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OPTIMIZATION OF VEHICLE ROUTE FOR URBAN CLASSIFIED WASTE TRANSPORTATION

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Abstract: With the acceleration of urbanization, China faces severe challenges in waste management. Currently, waste sorting and transportation have become a key aspect of urban environmental governance, influenced by factors such as vehicle capacity constraints and collection requirements for different types of waste. This paper addresses the issue of urban waste sorting and transportation by constructing and solving optimization models under different constraints, effectively reducing transportation costs and carbon emissions while enhancing transportation efficiency. This paper simplifies such problems into the capacitated vehicle routing problem(CVRP), aiming to minimize the total daily transportation distance while considering constraints such as vehicle capacity constraints and multiple round-trip deliveries. A single-type waste transportation route optimization model is constructed and solved using a hybrid heuristic algorithm. Further considering dedicated vehicles for different types of waste, as well as their load, volume, time, and transportation cost constraints, new constraints are introduced based on this model, and a divide-and-conquer strategy and hybrid heuristic algorithm(HHA) is adopted to solve the multi-type waste transportation route optimization problem. By iteratively optimizing the routes, the transportation routes for various types of waste are reasonably planned, effectively reducing the cost of urban waste transportation.
Keywords: Capacitated Vehicle Routing Problem(CVRP); Route optimization; Divide-and-Conquer strategy; Hybrid heuristic algorithm

1 INTRODUCTION

As urbanization accelerates, China is confronted with formidable challenges in waste management. The vast quantities of waste produced are nearing the limits of the processing capacities of cities and regions across the country, rendering the issue of waste management increasingly prominent and demanding higher standards for the collection, transportation, and disposal of household waste. Among these, the classified transportation of waste constitutes a pivotal aspect of urban waste management, and the formulation of scientific and efficient waste classification and transportation routes is vital for urban environmental governance.

In reality, the issue of waste transportation has garnered significant attention from scholars owing to its complexity, which encompasses factors such as time windows, vehicle capacity, and citizen satisfaction. Shi et al. modeled this as a multi-depot vehicle routing problem (MDVRP) [1], aiming to minimize the total transportation distance. Involving with constraints such as warehouse supply and demand, vehicle capacity, they introduced a two-stage heuristic algorithm to address it. Yousra Bouleft et al. proposed a linear mathematical programming model to address the dynamic multi-compartmental vehicle routing problem (DM-CVRP) for selective and intelligent waste collection [2], aiming to minimize the total cost and incorporating constraints such as vehicle compartment capacity, waste station access rules, etc., and used the hybrid genetic algorithm (HGA) to solve. Yu et al. focused on the college scene [3], constructed a route optimization model and used ant colony optimization(ACO) algorithm, aiming at minimizing total clearance distance as the goal and considering the vehicle capacity and start-stop constraints. Mou et al. aimed to minimize total costs and established two types of route optimization models for separate transportation and joint transportation of classified waste [4], discussing both models by the optimization results. Shen et al. introduced the fuzzy membership function of residents' dissatisfaction degree [5], established a multi-objective model with minimum cost and maximum satisfaction degree, and solved it with NSGAⅡ algorithm. Zhou et al. build a multi-objective model covering economy [6], society and environment, and solved it with an improved algorithm which combined NSGA-III with simulated annealing. Wu et al. constructed a priority considered green vehicle routing problem (PCGVRP) model in a waste management system [7], and designed specific algorithms to solve it.

The existing research mostly focuses on single or partial scenarios, and rarely involves the classification and transportation of urban multiple wastes. Aiming at this problem, this paper first constructs a single-type of waste transportation vehicle routing optimization model, with the minimum total distance as the goal, considering the vehicle load and multiple transportation constraints, and uses a hybrid heuristic algorithm to solve it; Furthermore, the collaborative constraints of multi-type special vehicles are introduced to construct a multi-type waste transportation vehicle routing optimization model with the goal of minimizing the total daily transportation cost, which effectively reduces the transportation cost and improves the transportation efficiency.

