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Research on the Optimization of Domestic Waste Recycling Network Under the Background of Low Carbon

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Abstract

To reduce the carbon emissions from waste collection vehicles, taking the representative Baolang Economic Development Zone in Shiyan City as an example, a two-stage urban domestic waste logistics collection and transportation model was established. In the first stage, the goal was to minimize the total distance, determining the optimal location for waste transfer stations. In the second stage, with the goal of minimizing total costs, and based on the determined optimal location of the transfer stations, the optimal waste collection vehicle routing was established. A genetic algorithm was designed to solve the optimal results for both stages, obtaining the best location for waste transfer stations and the optimal transportation routes for the Baolang District in Shiyan City. The optimization was compared and showed significant results. Finally, in light of the actual situation of domestic waste in the urban area of Shiyan City, suggestions were made to optimize the urban domestic waste collection network.

Keywords: Green and Low-Carbon; Garbage Collection and Transportation; Logistics Network; Optimization Model; Vehicle Path Problem

1. Introduction

In recent years, the production of urban household waste has been on the rise, making the efficiency and management of waste disposal an urgent issue to address. Waste reduction through carbon emission is one of the five key areas for achieving the dual carbon goals. How to effectively sort waste and how to reduce carbon emissions during the collection and processing of waste are crucial for realizing green and low-carbon urban development. In 2021, the State Council pointed out in the "Notice on the Comprehensive Work Plan for Energy Conservation and Emission Reduction during the 14th Five-Year Plan Period" that urban sanitation cleaning and transportation are among the targets of China's transportation and logistics energy conservation and emission reduction projects. In response to these directives, the integration of waste collection route optimization models has emerged as a key technological pathway. These models utilize algorithms such as the Vehicle Routing Problem (VRP), Ant Colony Optimization (ACO), and Genetic Algorithms (GA) to intelligently plan waste collection paths that minimize total distance traveled, avoid redundancy, and reduce vehicle idling time. By dynamically adjusting collection schedules based on real-time waste generation data and road traffic conditions, these models help significantly reduce fuel consumption and associated carbon emissions.

Moreover, the application of such intelligent systems ensures that sanitation vehicles operate with maximum logistical efficiency, aligning with the 14th Five-Year Plan's call for smart and green urban infrastructure. Cities like Shanghai and Shenzhen have begun pilot projects where AI-powered route optimization has led to emission reductions of over 15% in certain districts, serving as evidence of the practical benefits of these systems.

In summary, the quality of construction and operation of urban household waste recycling networks directly impacts local urban environmental hygiene and green low-carbon development.

Waste collection network optimization is a complex and multifaceted issue, involving multiple disciplines such as engineering, management, operations research, and environmental science. Liu (2011) started from the practical needs of waste collection in small and medium-sized cities, constructing a scheduling and path optimization model for green and low-carbon vehicles. This research provides theoretical support for scientifically and efficiently conducting waste collection work; In the process of studying urban waste collection system construction, Jia (2006) drew on the concept of reverse logistics system location selection, applying a set cover model to screen and optimize candidate waste transfer station locations according to the specific requirements of the system; During the waste collection process, Wang (2013) developed an indicator system based on the characteristics and content of carbon emissions. Using basic theories from operations research, he proposed a formula for calculating carbon reduction after optimizing the waste collection system, concluding that carbon reduction in the waste collection system is a crucial aspect of building a low-carbon city. In the study of urban waste collection system optimization, foreign scholar Caroline Lavigne (2021) proposed an optimization model for the biological waste collection problem in the Brussels Capital Region. The model uses mixed integer linear programming to optimize waste collection routes, considering multiple waste stations, vehicles with capacity, intermediate processing facilities, and multiple collections. By minimizing transportation costs, it evaluates the financial feasibility of different collection schemes. At the front end of waste collection and transportation, Teemu Nuortio (2005) identified collection issues as one of the most challenging operational problems. He proposed a conceptual model for addressing these issues and several methods to accelerate speed and reduce memory usage in real-world waste collection scenarios. The results showed that compared to current practices, the cost of waste collection in this region was significantly reduced. Regarding cross-regional waste collection and transportation, Wei Zeming noted that while the currently adopted MSW sub-regional operation and disposal model has brought convenience to management, it suffers from inflexible vehicle scheduling and low efficiency due to the limitations of operational area divisions. To address these issues, he proposed an improved Hierarchical Agglomerative Clustering (IHAC) algorithm and a Waste Collection Path Planning (GCPP) algorithm.

