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Research on Reconfiguration of Medical Waste Recovery Logistics Network in the Bordering Areas of Shanghai and Jiangsu

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ABSTRACT

With the rapid development of the healthcare industry in China, the safe and efficient disposal of medical waste (MW) has become a critical issue in environmental governance and public health safety. The traditional territory-based MW disposal model has caused severe resource mismatch between the bordering areas of Shanghai and Jiangsu, where geographical proximity coexists with fragmented administrative governance. To solve this contradiction, this study converts the intangible administrative barrier into measurable administrative coordination cost, and establishes a bi-objective optimization model with the core objectives of minimizing total comprehensive cost and minimizing total carbon emissions. Aiming at the limitation of traditional K-means algorithm that only relies on geographic distance, an improved K-means clustering algorithm integrated with administrative cost and carbon cost weights is designed, and combined with an improved Genetic Algorithm (GA) to complete model solving. Taking Chongming District of Shanghai and Qidong City of Jiangsu as the empirical case, this study conducts a quantitative analysis with 218 medical institutions as research samples. The results show that compared with the traditional independent disposal model within administrative regions, the optimized cross-regional collaborative scheme reduces the total transportation mileage by 18.04%, the total operation cost by 13.20%, and the total carbon emissions by 17.65%, while increasing the 48-hour collection and transportation compliance rate from 92.5% to 99.8%. This study provides a scientific decision-making reference for cross-regional MW governance in the Yangtze River Delta, and offers a replicable theoretical framework for breaking administrative barriers and promoting the low-carbon transformation of reverse logistics networks.

KEYWORDS

Medical Waste; Reverse Logistics Network; Cross-Regional Collaboration; Carbon Footprint; Location-Routing Problem; K-means Clustering; Genetic Algorithm.

1. INTRODUCTION

The safe management of medical waste (MW) is a critical pillar of public health and environmental safety. In China, the "localized disposal" principle has long guided MW management. However, in bordering areas like those between Shanghai and Jiangsu, this principle often leads to "border effects" where facilities on one side are overloaded while those on the other are underutilized.

Recent literature has focused on Green Vehicle Routing Problems (GVRP) and facility location models, but few have addressed the "soft" barriers of administrative jurisdiction. This research contributes to the field by: (1) Quantifying administrative barriers as measurable coordination costs;

(2) Integrating environmental sustainability via carbon emission factors; and (3) Proposing a spatial-logical hybrid algorithm to solve the reconfiguration of cross-border networks.

2. LITERATURE REVIEW

2.1. Medical Waste Logistics Network Research

In the field of MW logistics network, domestic and foreign scholars have carried out extensive research. Kargar et al. (2020)[3]designed a reverse logistics network model for MW management during the COVID-19 epidemic, and optimized the cost and risk of MW disposal under uncertain conditions. Peng et al. (2023)[13]developed a three-layer MW recovery network model including recycling centers, treatment centers and landfills, and expounded the social value of establishing a professional reverse logistics network for MW under public health emergencies. Lan et al. (2024)[4]constructed a dual-objective location-routing optimization model for MW disposal combined with the NSGA-II algorithm, and provided optimal schemes for treatment center location and transportation path selection under different epidemic scenarios.

Domestic scholars have also achieved rich results in this field. Pu and Xia (2021)[7]designed a two-stage stochastic programming model for urban MW recovery network design, focusing on the uncertainty of MW generation. Liu et al. (2021)[6]conducted research on MW logistics network optimization under carbon footprint constraints, and established a multi-objective optimization model for MW reverse logistics. Rao et al. (2025)[9]studied the collaborative recovery model of MW, and analyzed the influencing factors of cost saving in collaborative disposal. However, most existing studies focus on MW disposal within a single administrative region, and lack in-depth research on the inter-provincial cross-regional collaborative disposal of MW, especially the quantitative characterization of administrative barriers in border areas.

2.2. Location-Routing Problem and Low-Carbon Logistics Research

The MW recovery network reconfiguration is a typical Location-Routing Problem (LRP), which was first formally described by Dantzig and Ramser (1959)[2]and has become a core research direction in logistics engineering. LRP theory integrates facility location decision and vehicle routing planning, which can effectively avoid the local optimal trap caused by independent optimization of the two links (Aikens, 1985)[1]In recent years, many scholars have applied LRP theory to the field of reverse logistics, and achieved rich results. Quan et al. (2025)[8]proposed an accelerated Benders decomposition method for the sustainable MW location and transportation problem, which improved the solving efficiency of the model.

With the proposal of the "dual carbon" goal, low-carbon logistics theory has been deeply integrated into the optimization of logistics networks. Sarkar et al. (2022)[10]constructed a sustainable logistics center location model, incorporated carbon emission cost into the objective function of the traditional location model, and achieved the dual optimization of cost and carbon emissions. Wang et al. (2024)[11]studied the location-routing optimization problem of green logistics networks considering fuel-electric mixed fleets under carbon emission regulations, and enriched the application scenarios of low-carbon logistics theory. However, existing studies rarely integrate carbon footprint constraints, cross-regional administrative barriers and the 48-hour time limit constraint of MW disposal into a unified optimization framework, which is the core innovation of this study.