2 VEHICLE ROUTING OPTIMIZATION FOR SINGLE-TYPE WASTE

Considering the complexity of the actual situation, this paper makes the following assumptions: all transport vehicles start from the same fixed departure point and return after completing the task; Each type of waste must be transported by vehicles specially designed for that type; The traffic conditions of the roads used during transportation are stable, and sudden traffic jams or road closures are not considered.

2.1 The Construction of Single-type Waste Transportation Vehicles Routing Optimization(S-VRO) Model

Capacitated vehicle routing problem (CVRP) is a classical combinatorial optimization problem [8-10], which involves how to efficiently allocate vehicles to visit multiple customer points, and reduce the total distance or cost as much as possible under the condition of meeting the vehicle capacity constraints. CVRP is widely used in logistics, distribution, transportation and other fields. The vehicle routing problem for a single type of waste transportation described in this paper is a vehicle routing problem with vehicle load limit, which belongs to CVRP. Now the mathematical model of CVRP is introduced to build a single type of waste transport vehicle routing optimization model.

2.1.1 Definition of parameters

n: number of waste collection points; (x_i, y_i): coordinates of waste collection point i; ω_i: waste generation quantity at point i; Q: vehicle maximum load; (x_0, y_0):the fixed location of waste processing plant; d_{ij}: euclidean distance between points i and j, and $i, j = 1,2, \dots, n$.

2.1.2 Decision variables

Let x_{ijk} be a 0-1 variable, indicating whether the kth vehicle travels from the collection point i to the collection point j. Let y_{ik} be a 0-1 variable, denoting whether the kth vehicle serves the collection point i. e_k is the total transportation distance of the kth vehicle. m denotes number of vehicles used in the transportation.

2.1.3 Objective function

The model aims to minimize the daily total transportation distance, shown as formula(1)-(3).

$$\min \sum_{k=1}^{m} e_k \tag{1}$$

$$e_k = \sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij} x_{ijk} \tag{2}$$

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{3}$$

2.1.4 Constraints

Vehicle load limit: the transportation volume of each vehicle shall not exceed its maximum load Q tons, shown as formula (4):

$$\sum_{i=1}^{n} w_i y_{ik} \leq Q, \quad \forall k \tag{4}$$

Rationality of vehicle route: each vehicle must start from the waste processing plant and finally return to the waste processing plant, shown as formula (5). Among them, the first constraint ensures that each vehicle starts from the waste processing plant, and the second constraint ensures that each vehicle finally returns to the waste processing plant.

$$\sum_{j=1}^{n} x_{0jk} = 1, \ \sum_{i=1}^{n} x_{i0k} = 1, \quad \forall k \tag{5}$$

Service integrity: each waste collection points need be served by a vehicle, shown as formula(6)

$$\sum_{k=1}^{m} y_{ik} = 1, \quad \forall i = 1, \dots\dots, n \tag{6}$$

Route continuity: the route of each vehicle is continuous. For the collection point served by each vehicle, the route continuity must be guaranteed, that is, the number of routes entering and leaving a collection point is equal, shown as formula (7).

$$\sum_{i=0}^{n} x_{ipk} = \sum_{j=0}^{n} x_{pjk} = y_{pk}, \quad \forall \mathrm{p} = 1, \dots\dots, n, \forall \mathrm{k} \tag{7}$$

2.2 The Solution of S-VRO Model

This paper proposes a vehicle route planning problem based on 30 waste collection points to test the ability of the model and algorithm in solving the real urban waste transportation problem. The main content is to find the shortest path for waste transport vehicles under the condition that the load limit of a single vehicle is not more than 5 tons. Each vehicle is required to start from the waste processing plant, visit a certain point in turn and return to the waste processing plant. The amount of waste per trip shall not exceed the load limit of a single vehicle. Set the location coordinates of the waste processing plant to (0, 0), and the locations of 30 waste collection points and their waste volume distribution are shown in Figure 1.