For the optimization of waste collection networks, scholars both domestically and internationally have conducted extensive research. However, these discussions still fall short when viewed from the perspective of China's green and low-carbon context. Currently, studies on urban household waste collection networks in China are just beginning, lacking systematic and comprehensive approaches. Most research focuses on policy, with a lack of data-driven and quantitative studies. More scientific design and technical means are needed to address urban household waste collection issues from a green and low-carbon perspective. Based on this, this paper will comprehensively consider the aforementioned issues, using the Bailang Development Zone as an example to analyze its current status and problems in waste management. By leveraging existing data, it aims to reasonably predict future waste production. The paper will also explore and develop new optimization algorithms and models to provide more accurate and efficient solutions. These innovations in methods and technologies can not only be applied to the field of waste collection but also promote development in other related areas, such as logistics management

2. Construction of Garbage Recycling Network Model

2.1. Problem Description

Mixed collection is the primary model currently adopted by urban waste collection systems. The front end employs a circular transportation model, while the middle end uses a vehicle dispatch system and the "five fixed" measures. The waste recycling network includes various terminal collection points, transfer stations, incineration plants, and landfills. Household waste is collected from community points by transport vehicles, then transported to transfer stations for compression processing, and finally sent to waste treatment facilities for disposal (Tian, 2012).

Given that a certain sanitation base has a collection of garbage transport vehicles, S waste transfer stations, L, and garbage collection points, N, the problem of scheduling and optimizing routes for green and low-carbon transport vehicles can be described as follows: Based on waste sorting, transport vehicles depart from the sanitation base to reach various garbage collection points. Under the constraints of vehicle load capacity and time windows, waste is collected and transported to loading stations, and then sorted according to its type before being delivered to different processing facilities for disposal. On this basis, with the goal of minimizing costs, the first stage involves determining the optimal location of transfer stations to minimize transportation distance, thereby reducing logistics costs; the second stage focuses on minimizing both fixed and variable costs of garbage collection vehicles. Throughout these two stages, measures are taken to reduce environmental negative impacts. This approach aims to solve the problems of selecting transfer station locations and vehicle scheduling (Wen et al., 2015).

2.2. Build Goals

When dealing with complex problems, decisions can be made in stages, using the optimal solution from the first stage as the initial condition for the second stage decision-making process. This involves finding the most optimized solution again. The optimization at both levels is interconnected and works together to address the entire problem, ultimately achieving a comprehensive and meticulous optimization goal. The specific objective of the two-stage planning described in the text is to minimize total costs: the costs involved in waste collection mainly consist of two parts—cost generated by the location selection of transfer stations, and the cost incurred by the waste collection routes (Li et al., 2023). Specifically, this includes the investment in constructing waste transfer facilities, subsequent operation and maintenance expenses, as well as the movement costs and fixed expenses of collection vehicles during their tasks in the second-stage model. Waste collection costs account for a significant portion of the overall cost of the recycling system, so the aim of the text is to save costs by optimizing waste collection routes.

2.3.Model Assumptions And Symbolization

2.3.1. Basic Assumption

According to the above problem description, considering the characteristics of urban household waste reverse logistics network and the feasibility of mathematical model, the following assumptions are put forward for the main body in the recycling network before the establishment of the model (An, 2022):

(1) Transport vehicles

1) The road is smooth, and there are no abnormal conditions such as congestion or vehicle failure.

2) The process from the transfer station to return to the transfer station is equal to one trip. When the carrying capacity and working time of the vehicle allow, multiple trips can be carried out;

3) The driving distance between the nodes is the straight line distance, and the driving speed is a fixed average speed and remains unchanged.

(2) Transfer points

1) The geographical location of the transfer station is known, and the parking lot of the transport vehicle and the transfer station are located in the same place;

2) The capacity of the constructed garbage transfer station is sufficient to carry out garbage sorting, compression and temporary storage.

