Journal of Computer Science and Artificial Intelligence
ISSN: 3078-8242 (Print), ISSN: 3078-2309 (Online) | Vol. 5, No. 1, 2025

Research on Path Optimization of Urban Garbage Classification and Transportation Based on CVRP Model

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Abstract: With the acceleration of urbanization in China, the management of urban household waste is facing severe challenges. Optimizing and scheduling the path of garbage classification and transportation has become the key to improving efficiency and reducing costs. This article is based on the Vehicle Routing Problem (CVRP) model and combines multi-objective optimization methods to study complex scenarios involving single vehicles, multi vehicle collaboration, and intermediate stations. This article establishes a CVRP model with capacity constraints and uses greedy algorithm to generate paths, achieving the minimization of total driving distance. Through the verification of 30 collection points, the total driving distance was optimized to 1332.9 kilometers, and the time complexity and limitations of the algorithm were analyzed. The feasibility of introducing dynamic road network data to improve path planning was proposed. Then, the extended model is used for multi vehicle collaborative scheduling, taking into account the differences in load capacity, volume, and cost among the four types of garbage. Design a categorized path optimization algorithm to achieve the optimal solution for a total transportation cost of 1402.4 yuan, and explore the impact of time constraints on task splitting to verify the flexibility and robustness of the model.

Keywords: Vehicle Routing Problem (CVRP), Greedy Algorithm, Multi Vehicle Collaborative Scheduling.

1. Introduction

In recent years, with the rapid development of China, it has become the country with the largest global waste production since 2004 [1]. With the sharp increase in waste in recent years, corresponding problems have become increasingly prominent. Different waste classification and transportation routes can also affect energy consumption, time consumption, carbon emissions, and other issues [2].

This article aims to optimize the transportation path, taking into account various restrictions such as different types of garbage, collection, vehicle load and volume limitations, transfer station processing capacity, and cost control. Based on this, mathematical modeling is used to complete the corresponding optimization. Various types of garbage generated in daily life require classification and transportation by vehicles. Due to the different locations of residential buildings, vehicles need to go to different locations for collection. Different types of vehicles and their capacity and load capacity require vehicles to start from fixed locations for collection. During the collection process, transfer stations need to be established for transfer. There are n garbage classification collection points in a certain urban area, only considering the single type of "kitchen waste", which is transported by dedicated vehicles. Given the coordinates of each collection point, the amount of garbage generated, the maximum load capacity Q of the vehicle, and the fixed departure point (garbage treatment plant), the vehicle departs from the treatment plant and returns after completing the task, allowing multiple round trips. A mathematical model should be established with the goal of minimizing the total distance traveled, to determine the number of vehicles, transportation routes, and task allocation; Design an algorithm to solve the optimal solution and analyze the time complexity for the scenario of n=30 and Q=5 tons; Discuss the limitations of the model (such as not considering traffic congestion) and propose directions for improvement. Consider four types of garbage (kitchen waste, recyclables, hazardous, and others), each transported by dedicated vehicles with different vehicle loads, capacity limitations, and unit transportation costs. Each collection point may generate multiple types of garbage. The vehicle departs from the processing plant, completes the collection of similar garbage, and returns. Establish a multi vehicle collaborative model with the goal of minimizing total transportation costs; Analyze the changes in constraint conditions and solve the optimal solution for the four types of garbage data collected from 30 collection points and given vehicle parameters; If the constraint of "maximum daily travel time of vehicles" is added, explain the modification method of the model and its impact on path planning.

2. Research on Vehicle Routing Problem with Capacity Constraints

This article allows vehicles to travel multiple times to and from the processing plant, but assuming $i \leq Q$, there is no need to split tasks, so it can be considered as a path closure requirement for a single task. Path closure can be applied to single objective optimization, symmetric road network assumptions, and other parts, similar to the classical CVRP (Vehicle Routing Problem with Capacity Constraints) model [3]. This commonality is extended and based on the CVRP model and greedy algorithm, the efficient solution of path optimization under a single vehicle type is achieved. The model framework also provides a theoretical basis and algorithm support for the subsequent expansion of complex scenarios.