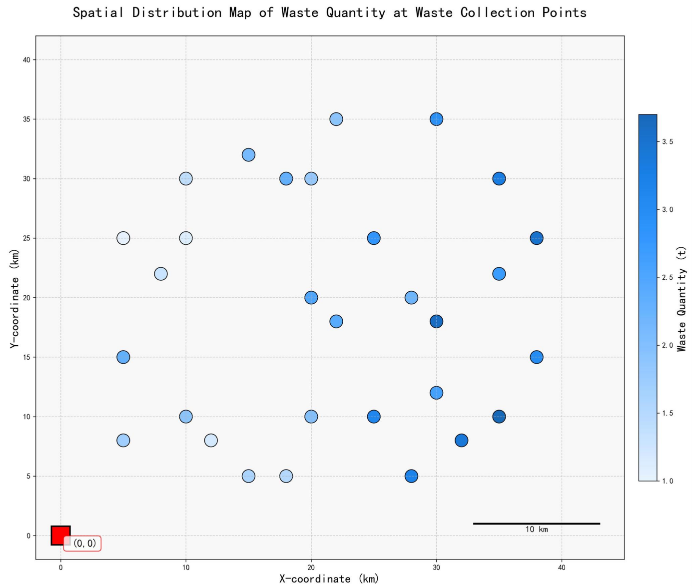

Figure 1 Thermodynamic Diagram of Spatial Distribution of Waste Quantity

This study uses hybrid heuristic algorithm(HHA) to solve S-VRO model.

In the initial solution construction phase, a feasible initial solution is rapidly generated via the cheapest insertion constructive heuristic algorithm, utilizing Euclidean distances computed from the coordinates of collection points. This solution satisfies the following constraints:

(1) Each vehicle departs from and returns to the disposal plant.

(2) Every collection point is serviced exactly once.

(3) The total load on any vehicle does not exceed the maximum load Q.

In the local search optimization phase, path refinement is performed through 2-opt edge exchange and node relocation operations. These mechanisms iteratively improve routes by targeting the minimization of total transportation distance, directly contributing to distance reduction by eliminating circuitous subpaths.

In the stage of constraint propagation, the solutions violating constraints are detected and trimmed in real time, and the load limit and the route continuity are dynamically maintained.

In the constraint propagation phase, solutions violating constraints are detected and pruned in real-time, dynamically enforcing capacity limits and route continuity.

In the search tree exploration phase, depth-first and best-first strategies are integrated. Through pruning of suboptimal branches and periodic restart mechanisms, global optimization is balanced with computational efficiency within limited time.

The algorithm ultimately outputs a near-optimal solution satisfying all constraints with minimized total transportation distance. This collaborative four-stage framework achieves efficient resolution of the waste collection vehicle routing problem.

The optimization result is shown in Figure 2. By optimizing the routes, under the premise of ensuring that each waste collection point is served by one vehicle, the detour of vehicles is avoided, which helps to reduce the total transportation distance of waste vehicles and improve the transportation efficiency.

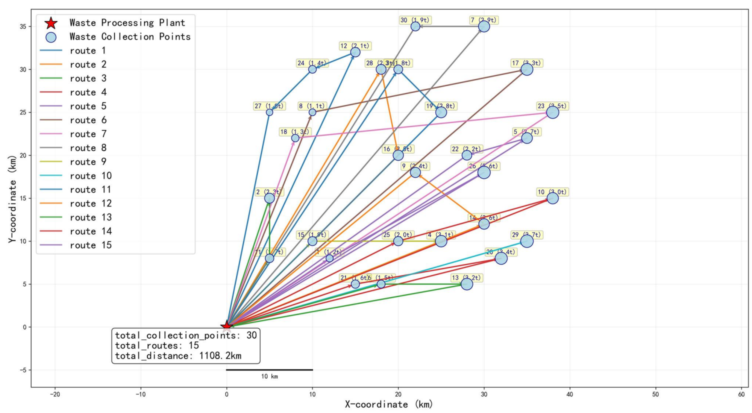

Figure 2 Single-Type Waste Transportation Routes

3 VEHICLE ROUTING OPTIMIZATION FOR MULTI-TYPE WASTE

3.1 The Construction of Multi-type Waste Transportation Vehicles Routing Optimization(M-VRO) Model

Various types of waste need different types of special vehicles to transport, and different vehicles have different capacity constrains (including load and volume) and transportation costs per unit distance. The working hours of each vehicle are also limited. A collection point may contain a variety of waste types, and the transportation routes and task allocation of each vehicle of different types schedules separately.

