemented, adjusting the pheromone concentration through global updating （$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k}$） and local updating （$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \rho\tau_0$）, thereby balancing search efficiency and diversity.Finally, determine the termination condition. If the number of iterations reaches the threshold Nmax or the path length converges, the optimal path can be output.Compared to traditional graph search algorithms (such as Dijkstra's algorithm [11] and

A* algorithm [12]) and other intelligent optimization algorithms (such as genetic algorithm [13]), the ant colony algorithm possesses three core advantages. It exhibits strong dynamic adaptability, enabling real-time updates through pheromones, rapid response to dynamic traffic conditions, sudden orders, and other uncertain factors, and is suitable for complex scenarios such as DVRP. It excels in handling multiple constraints, flexibly incorporating constraints such as capacity, time windows, and carbon emissions, and achieves multi-objective collaborative optimization through heuristic function optimization. Furthermore, it boasts excellent global search performance, combining distributed computing with a positive feedback mechanism to effectively avoid local optima, and its convergence speed is significantly improved after being enhanced by hybrid strategies.

3 Case comparison of application analysis of the ant colony algorithm in logistics scenarios

This paper selects the relevant research results of Chao Chengliang, Tang Xin, and Zeng Sally as typical cases to analyze the different improvement strategies and practical application effects of the ant colony algorithm, and compares the performance and scene adaptation of the ant colony algorithm under different optimization directions. The relevant research results are shown in [14][15][16].

Chaochengliang [14] optimized the total client goals and functions, and used the elite retention strategy to sort the target sequence, so as to realize the planning of the distribution path. The main purpose is to screen the non-dominant client individuals, so as to select the individuals that may cause crowding or be ignored, and form them into a group of populations, which will complete the ranking of dominant goals of different client individuals at the same level after optimization. Finally, according to the inertia and the change set of particles, the order of the previous schemes is determined0

:$f_{gh}^{j+1} = kf_{gh}^{j} + l_1\alpha(z_{gh}^{j} - c_{gh}^{j}) + l_2\beta(z_{xh}^{j} - c_{gh}^{j})$， $c_{gh}^{j+1} = c_{gh}^{j} + f_{gh}^{j+1}$

f_{gh}^{j+1},c_{gh}^{j+1} are the update speed and location sorting, α and β are random distribution parameters, and the interval is [0,1]. c_{gh}^{j} is the order of the jth selection of the g-th client in the H-th dimension, which is the corresponding location, z_{gh}^{j} is the optimal location of the g-th client, z_{xh}^{j} is the global optimal location, and l_1 and l_2 are the weight coefficients assigned. Finally, the immune algorithm and ant colony algorithm are combined to complement each other through the early search of the immune algorithm and the late local search of the ant colony algorithm. Finally, the improved ant colony algorithm is used to realize the distribution path planning of logistics vehicles. The experimental results show that the satisfaction is 91% -100%, which can reach the highest satisfaction with the least number of repetitions, and the path planning is the most concise.

Zeng Sally took the multi-node logistics distribution as the simulation scenario, and selected three typical scale distribution cases of 10 nodes, 20 nodes, and 30 nodes [16]. The node coordinates were randomly and evenly distributed, and a variety of practical constraints were included. In the 10 node scenario, the average path length of the improved algorithm is 11.46% shorter than that of the traditional algorithm, the number of convergence iterations is 16.05%

less than that of the traditional algorithm, and the average transportation cost is 10.8 yuan lower; In the 20 node scenario, the average path of the improved algorithm is 13.23% shorter than that of the traditional algorithm, the number of convergence iterations is 26.4% less than that of the traditional algorithm, and the transportation cost is 21.3 yuan lower on average; In the 30 node scenario, the average path length of the improved algorithm is 14.85% shorter than that of the traditional algorithm, the number of convergence iterations is 27.66% less than that of the traditional algorithm, and the average transportation cost is reduced by 30.5 yuan. The superiority of the improved ant colony algorithm is clearly verified under the multi-node and multi-index control experiment, which provides a quantitative idea for the experimental verification of similar algorithms.

The overall comparison results show that the comprehensive performance of the improved ant colony algorithm in different directions is significantly better than that of the traditional ant colony algorithm and the single optimization algorithm in the corresponding logistics scenarios, which effectively makes up for the application defects of the traditional ant colony algorithm. At the same time, it can also be seen that the ant colony algorithm has strong flexibility and expansibility. By integrating with other algorithms and optimizing the parameter mechanism, it can adapt to various complex logistics scenarios with multiple constraints, dynamics, and scale, and has become the optimal algorithm in the current logistics transportation path planning.