2.1. Establishment of CVRP Model

In the objective function equation, F (x) represents the objective function; M is an infinite integer, and by introducing the parameter M into the objective function, the algorithm can ensure that the number of vehicles is the first optimization objective and the vehicle path is the second optimization objective when solving the vehicle routing problem. That is, a solution with fewer vehicles is better than a solution with larger vehicles but smaller vehicle distances:

$$\min F(x)=M\sum_{i=1}^{n}\sum_{v=1}^{m}x_{0iv}+\sum_{j=0}^{n}\sum_{i=0}^{n}\sum_{v=1}^{m}x_{ijv}c_{ij} \quad (1)$$

Constraints:

(1) Indicate that each collection point is subject to at least one vehicle service constraint condition

$$\sum_{v=1}^{m}\sum_{i=0}^{n}x_{ijv}\geq 1 \qquad \forall j\in V' \quad (2)$$

(2) To constrain traffic flow, it requires a vehicle to arrive at a point and must leave that point after completing the service

$$\sum_{i=0}^{n}x_{ipv}-\sum_{j=0}^{n}x_{pjv}=0 \quad \forall p\in,\ v\in R \quad (3)$$

(3) Indicating that customer point i can only be served by one vehicle under the constraint condition

$$\sum_{v=1}^{m}y_{iv}=1 \quad \forall i\in V' \quad (4)$$

(4) Customer point j can only be served by one of the vehicles from other customer points i.

$$\sum_{i=1}^{n}d_i y_{iv}\leq Q \qquad \forall v\in R \quad (5)$$

(5) It indicates that the sum of the demands of vehicle V and customer points on the service route cannot exceed the loading capacity Q of the vehicle

$$y_{jv}=\sum_{i=1}^{n}x_{ijv} \quad \forall j\in V',\ v\in R \quad (6)$$

2.2. Model Solving Based on Greedy Algorithm

From the above analysis, it can be seen that path optimization under capacity constraints, minimizing total travel distance, etc., are consistent with the core characteristics of greedy algorithms (local optimal selection, efficiency). Greedy algorithms have become an ideal choice for solving problems due to their local optimal strategy, efficiency, and natural adaptation to capacity constraints and path closure. Despite the existence of local optimal risks, high-quality feasible solutions can still be generated through post optimization methods such as 2-opt, fully meeting the requirements of this article.

2.3. Algorithm Generation Under Capacity Constraints

(1) Read the coordinates (Xi, Yi,) and garbage amount Wi of 30 collection points.

(2) Ensure that the amount of garbage at each collection point Wi ≤ Q (Q=5 tons), and if Wi ≤ Q exists, it needs to be transported in batches.

(3) The validity of the input data needs to be verified (such as non negative coordinates, positive garbage amount, etc.).

(4) If Wi>Q actually exists, the task needs to be split into multiple transports, but the current model defaults to all Wi ≤ Q, simplifying the complexity of the problem.

(5) The algorithm can be extended to larger scale data (such as Q=100), but the time complexity will significantly increase.