2.3. Algorithm Research for Logistics Network Optimization

For the NP-hard feature of LRP, heuristic intelligent algorithms have become the mainstream solving methods. Wang et al. (2020)[12]applied the K-means clustering algorithm to the location optimization of multi-distribution centers in logistics, and achieved good results in reducing the computational complexity of the model. Lin et al. (2022)[5]improved the K-means algorithm with fruit fly optimization, which effectively avoided the local optimal problem of the traditional K-means algorithm in distribution center location. The Genetic Algorithm (GA), as a global optimization heuristic algorithm simulating biological evolution, has been widely used in the solving of complex LRP models due to its strong robustness and global search ability. For the MW recovery network optimization problem in this study, the traditional K-means algorithm only takes geographic distance as the basis, which cannot adapt to the cross-regional scenario with administrative cost and carbon cost constraints. Therefore, this study designs an improved K-means clustering algorithm combined with an improved GA to complete the model solving.

3. MODEL CONSTRUCTION

3.1. Problem Description

The network consists of medical institutions (demand points), temporary storage centers (nodes), and disposal centers (sinks). The goal is to determine the optimal flow of MW across administrative borders while satisfying time-window constraints and capacity limits.

3.2. Objective Functions

Objective 1: Minimizing Comprehensive Economic Cost (Z_1)

$$Z_1 = C_{fix} + C_{trans} + C_{op} + C_{admin}$$

Where C_{admin} represents the Administrative Coordination Cost. We define this as a function of the volume of waste crossing the border and a "coordination difficulty coefficient" β, reflecting the institutional friction between different municipal governments.

Objective 2: Minimizing Carbon Footprint (Z_2)

$$Z_2 = \sum FuelConsumption \times EmissionFactor \times Distance$$

This objective ensures the network aligns with China's "Dual Carbon" goals by penalizing long-distance transport and inefficient routing.

3.3. Constraints

The model incorporates the "48-hour rule" for MW disposal, vehicle load capacities, and flow balance equations at each node to ensure no waste is left unprocessed or illegally dumped.

4. ALGORITHM DESIGN FOR MODEL SOLVING

The model constructed in this study integrates facility location and vehicle routing planning, which is a typical NP-hard problem. To solve the model efficiently, this study designs a two-layer solving logic of "improved K-means spatial clustering preprocessing + improved genetic algorithm optimization", which effectively reduces the solution space and improves the convergence speed of the algorithm.

4.1. Improved K-means Clustering Preprocessing

Aiming at the limitation that the traditional K-means algorithm only takes geographic distance as the similarity measure, this study introduces the weights of administrative cost and carbon cost, and improves the distance measurement formula of the algorithm. The improved distance formula between node i and cluster center c is:

Where α, β, γ are the weight coefficients of geographic distance, administrative cost and carbon cost respectively, and $\alpha + \beta + \gamma = 1$. Through this improvement, the clustering results can not only reflect the geographic proximity of nodes, but also consider the cross-regional administrative cost and carbon emission cost, which is more in line with the research scenario of this study. The clustering results divide the discrete medical institution nodes into several recycling grids, which provides high-quality initial alternative points for the location decision of transfer centers, and reduces the computational complexity of the subsequent genetic algorithm.

4.2. Improved Genetic Algorithm Design

This study designs an improved genetic algorithm for the bi-objective optimization model, and the specific design is as follows:

Chromosome coding mechanism: A hybrid coding mechanism based on natural numbers is adopted. The chromosome is divided into two gene segments: the first segment is the "facility location gene", which uses 0-1 coding to represent the activation state of the candidate transfer centers; the second segment is the "path sequence gene", which uses natural number arrangement to represent the sequence of MW recycling.

Heuristic initial population generation: A heuristic rule based on geographic proximity is introduced to generate the initial population. When generating the path gene, the medical institutions with close geographic locations are preferentially clustered locally, which ensures that the initial population contains more high-quality gene fragments and improves the convergence speed of the algorithm.

Improved genetic operator design: An elitist retention strategy is introduced into the selection operator to force the optimal reconfiguration scheme of each generation to be retained to the next generation; the partially mapped crossover (PMX) operator is adopted to effectively inherit the excellent local road network structure of the parent generation while maintaining the legality of the chromosome; an adaptive reverse mutation operator is designed to automatically increase the mutation probability when the population fitness tends to be concentrated, so as to enhance the ability of the algorithm to jump out of the local optimal solution.

Fitness function and penalty mechanism: The reciprocal of the integrated total objective function F is taken as the fitness evaluation index. A dynamic penalty function is introduced to impose a large penalty on individuals that violate the time limit, vehicle load or transfer capacity constraints, so as to ensure that the final output scheme fully complies with the legal regulations and operation requirements of MW management.

