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Research on Medical Waste Collection and Loading Optimization Considering Customer Satisfaction

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Abstract: With the rapid development of China's economy and significant improvements in medical standards, the generation of medical waste has increased sharply. Inefficient and untimely recycling of such waste poses severe threats to environmental health and public safety. This paper addresses the critical challenge of optimizing medical waste collection and processing through an innovative approach. The research categorizes medical waste into infectious and non-infectious types, with a focus on minimizing pollution and maximizing customer satisfaction. By integrating and enhancing the Isolation Forest algorithm with DBSCAN clustering, the proposed method achieves efficient route planning, reduced operational costs, and significant environmental benefits.

Keywords: Medical waste collection, Clustering algorithms, Algorithm optimization.

1. Introduction

The global population growth and expansion of medical facilities have led to a surge in medical waste generation. Improper disposal of medical waste risks environmental contamination and public health. While advancements in logistics have addressed waste management challenges, existing studies often prioritize cost reduction, carbon emissions, and route efficiency while neglecting customer satisfaction in healthcare institutions. This research fills this gap by proposing a customer-centric optimization framework for medical waste logistics.

2. Literature Review

(1) Medical Waste Collection Approaches

Tirkolaee et al. (2019）emphasized the significance of optimizing waste management systems to reduce landfill disposal through recycling, arguing that efficient collection networks can mitigate environmental impacts. Hajar et al. (2018) investigated on-site medical waste collection by modeling it as a time-windowed vehicle routing problem (VRP), addressing service reliability constraints in healthcare facilities. Rabbani et al. (2018）proposed a multi-objective model for hazardous waste collection, balancing cost minimization with environmental safety considerations. Baradaran (2019) explored stochastic VRPs with heterogeneous vehicle fleets and priority time windows for multiple service nodes, enhancing robustness in real-world waste collection scenarios. Taslim et al. (2020) integrated risk assessment into medical waste logistics, considering both transportation hazards and occupational risks associated with temporary storage at healthcare centers. Ghannadpour et al. (2021) focused on minimizing public health risks by prioritizing high-risk waste generators (e.g., hospitals producing large quantities of infectious waste). Ma Yanfang & Liu Chang (2024) developed a multi-objective robust optimization model for medical waste recycling site selection, incorporating operational uncertainties and risk mitigation strategies. He Zhenggang & Liu Sha (2016) designed a three-tier recycling network structure to comprehensively cover waste sources and reduce exposure risks through intermediate transfer stations. Zhang Yamin & Yuan Yuan (2013) optimized military hospital waste management by evaluating disposal methods based on comprehensive environmental and economic criteria.

(2) Waste Treatment and Supply Chain Development

Govindan et al. (2022) proposed a multi-project, multi-period mixed-integer linear programming (MILP) model for sustainable medical waste management, aiming to transform disposal networks into green reverse systems through circular economy principles. Kargar et al. (2020) established a multi-objective framework for medical waste reverse supply chains, minimizing total costs, optimizing treatment technology selection, and reducing storage quantities.

However, most literature overlooks client satisfaction in medical waste logistics, which is crucial due to strict time constraints and service reliability requirements.

3. Model Development

3.1. Problem Description

The goal is to serve known collection points within capacity and time window constraints.

3.2. Assumptions

1. Geographical and demand data for medical institutions are accessible in real time.
2. Vehicle capacities and availability are predefined.
3. Each institution is serviced by only one vehicle.

3.3. Formulation

Parameters and Variables:

K: Set of dispatched vehicles

I: Number of collection points

q_k: Capacity of vehicle k

w_{ij}: Weight loaded between locations i and j

FE: Carbon emission factor per unit fuel

FC_{ij}: Fuel consumption rate between i and j

R: This is a binary variable that takes the value 1 if the route is selected and 0 otherwise

x_{ijk}: Binary variable indicating whether vehicle k travels from medical institution i to j (1 if selected, 0 otherwise)

Objective Functions:

1. Maximize Customer Satisfaction:

$$minS = 1 - \frac{\sum_{a \in c_0} s_{ap}}{a_0}$$

where s_{ap} is a triangular membership function indicating service compliance within time windows.

$$s_{ap} = \begin{cases} 0 & \tau_{ap} < ET_{ap} \\ 1 & ET_{ap} \leq \tau_{ap} \leq LT_{ap} \\ 0 & LT_{ap} < \tau_{ap} \end{cases}$$

Let τ_{ap} denote the service start time for customer α. The problem is subject to a soft time window constraint [ET_{ap} ,LT_{ap}].

2. Minimize Pollutant Emissions:

$$minC = \sum_{k=1}^{K} \sum_{i=1}^{m} \sum_{j=1}^{n} FE \times FC_{ij}$$

Constraints:

$$\sum_{j=1}^{n} I_{ij}^{k} - \sum_{j=1}^{n} I_{ji}^{k} \leq 0 \qquad i = 1 \ldots\ldots m$$

The route sequence is determined by dispatching vehicles from the depot to collect medical waste according to predefined service priorities.

$$\sum_{i=1}^{m} R_i^k = 1$$

Each vehicle departs from exactly one depot.

$$\sum_{j=1}^{n} I_{ji}^{k} \leq q_k \qquad i = 1 \ldots\ldots m$$

The vehicle's loading capacity imposes a constraint that the quantity of waste accepted by any center must not exceed its maximum capacity.

$$\sum_{i=1}^{m} I_{ij}^{k} = 0$$

The vehicle's payload is initialized to zero when departing from either the waste collection center or the starting node.