2.4. Using Greedy Method to Obtain Visual Features Based on Matlab

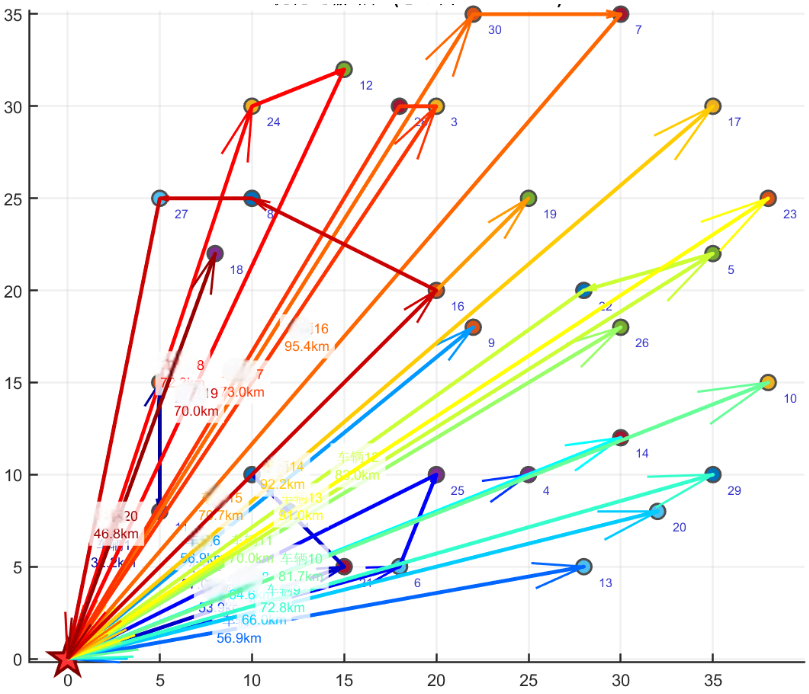

Figure 1. Optimized Path Image

From Figure 1, it can be seen that within the same cluster, points are spatially clustered, and the path naturally forms a radial shape, reducing cross regional intersections. Different nodes are assigned vehicles separately, showing a "star shaped" short line, and the dynamic labeling is clear, fully reflecting that under this path condition, the shortest distance of the optimized transportation path is about 1332.9 km.

2.4.1. Simplification of Road Network and Neglect of Traffic Factors

Symmetric distance assumption: The model uses Euclidean distance to calculate the distance between nodes, ignoring asymmetric constraints such as one-way streets, restricted areas, and traffic congestion in the actual road network. For example, the actual distance traveled from point i to point j may differ from the reverse distance, resulting in path planning results deviating from the optimal solution.

Constant speed assumption: Assuming that the vehicle always travels at a constant speed, without considering the speed fluctuations caused by congestion or road construction during peak hours, it may underestimate the actual transportation time.

Improvement direction: Introduce real-time data update module, combine historical data to predict fluctuations in garbage volume, and dynamically adjust path planning [4]. Add time window constraints and incorporate vehicle travel time into the model to ensure task completion within 12 hours. Construct an asymmetric distance matrix based on actual road network data and calculate the shortest feasible path using algorithm.

2.4.2. The Global Optimization Ability of Greedy Algorithm is Limited

Local optimal trap: The greedy algorithm only selects the current nearest node at each step, which may lead to path redundancy. For example, prioritizing access to nodes in dense areas may force subsequent vehicles to detour around sparse areas, increasing the total distance traveled.

Insufficient capacity utilization: If the amount of garbage at the end node of a certain path is close to the remaining capacity of the vehicle, but the demand of the next nearest node exceeds the remaining capacity, it will cause the vehicle to return early and the load utilization rate will be insufficient (such as the remaining 1 ton capacity cannot serve the 0.8 ton node).

Improvement method: Combine greedy algorithm with local search algorithms such as BBBB simulated annealing to optimize the path and reduce detours. By using genetic algorithm or ant colony algorithm, we can escape from local optima through population evolution and improve the quality of global solutions.

3. Optimization Research on Multi Type Vehicle Collaboration and Multi Constraint Conditions

The core of this chapter lies in the collaboration of multiple types of vehicles and global optimization under multiple constraint conditions. Through mathematical modeling, algorithm extension and solution, optimization results and analysis, etc., transportation costs can be minimized while ensuring feasibility [5]. The addition of time constraints further tests the flexibility and robustness of the model, requiring efficient scheduling through task splitting and dynamic adjustment.