On account of the different types vehicles schedule separately, this multi-type vehicle routing problem (M-VRP) can be decomposed into multiple single-type vehicle routing subproblems. Namely, the divide-and-conquer strategy is used to solve the M-VRP:

(1) The original M-VRP is partitioned into homogeneous vehicle-specific subproblems based on type constraints;

(2) Each single-type VRP subproblem is solved independently using HHA;

(3) The partial solutions are then integrated through a coordination mechanism to construct a complete vehicle scheduling scheme.

This study is based on the single type of waste transportation vehicle routing optimization model proposed in the previous paper, aiming at minimizing the total daily transportation cost, and introduces new constraints to build a multi type of waste transportation vehicle routing optimization model. Apart from the parameters, variables and constrains defined in 2.1 part, this part adds some new things.

3.1.1 Definition of parameters

t: waste category index; w_{it}: weight(ton) of category t waste at collection point i; v_{it}: volume (m³) of category t waste at collection point i ; Q_t: maximum payload capacity (ton) for type-t vehicles; V_t: maximum volumetric capacity (m³) for type-t vehicles; C_t: unit transportation cost (yuan/km) for type-t vehicles; T: daily maximum work time of each vehicle. S: the travel speed of each vehicle.

3.1.2 Decision variables

Let m_t denotes number of type-t vehicle in the transportation.

3.1.3 Objective function

The model aims to minimize the daily total transportation cost, shown as formula(8)

$$\min\sum_{i=1}^{n}\sum_{j=1}^{n}C_t\,d_{ij}x_{ijk},\ \forall \mathrm{t},k \tag{8}$$

3.1.4 Constrains

Vehicle load limit: the transportation load of each type-t vehicle shall not exceed its maximum load Q_t tons, shown as formula (9).

$$\sum_{i=1}^{n}w_{it}\,y_{ik}\le Q_t,\quad \forall \mathrm{t},k \tag{9}$$

Vehicle volume limit: the transportation volume of each type-t vehicle shall not exceed its maximum load V_t tons, shown as formula (10).

$$\sum_{i=1}^{n}v_{it}\,y_{ik}\le V_t,\quad \forall \mathrm{t},k \tag{10}$$

Vehicle work time limit: the daily work time of each vehicle shall not exceed its maximum time T hours, shown as formula (11).

$$\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}d_{ij}\,x_{ijk}}{S}\le \mathrm{T},\quad \forall k \tag{11}$$

And the constrains of rationality of vehicle route, service integrity, route continuity is same as the formula(5)-(7).

3.2 The Solution of M-VRO Model

Similarly, in the scenario of 30 waste collection points and 1 waste processing plant, there are four types of waste, namely food waste, recyclables, hazardous waste and other waste. Each collection point can produce four types of waste. Each type of waste needs to be transported by special vehicles. The vehicle types correspond to the above four types of waste respectively. Their load limit, volume limit and transportation cost per unit distance are different, as shown in Table 1. Vehicles start from the treatment plant and return after collecting the same type of waste. Different types of vehicles can be scheduled independently. The density of food waste, recyclables, hazardous waste and other waste is 700 kg/m³, 200 kg/m³, 900 kg/m³, 400 kg/m³.

Table 1 Parameters of Four Types Waste Transport Vehicles

Type	Load(tons)	Volume(m³)	Cost(yuan/km)
Food waste	8	20	2.5
Recyclables	6	25	2

Hazardous waste	3	10	5
Other waste	10	18	1.8

The spatial coordinates of the waste processing plant and 30 collection points remain fixed. Each collection point generates multiple waste categories, with the spatial distribution of waste streams visualized in Figure 3. Analysis confirms that all points produce quantifiable amounts of four waste types.