4 Discussion

In recent years, the research and application of the ant colony algorithm in the field of logistics path planning has continued to deepen. However, combined with the latest research results after 2021, the algorithm still faces many unsolved problems and practical challenges: the real-time contradiction of large-scale scenes. When the size of customer points exceeds 500, even the improved ant colony algorithm will have the problem of a sharp increase in computational complexity, which makes it difficult to take into account both optimality and real-time. For example, during the e-commerce promotion period, the rookie intelligent logistics system faced the scenario of more than 800 distribution customer points in a single warehouse and single day during the peak period of the "double 11" promotion. Even if the improved ant colony algorithm was used for path planning, the solution time was still more than 2.5 hours, far exceeding the preparation cycle for the distribution vehicles to leave one hour in advance, which directly limited its application in the super large-scale logistics scenario; Moreover, the scene adaptation is insufficient, and the existing algorithm models are mostly based on idealized assumptions, ignoring the key factors in the real operation, resulting in obvious deviation between the theoretical optimization results and engineering practice. To solve these outstanding problems, scholars have put forward highly targeted improvement ideas. Li Qiangqiang proposed the "multi task assisted evolutionary algorithm", which combines the core advantages of ant colony algorithm and genetic algorithm, and reduces the calculation time by 40% in the super large-scale scenario test of 1000 customer points, providing a new solution to the real-time problem of large-scale scenarios [17]; Pang Lian introduced the analytic hierarchy process to scientifically determine the multi-objective weights, and achieved the balanced optimization of the economic and environmental benefits of logistics and transportation through the weighted summation method. These research results clearly pointed out the core optimization direction of ant colony algorithm in the future, that is, cross domain fusion of the algorithm, dynamic adjustment of multi-objective weights, and accurate modeling of actual constraints [18]. In addition, the real-time data support ability of logistics scenarios continues to improve, and the integration of ant colony algorithm with digital twins and deep reinforcement learning has become a new trend in industry development. By building a virtual logistics network to accurately simulate the real operation environment, the core parameters of the algorithm can be optimized in advance, and the adaptability and practicability of the ant colony algorithm in a dynamic and complex logistics environment can be further enhanced.

5 Conclusion

This article centers on the ant colony algorithm and systematically reviews its theoretical foundation, application cases, and optimization directions in logistics transportation route planning. Research indicates that, after improvements such as hybrid strategy integration, parameter adaptive adjustment, and algorithm collaborative optimization, the ant colony algorithm exhibits significant advantages in multi-constraint, dynamic, and large-scale logistics scenarios. Compared to traditional algorithms, it reduces transportation costs by 6%-12%, enhances convergence speed by 30%-42%, and shortens dynamic response time by 30%-40%. It has become the preferred algorithm for logistics route planning. Meanwhile, through a comparison of three typical cases, it also clarifies the applicable scenarios for different improvement strategies. The hybrid algorithm is suitable for multi-objective scenarios such as green logistics, the parameter adaptive algorithm is suitable for dynamic order scenarios, and the fusion algorithm is suitable for large-scale distribution scenarios.

However, there are still certain limitations in this study, which are mainly reflected in two aspects. Firstly, the case comparison focuses on domestic research results, with insufficient coverage of the latest international improved algorithms. Secondly, no customized analysis has been conducted for specific logistics segments such as cold chain logistics and bulk logistics. Although the research is universal, its pertinence is somewhat lacking.

Based on the research results and existing limitations, the future research on ant colony algorithm can be further promoted in three directions: first, promote the deep integration of ant colony algorithm, deep reinforcement learning and digital twins, so as to solve the real-time contradiction of large-scale dynamic scenes; second, establish a dynamic adjustment mechanism with multi-objective weights, and realize customized optimization in combination with the strategic needs of enterprises; third, strengthen the modeling of actual operation factors such as vehicle loading and customer priority, and further improve the engineering adaptability of the algorithm. As the core technology of intelligent logistics, the continuous innovation and development of ant colony algorithm will continue to promote the logistics industry to move towards the direction of high efficiency, low carbon and intelligence, and provide important technical support for the cost reduction and efficiency increase of the industrial chain supply chain.

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