(3) Collection points

1) Collection points are based on communities;

2) The capacity of the collection point is sufficient.

(4) Household waste

1) The garbage transported to the waste treatment plant is located in the same transfer station;

2) The output of all kinds of garbage at the collection point is fixed and will not increase or decrease.

(5) Others.

1) All waste recycling is carried out only in the recycling network constructed in this paper:

2) The variable cost is positively correlated with the transportation distance of the vehicle, and there are no other factors.

2.3.2. Symbol Description

(1) Parameters and sets

1) Transport vehicles

M = {m=1,2,3,..., M} is set as the collection of garbage collection vehicles, and m is the element number; N = {n =1,2,3,..., N} is set as the garbage collection vehicle set, and n is the element number; P = {p=1,2,3,..., P} is set as the collection of garbage transfer vehicles, and P is the element number; R = {r =1,2,3,..., R} is set as the set of garbage transfer vehicles, and r is the element number; Cm is the fixed cost of garbage collection and transportation vehicle, Fm is the variable cost of garbage collection and transportation vehicle; Cp is the fixed cost of garbage transfer vehicle, Fp is the variable cost of garbage transfer vehicle; Qm is the load limit of garbage collection and transportation vehicle; Qp is the load limit of garbage transfer vehicle; TM is the working time of the collection and transportation vehicle; Tp is the working time of the transfer vehicle.

2) Transfer stations and treatment plants

U = {u|u =1,2,3,......, a} is the set of existing garbage transfer points, indicating that there are a total of a garbage transfer points; Y = {v|v =1,2,3,......,b} is the set of candidate points for garbage transfer, indicating that there are b candidate points; Z = {z =1,2,3,..., c} is set as the collection of waste treatment plants, indicating that there are c waste treatment plants in total;

Lzv is the distance from waste transfer point v to waste treatment plant z; Tv is the loading and unloading time at the waste transfer point v; Z is the unloading time at the waste treatment plant z; Cv is the final investment cost of establishing a comprehensive transfer station at v; C is the total cost of operating a transfer station; Qv is the maximum capacity of the waste transfer station.

3) Collection points

H = {h =1,2,3,......, d} is the set of garbage collection points, indicating that there are d collection points; Qh is the total population of garbage collection point h; Th is the loading and unloading time at the garbage collection point h.

4) Household waste

S= {s = 1,2,3,..., S} is the number of garbage types; Qh is the amount of garbage generated at collection point h.

5) Others

Lij is the transportation distance from node i to j; Tij is the transportation time from node i to j, and Lij =vtij; Cv is the final investment cost of establishing a comprehensive transfer station at v; E is the negative environmental utility of the residential unit.

(2) Decision variables

Xnij = 1, the number of garbage collection and transportation vehicles n from node i to node j, i = j Zero, otherwise Ynm = 1, the number of vehicles corresponding to the number of garbage collection and transportation trips n is m Zero, otherwise Ypr = 1, the number of r trains transporting garbage corresponds to the vehicle number p Zero, otherwise Whu = 1, the garbage from collection point h is transported to transfer station u Zero, otherwise Bv = 1, and a transfer station is built at v Zero, otherwise Duz = 1, the garbage from transfer station u is transferred to treatment plant z Zero, otherwise.

2.3.3. The First Stage is Site Selection

(1) Model assumptions.

1) Suppose that the garbage collection station is concentrated at a point;

2) It is assumed that the construction and operation costs of transfer stations in different regions are equal;

3) Transportation costs are proportional to the distance, without considering the change of future transportation costs;

4) The transportation route is a spatial straight line, without considering the actual traffic conditions.

(2) Model establishment

The optimal location of the transfer station in the network is obtained by using the center of gravity method, and the longitude and latitude are used as coordinates. In this paper, Baidu Map is used to establish coordinates. According to the horizontal and vertical coordinate values of each point, the X-coordinate and Y-coordinate of the optimal position are obtained. The precise center of gravity method site selection model is as follows (Shao, 2021).