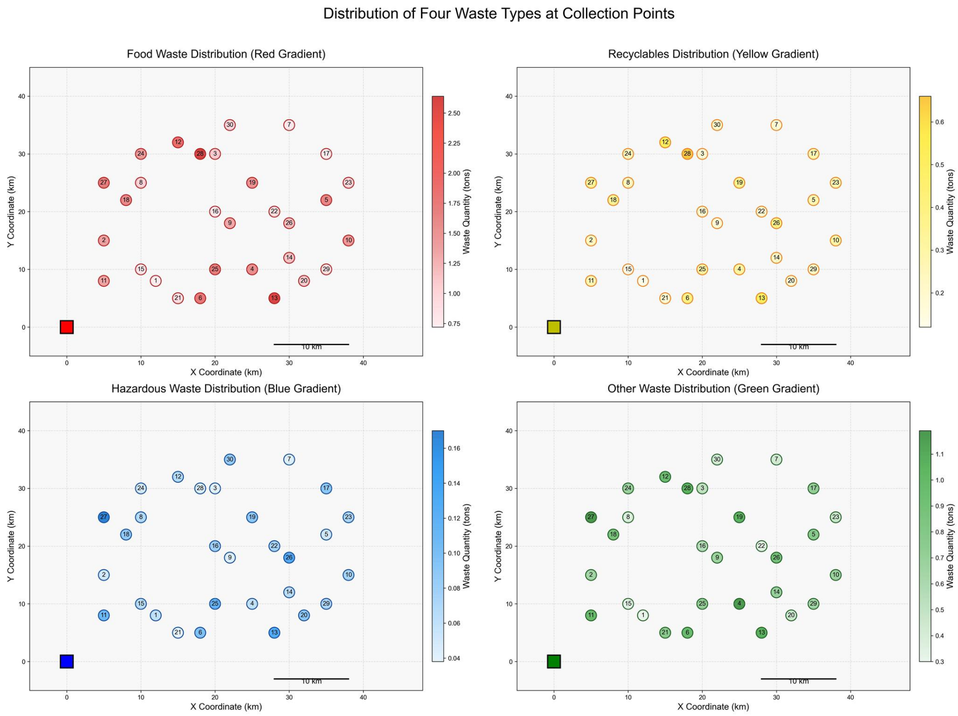

Figure 3 Thermodynamic Diagram of Spatial Distribution of Four Types Waste Quantity

In this paper, the divide-and-conquer strategy is used to solve each type of waste transportation route one by one using HHA. The final optimization results are shown in Figure 4. After route optimization, the transportation routes of different types of waste are reasonably allocated, and the vehicle load, volume requirements and time constraints are not violated.