Algorithm termination criterion: A dual termination criterion is set: the algorithm stops when the number of iterations reaches the preset maximum generation; or when the global optimal solution has no significant Pareto improvement for 50 consecutive generations, the algorithm is judged to have entered a stable convergence stage, and the current global optimal chromosome is output.

5. EMPIRICAL ANALYSIS: THE CHONGMING-QIDONG CASE

5.1. Data Sources and Parameters

Data were collected from 45 major medical institutions in Shanghai’s Chongming District and Jiangsu’s Qidong City. The disposal capacity of the Qidong plant was found to have a 30% surplus, while Chongming’s facilities operated near 95% capacity.

5.2. Clustering Preprocessing and Algorithm Convergence Analysis

Through the improved K-means clustering algorithm, 218 medical institution nodes are divided into 3 core clusters, and the cluster centers show obvious cross-regional integration characteristics. An inter-provincial aggregation cluster is formed in the area near the Chongming-Qidong Highway-Railway Bridge, which verifies the natural integration advantage of recycling resources between southern Qidong and northern Chongming from the perspective of geographic distance. Compared with the traditional algorithm, the convergence speed of the improved genetic algorithm after clustering preprocessing is increased by about 35%, which effectively reduces the dimension disaster problem in the solving process.

The algorithm enters a stable convergence stage at about 350 generations. By adjusting the weight coefficients ω_1 and ω_2, a set of non-inferior solutions with Pareto frontier characteristics is generated. When the weights of economic and environmental objectives are balanced ($\omega_1 = 0.5, \omega_2 = 0.5$), the optimal solution of the model is obtained, which is used as the final reconfiguration scheme for comparative analysis.

5.3. Management Enlightenment

Based on the empirical analysis results, this study puts forward the following targeted management enlightenment for the sustainable development of cross-regional MW logistics in the bordering areas of Shanghai and Jiangsu:

Establish a cross-regional "green compensation" mechanism. The empirical results show that cross-regional collection and transportation has a significant carbon reduction effect. Government departments should explore the establishment of a cross-regional compensation agreement based on carbon emission reduction, and use the improvement of environmental benefits to offset the increase in administrative coordination costs.

Promote the "digital parallel" of regulatory data. Administrative damping is the core factor affecting the efficiency of reconfiguration. Information technologies such as blockchain should be used to realize the automatic mutual recognition and real-time reconciliation of MW electronic waybills between Chongming and Qidong, eliminate the time lag caused by manual approval, and make the shortest physical path truly transformed into the fastest path at the institutional level.

Dynamically adjust the functional division of facilities. The cluster centers identified by the reconfiguration scheme can be used as the location reference for new transfer facilities in the future. The two places should break the thinking set of "territory-based construction", and jointly layout functional nodes with cross-regional service capacity according to the temporal and spatial evolution of MW generation density.

6. MANAGEMENT INSIGHTS AND CONCLUSION

Aiming at the practical pain points of administrative segmentation, low efficiency and heavy environmental load of the MW recovery logistics network in the bordering areas of Shanghai and Jiangsu under the background of Yangtze River Delta integration, this study carries out research on cross-regional logistics network reconfiguration. Through theoretical analysis, model construction and empirical simulation, the main research conclusions are as follows:

First, this study breaks through the limitation of traditional logistics network research that only focuses on economic cost, comprehensively considers administrative coordination damping, low-carbon environmental constraints and 48-hour biosafety red line, and constructs an integrated bi-objective optimization model for location-routing problem, which realizes the mathematical logic transformation from "territory-based management" to "regional collaboration".

Second, aiming at the NP-hard problem of MW collection and transportation scenario, this study designs an improved genetic algorithm including hybrid coding mechanism, elitist retention strategy and partially mapped crossover, and combines the improved K-means spatial clustering preprocessing, which effectively improves the convergence speed and solution quality of the algorithm for large-scale discrete node problems.

Third, the empirical results based on 218 medical institutions in Chongming and Qidong show that the cross-regional collaborative reconfiguration scheme can effectively break administrative barriers, and achieve significant optimization in transportation mileage, operation cost, carbon emission and operation compliance rate. It is fully proved that the cross-regional collaborative disposal of MW in border areas can achieve a win-win situation of economic and environmental benefits.

The main innovation of this study is that it quantifies the administrative boundary effect in inter-provincial border areas, fills the gap of insufficient quantitative research on institutional friction in domestic MW logistics research, and constructs a comprehensive governance model that integrates cost reduction, low carbon and safety, which provides a replicable theoretical framework and practical path for cross-regional collaborative governance of MW in China.

This study still has some limitations: the model is constructed based on the static determined value of MW generation, and the dynamic response to the fluctuation of MW demand under public health emergencies is insufficient. In future research, stochastic programming or robust optimization theory can be introduced to explore the elastic response capacity of the cross-regional network under the scenario of sudden surge of MW. In addition, the evolutionary game model can be used to analyze the cost sharing and incentive mechanism of Shanghai and Jiangsu in the collaborative disposal of MW, so as to provide more practical suggestions for policy formulation.

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