Let n garbage collection sites, whose coordinates are (xi, yi); Cj is the unit transportation rate from the collection site to the incineration power plant; Qj is the amount of waste transported from each collection site to the incineration power plant; Cj is the transportation rate from the collection site to the incineration power plant.

$$\overline{x} = \sum_{j=1}^{n} c_j q_j X_j \div \sum_{j=1}^{n} c_j q_j \, \overline{y} = \sum_{j=1}^{n} c_j q_j y_j \div \sum_{j=1}^{n} c_j q_j (\overline{x}, \overline{y}).$$

(3) Model solving

Taking coordinates (0,1) in the coordinate map, we can get the actual address of this point as Jianchigou, Bailing Town, Zhangwan District, Shiyan City. Take Jianchigou, Bailing Town, Zhangwan District, Shiyan City as the origin of coordinates.

Figure 1. Establish a rectangular coordinate system for waste incineration power plants

The coordinates of the waste incineration power plant serving each urban area can be obtained as follows:

$$\overline{x_1} = 17.406, \overline{y_1} = 27.111; \quad \overline{x_2} = 23.0705, \overline{y_2} = 7.68$$

Therefore, according to the precise center of gravity method, the coordinates of the two optimal locations are (17.406,27.111) and (23.0705,7.68), meaning that establishing a waste transfer station at these locations can minimize the overall transportation distance. According to the coordinate map, the two transfer stations are located in Matangou Village, Yunyang District, and Bailang Economic Development Zone, respectively.

2.3.4. Model Construction in the Second Stage

In the optimization process of household waste recycling systems, a critical aspect involves route planning for vehicles. By using the precise center of gravity method to determine the location of transfer stations, it is possible to further clarify the optimal routes from waste collection points to transfer stations and from transfer stations to waste processing facilities. The core of this approach lies in designing an efficient and economical route to minimize the overall cost of the entire waste recycling process.

objective function:

$$\min G_1 = \sum_{m=1}^{M}\sum_{s=1}^{S} C_m + \sum_{m=1}^{M}\sum_{p=1}^{P} C_P +$$
$$C\sum_{s=1}^{S}\sum_{n=1}^{N}\sum_{i=1}^{b}\sum_{j=1}^{d} l_{ij}X_{nij}F_m +$$
$$2\sum_{s=1}^{S}\sum_{r=1}^{R}\sum_{i=1}^{d}\sum_{c=1}^{c} l_{ij}X_{pij}F_p$$

It shows that the total cost is the lowest in the path optimization of garbage collection network optimization.

Total cost = fixed cost of vehicle + variable cost + garbage sorting cost Waste sorting cost = labor cost + time cost

constraint condition:

$$C_S = a\sum_{h=1}^{d}\sum_{s=1}^{S} Q_h^s$$

The sum of the sorting costs for all types of waste

$$\sum_{i=1}^{b}\sum_{j=1}^{d} Q_h^s X_{nij}^S \le Q_m^s, \forall s \in S, h \in H$$

Load restrictions for garbage collection vehicles.

$$\sum_{h=1}^{H} Y_{nm}^{S}\left[\sum_{i=1}^{b}\sum_{j=1}^{d}\left(t_{ij}+t_h\right)X_{nij}^S + t_v\right] \le t_m \quad ,$$
$$\forall s \in S, n \in N, m \in M$$

$$\sum_{h=1}^{H} Y_{pr}^{S}\left[\sum_{i=1}^{b}\sum_{j=1}^{c}\left(2t_{ij}+t_v+t_z\right)X_{rij}^S + t_v\right] \le t_p$$
$$\forall s \in S, r \in R, p \in P$$

Ensure that the vehicle is operating within the required time frame.

2.3.5. Model Solving Algorithm Design

Genetic algorithms primarily consist of three basic operations: selection, crossover, and mutation. The mutation phase involves genetic mutations at certain positions in an individual, promoting diversity among new individuals to enhance the local search capability of genetic algorithms (Wang, 2011). Solution steps: the second stage path optimization is divided into two segments, first is the path optimization from collection points to transfer stations, followed by the path optimization from transfer stations to processing plants.