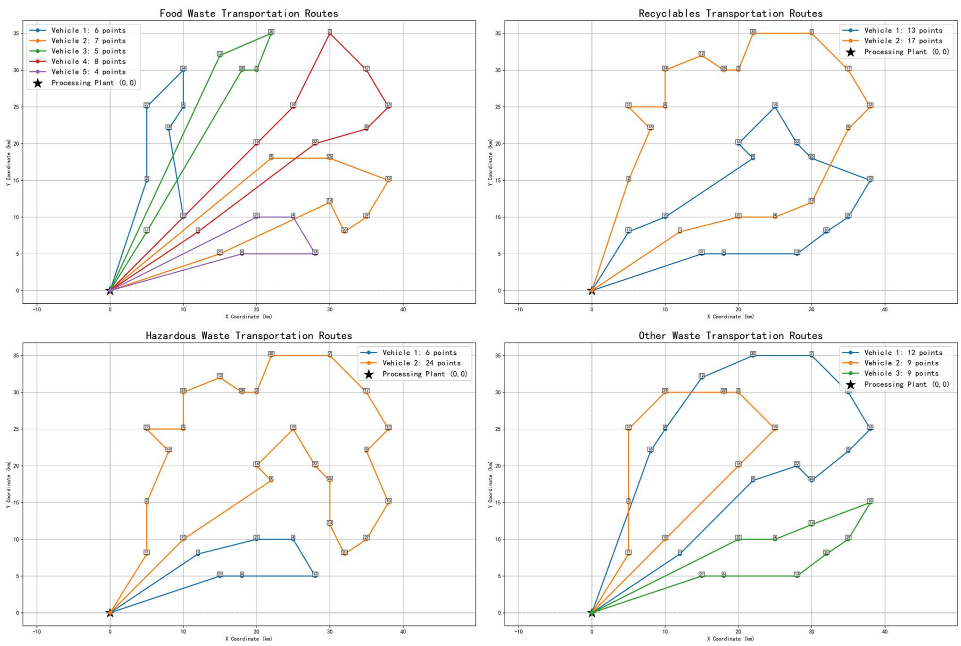

Figure 4 Four Types Waste Transportation Routes

The Figure 5 illustrates the load and volume utilization rates of specialized waste collection vehicles. For food waste, recyclables, and other waste vehicles, both load and volume metrics approach operational maxima (98-100% utilization), achieving near-full capacity efficiency. This phenomenon further demonstrates the critical influence of waste density on transport operations: lower-density waste streams predominantly constrain vehicle volume capacity.

Conversely, hazardous waste vehicles exhibit suboptimal utilization rates. This inefficiency stems from the daily work time constrains. When a vehicle's daily operating time reaches its 8-hour regulatory limit, remaining tasks are reallocated to supplementary vehicles. Although this time-based scheduling inevitably incurs additional costs, it ensures compliance with occupational safety regulations.

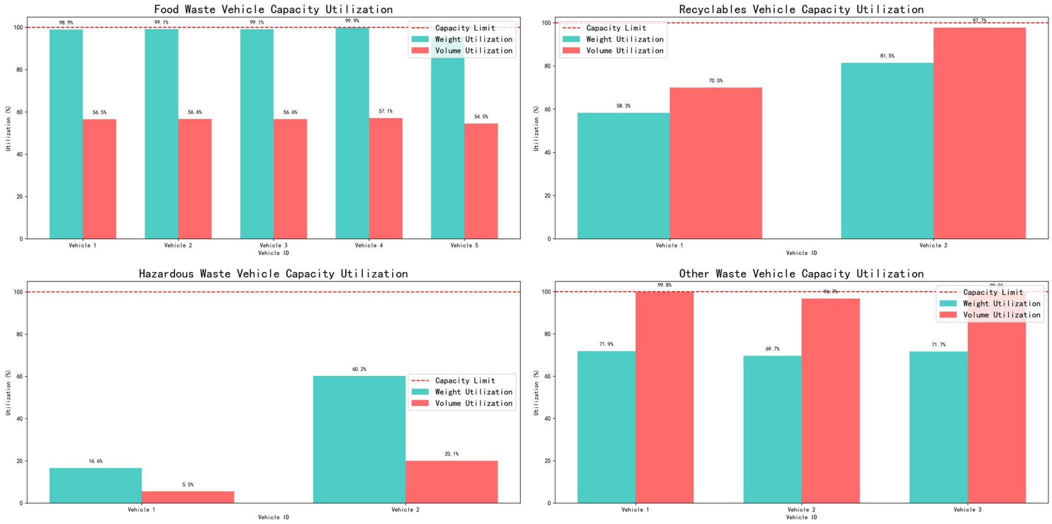

Figure 5 The Capacity Utilization of Four Types Waste Vehicles

4 CONCLUSION

The optimization model constructed in this paper provides scientific decision support for the management of classified waste transportation. Firstly, this paper constructs a single-type of waste transportation vehicle routing optimization model, based on which a multi type of waste transportation vehicle routing optimization model is proposed, and the model is solved by combining divide-and-conquer strategy and hybrid heuristic algorithm. Finally, this paper verifies the effectiveness of the model and algorithm through the analysis of an example, and draws a conclusion. The model not only reduces the transportation cost, shortens the driving distance, but also meets the actual operation requirements such as specialized vehicles coordination and time limit. At the same time, the model solving idea of the combination of divide-and-conquer strategy and hybrid heuristic algorithm proposed in this paper can be applied to the actual scene of urban domestic waste transportation, and provide technical support for improving the economy, efficiency and environmental protection of classified waste transportation. Future research can further consider dynamic traffic conditions, waste production fluctuations and other factors to enhance the robustness and practical adaptability of the model.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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