3.1. Establishment of Mathematical Models

Objective function:

With the goal of minimizing the total transportation cost, taking into account the differences in vehicle load, volume, and transportation costs, a multi vehicle collaborative transportation model is established:

$$\min \sum_{k=1}^{4}\sum_{l=1}^{m_k} c_k d_{l,k} \tag{7}$$

Constraints:

Load and Capacity Limitations:

$$\sum_{i\in R_{l,k}} w_{i,k} \le Q_k \tag{8}$$

$$\sum_{i\in R_{l,k}} v_i \le V_k \tag{9}$$

Service integrity:

$$\sum_{l=1}^{m_k}\sum_{i\in R_{l,k}} w_{l,k} = \sum_{i=1}^{30} w_{i,k} \forall k \tag{10}$$

Path closure: The vehicle path needs to depart from the processing plant and return without duplicate nodes.

3.2. Algorithm Extension and Solution

The multi type vehicle collaborative model needs to be extended to multi vehicle collaborative transportation based on the CVRP model, which will face the challenge of coordinating multiple vehicle transportation and independent scheduling. At this time, it is necessary to optimize independently by type and adjust globally, as well as enhance the requirements for algorithms.

3.3. Optimization Results and Analysis

For multi vehicle collaborative transportation scenarios, the model achieves the minimization of total transportation costs through classification based path optimization and global collaborative strategies. Under the condition of no time constraint, the transportation task of four types of garbage was reasonably allocated to 11 dedicated vehicles, and the total cost was reduced to 1402.4 yuan. Among them, kitchen waste is handled by three vehicles with a load capacity of 8 tons, with path examples of [0 → 13 → 28 → 0] and [0 → 12 → 19 → 27 → 0]. The total load capacity is 7.8 tons, which is close to the upper limit of vehicle capacity and effectively improves the utilization rate of load capacity; Recyclable materials and hazardous waste are transported by 3 and 2 vehicles respectively, and the path design avoids redundant driving across regions. The total cost is 400 yuan and 300 yuan, respectively. It is worth noting that other garbage is scattered and needs to be covered by 3 vehicles. Although the total load capacity is 9.5 tons, the unit distance cost is reduced through path merging strategy, as shown in Table 1.

Table 1. Time unconstrained scenario chart

Garbage type	Number of vehicles	Path Example	Total load capacity (ton)	Total cost (yuan)
kitchen waste	3	[0→13→28→0], [0→12→19→27→0]	7.8 / 8	400
recyclable	3	[0→6→26→0], [0→4→5→0]	5.9 / 6	400
hazardous waste	2	[0→7→15→22→0]	2.8 / 3	300
Other Waste	3	[0→2→10→0], [0→8→17→0]	9.5 / 10	302.4
total	11	—	—	1402.4

Time constrained scenario (Tmax=6 hours):

The original path [0 → 12 → 19 → 27 → 0] [0 → 12 → 19 → 27 → 0] (distance 120 km, time 3 hours) does not require adjustment; If the path distance is 300 km (7.5 hours), it can be divided into [0 → 12 → 0] [0 → 12 → 0] and [0 → 19 → 27 → 0] [0 → 19 → 27 → 0]. Cost comparison: The total cost has increased to 1402.4 yuan, the number of vehicles has increased to 11, and the time compliance rate is 100%.

4. Conclusions

Through classified scheduling and path optimization, the model achieved a minimum total transportation cost of 1402.4 yuan while satisfying load, volume, and time constraints. It can also be further improved in practicality by combining dynamic road network data with multi-objective optimization. At the same time, this article can support the differences in load capacity, volume, and cost of different vehicle types, adapt to the independent transportation needs of four types of garbage, adjust the path through time constraints, flexibly respond to timeout scenarios, ensure timely completion of tasks, extend the algorithm, and retain the efficiency of greedy strategies, making it suitable for multi type garbage scenarios.

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