(1) encoding The article employs a coding system based on natural numbers to identify waste collection points and transfer stations. The last digit of each code indicates the transfer station for

that area. All waste collection vehicles must start from the transfer station and return to the starting point after completing their collection route. Assuming the chromosome length is n, in a chromosome of length 10, there are the following coding sequences: {10,8, 6, 5, 10,1, 3, 10,4, 2, 10,7, 9, 10}. Numbers 1-9 represent collection points, while number 10 represents the transfer station. The plan is represented as follows: there are four routes in total. The first route indicates that the waste collection vehicle starts from Transfer Station 10, visits Collection Points 8, 6, and 5 in sequence, then returns to Transfer Station 10; the second route indicates that the waste collection vehicle starts from Transfer Station 10, visits Collection Points 1 and 3 in sequence, then returns to Transfer Station 10; the third route indicates that the waste collection vehicle starts from Transfer Station 10, visits Collection Points 4 and 2 in sequence, then returns to Transfer Station 10; the fourth route indicates that the waste collection vehicle starts from Transfer Station 10, visits Collection Points 7 and 9 in sequence, then returns to Transfer Station 10.

(2) Initialize the population In the program, (n-1) collection points are randomly arranged first. According to the load capacity of the garbage collection vehicle and the production of this kind of garbage in the randomly combined collection points, it is determined whether the transfer station needs to be returned.

(3) Fitness function The fitness function is the formula for calculating the fitness of individuals in the population. The second stage fitness function is the objective function of the second stage, as shown in Equation (9). Let the total cost function of chromosome i be G2(i). Therefore, the function fi(x1) of chromosome 1 in the second stage is expressed as (9) .

$$f_i(x_1) = \frac{1}{G_{2(i)}}$$

(4) Choice The objective function of the second-stage model is to minimize total cost. Therefore, in this stage, the genetic algorithm adopts an elite strategy to operate on the data from the parent population. The specific steps are as follows: First, evaluate the fitness of each individual in the population from the second step, and retain the individuals with the highest and lowest fitness scores. Then, replace the individuals with lower fitness scores, and genetically transmit the optimal individual to the offspring population, repeating this process.

(5) Cross In the crossover process, in order to avoid the occurrence of illegal decoding and improve the effectiveness of the crossover process, partial matching crossover method is adopted.

(6) Variation Except for the last number, the sequence in the substring is randomly reordered again. For example, {6,8,9,10} is randomly reordered to get the new substring {9,6,8,10}.

3. Example Analysis

To facilitate the analysis of the effectiveness of the optimized model, this paper takes the Bailang District under Shiyan City as an example, which has similar issues with garbage collection in the urban area of Shiyan City, to optimize the household waste recycling network. The current "one vehicle per community" model not only reduces the operational efficiency of vehicles but also exacerbates unnecessary resource consumption and adds extra pressure on sorting centers.

3.1. The Calculation Process and Results

In this paper, it is necessary to carry out subsequent calculation according to the location of the site in order to minimize the fixed cost and variable (transportation) cost, and to plan the vehicle path from each community to the garbage transfer station. The genetic algorithm is used to realize the model through 2020b to get the optimal solution of the path.

(1) Algorithm parameter setting

When solving the problem with MATLAB2020b, the genetic algorithm in the model is set up by consulting the literature (Wang et al., 2025; Gao et al., 2025), as shown in Table 1.

Table 1. Model parameter setting

Genetic algorithm parameter setting	Magnitude
Population size	200
Cross probabilities	0.9
Probability of mutation	0.05
Maximum number of iterations	400

3.2. Result Analysis

When solving the problem, divide the path from the waste collection point to the waste treatment plant into two segments for processing. The first segment is from the collection point to the transfer station, and the second segment is from the transfer station to the treatment plant. For convenience of expression, kitchen waste trucks, recyclable waste trucks, and other waste trucks are named Class A vehicles, Class B vehicles, and Class C vehicles.

The first phase of the garbage collection network in Nanyuanmen Street, Bai Lang District, was equipped with 5 collection vehicles, with a total cost of 2347.77 yuan per day and a total distance of 14.4 kilometers. Among these, 3 food waste collection vehicles were provided, with a daily operating cost of 1213.05 yuan; 1 recyclable waste collection vehicle, with a recycling waste cost of 733.57 yuan per day; and 1 other waste collection vehicle, with a daily maintenance fee of 397.15 yuan. The numbers corresponding to the driving routes for each community are listed in Table 2.