4. Regional Division of Medical Waste Collection

4.1. Improved DBSCAN with Isolation Forest

The hybrid algorithm addresses DBSCAN's sensitivity to initial data points and noise. By sorting data via Isolation Forest and initiating clustering from edge points, the method ensures robust clustering for medical institutions in Shanghai.

4.2. Case Study: Shanghai's Secondary Medical Institutions

Using Shanghai's 73 secondary hospitals (excluding military facilities), the study calculates daily waste generation based on bed capacity and type-specific coefficients (Table 4.1). Geographical coordinates and service time windows are integrated into a distance metric:

$$d_{ij} = d_{API((x_i,\ y_i),\ (x_j,\ y_j))} + \varphi|m_i - m_j| + \varphi|n_i - n_j|$$

whereφ balances spatial and temporal factors.

Table 4.1. Medical Waste Accounting Coefficients by Hospital Type and Scale

Hospital Type	Scale	Calculation Unit	Accounting Coefficient
Stomatological Hospital		kg/bed/day	0.65
Oncology Hospital		kg/bed/day	0.52
Ethnic Hospital		kg/bed/day	0.45
Integrative Medicine Hospital		kg/bed/day	0.41
Nursing Home		kg/bed/day	0.15
Traditional Chinese Medicine (TCM) Hospital	10–100 beds	kg/bed/day	0.42
	101–500 beds	kg/bed/day	0.51
	>500 beds	kg/bed/day	0.62
General Hospital	10–100 beds	kg/bed/day	0.42
	101–500 beds	kg/bed/day	0.53
	>500 beds	kg/bed/day	0.65

Table 4.2. Regional Division of Medical Waste Collection (Without Optimization)

Region	Hospital IDs Included	Total Collected Waste (kg)	Loading Rate (%)	Pollutant Emissions (kg/Time Unit)
A	1、6、14、25、36、40、45、61、67、71	1998.62	99.93%	529.8
B	2、5、23、24、26、29、33、42、52、54、55、69、72、73	1925.69	96.28%	520.7
C	3、7、22、28、30、43、44、53、66、68	1994.92	99.75%	529.3
D	4、8、13、32、34、46、47、70	1809.47	90.47%	506.2
E	9、10、12、17、27、38、57、59、63、65	1976.01	98.80%	527.0
F	11、19、21、35、41、50、51、62、64	1994.99	99.75%	529.4
G	15、20、37	800.45	40.02%	380.1
H	18、31、39、48、49、56、58、60	1291.99	64.60%	441.5
I	16	265	13.25%	313.1

4.3. Clustering Results

Using the improved DBSCAN algorithm, nine medical waste collection regions (A-I) were identified, with node distribution details shown in Table 4.2. When applying the Isolation Forest-enhanced DBSCAN algorithm, eight regions (A-H) were clustered, and the corresponding node distribution is presented in Table 4.3. While the modified DBSCAN algorithm partially addresses the shortcomings of the conventional DBSCAN, it still generates noise points. To mitigate this limitation, Isolation Forest was integrated to eliminate noise interference, thereby refining the clustering outcomes. These optimized clusters not only satisfy waste collection requirements but also significantly shorten operational time. As evidenced by Table 4.2, the unoptimized algorithm yielded a total pollutant emission of 4,277 kg, whereas the optimized approach reduced emissions to 3,997 kg, The optimized clustering results (Table 4.3) demonstrate a 7% reduction in pollutant emissions compared to the baseline method (Table 4.2). confirming the effectiveness of the proposed method.

Table 4.3. Regional Division of Medical Waste Collection (DBSCAN with Isolation Forest)

Region	Hospital IDs Included	Total Collected Waste (kg)	Loading Rate (%)	Pollutant Emissions (kg/Time Unit)
A	2、4、5、8、13、23、24、26、29、33、42、52、54、55、69、70	1974.06	98.70%	526.7
B	1、14、15、20、25、27、36、37、38、45、59、61、67	1978.57	98.93%	527.3
C	7、19、30、31、39、44、53、56、58、60、62、68	1956.1	97.81%	524.5
D	6、12、16、17、40、63、65	1967.35	98.37%	525.9
E	3、18、22、28、48、49、50、51、64、66	1950.59	97.53%	523.8
F	9、10、57、71	1094.16	54.71%	416.7
G	32、34、46、47、72、73	1761.1	88.11%	500.1
H	11、21、35、41、43	1375.21	68.76%	451.9

5. Conclusion

This research presents a hybrid clustering-based approach to balance customer satisfaction and environmental sustainability in medical waste logistics. The case analysis confirms the superiority of the proposed method over traditional algorithms, offering practical insights for green logistics in healthcare.

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