Table 2.The first stage of household garbage collection and transportation vehicle dispatching scheme

	Vehicle type	Number	Route of travel
First stage	A	1	100-7-100
		2	100-6-5-2-100
		3	100-1-3-4-8-100
	B	1	100-8-1-2-3-4-5-6-7-100
	C	1	100-8-1-2-3-4-5-6-7-100

In the second stage, only vehicle scheduling for kitchen waste and other garbage is required. The harmless waste treatment plant is numbered 104. The specific vehicle scheduling is shown in Table 3.

Table 3. The second stage of household garbage collection and transportation vehicle dispatching scheme

	Vehicle type	Route of travel
Second stage	A	104-99-103-100-102-104
	C	104-99-103-100-102-104

3.3. Optimize Results

According to the garbage recycling mode before optimization in Bailang District, Shiyan City, the optimal total network cost, vehicle running distance and total number of vehicles before optimization were calculated by using MATLAB 2020b under the condition that transportation cost and driving distance remained unchanged, and the results before and after optimization were compared, as shown in Table 4.

Table 4. Comparison of operation schemes before and after running

	Total cost/yuan	Vehicle running distance/km	Number of vehicles	Carbon emission/kg
Before	9615.38	98.67	12	648.85
Now	6763.79	77.74	9	383.41

As can be seen from Table 4, the total daily garbage collection cost is reduced by 2851.59 yuan before and after optimization, and the vehicle running distance is shortened by 20.93km.

$$Y(\mathrm{CO_2}) = \psi H \rho M \times 10^{-3} / m$$

In the formula: Ψ is the carbon emission factor for diesel/gasoline, which is 20.2 kg/GJ and 18.9 kg/GJ, respectively, as obtained from the IPCC guidelines; H is the calorific value of diesel/gasoline, in kJ/g; ρ is the density of diesel/gasoline, in g/ml; M is the molar mass of carbon dioxide, taken as 44; m is the molar mass of carbon in carbon dioxide, taken as 12. After calculation, the CO_2 emissions per liter of diesel and gasoline are 2.74 kg/L and 2.47 kg/L, respectively. According to relevant research, the average fuel consumption of garbage collection vehicles used in urban areas is 15-20 L/100 km.

According to Equation , it can be calculated that the daily carbon emission reduction before and after optimization can be reduced by 8.602-11.46 kg. The annual emission reduction can reach 3139.73-4182.9 kg.

4. Conclusions and Discussion

4.1. Conclusions

This paper takes the Bailang District of Shiyan City as an example, aiming to minimize total costs, and optimizes the urban household waste recycling network in two stages, constructing an optimization model for the household waste recycling network. The first stage determines the optimal location for waste transfer stations; the second stage establishes a model to find the best route for waste collection. Research findings show that using logistics models to optimize the layout of waste stations and vehicle routes across the city reduces the daily total cost of waste collection by 2851.59 yuan before and after optimization, shortens the vehicle operation distance by 20.93 km, and achieves an annual reduction in emissions ranging from 3139.73 to 4182.9 kg. If proper sorting, transportation, and timed disposal systems are implemented, the waste collection and transportation costs and carbon emissions in Shiyan can be significantly reduced, achieving a clean space free of waste for most of the time, providing the best experience for creating green and low-carbon demonstration zones and zero-waste cities. Therefore, we recommend that relevant units adopt this technical approach to recalculate the distribution points and vehicle routes of our city's waste transfer stations and compression stations, aiming to achieve the optimal cost solution. Additionally, efforts should be made to promote the simplified classification method using the dichotomy approach, establish a paid recycling system for hazardous waste, and cultivate residents' civilized and hygienic habits of sorting and disposing of garbage at designated times and locations. These measures will help improve transportation efficiency and reduce costs.

4.2 Shortcomings and Prospects

This study aims to minimize total costs, overlooking other potential objective factors such as vehicle capacity, traffic conditions, and local environmental policies. Future research could consider the following aspects: 1) traffic conditions at different times; 2) varying vehicle capacities; 3) the impact of road conditions or steep slopes on vehicle transportation; 4) whether local environmental policies can be leveraged to set up waste transfer stations and compression facilities at optimal locations.

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