Asia Pacific Science Press

Journal of Advances in Engineering and Technology
ISSN(O):3005-7507
ISSN(P):3005-7493
Vol. 2 No.4 (2025)

Research on Optimization Pathways for Reverse Logistics Networks Based on Ecological Civilization

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Abstract: Against the backdrop of global urbanization and the transition to a circular economy, the design of reverse logistics networks for municipal solid waste (MSW) is a critical link in advancing urban sustainability. This study aims to develop a ubiquitous optimization framework for MSW reverse logistics networks. By analyzing the current state of urban waste management, a three-tier network structure comprising generation sources, transfer stations, and treatment centers was constructed. Furthermore, regional waste generation quantity was introduced as a fuzzy parameter to address uncertainty. Based on this, a mixed-integer programming (MIP) model was established with the objective of minimizing the total system cost, and a genetic algorithm was designed to solve it. An empirical case study of Hefei City, China, demonstrates that the optimized model can effectively reduce the total network operating cost by approximately 8%. The significant decrease in transportation costs directly enhances the overall efficiency of waste treatment. This research provides a transferable methodology and decision-making support for addressing the solid waste management challenges faced by cities worldwide.

Keywords: Reverse Logistics; Municipal Solid Waste (MSW); Ecological Civilization; Network Design

Published: Dec 9, 2025

DOI: https://doi.org/10.62177/jaet.v2i4.920

1.Introduction

1.1 Research Background and Importance

Ecological civilization serves as a critical indicator of societal development progress, with its core focus on harmonizing environmental protection with sustainable socio-economic development.[1] Since the concept of "ecological civilization" was introduced in China, its connotation has been continuously enriched, and it has been established at the strategic national level as a scientific framework guiding the harmonious coexistence of humans and nature. Particularly in the realm of urban environmental governance, the shift from emphasizing "the construction of municipal solid waste treatment facilities" to implementing "the strictest ecological protection systems" underscores that building an efficient waste management system has become a key task in advancing ecological civilization.[2-4]

Against this backdrop, achieving the "reduction, recycling, and harmless treatment" of waste is not only a concrete implementation of the "tri-integrated" development strategy but also an inevitable trend in enhancing urban governance efficiency.[5-7] This paper begins with the design of a reverse logistics network for municipal solid waste, viewing it as a central link in achieving source reduction and systemic optimization. The study aims to provide actionable technical pathways for ecological civilization development by optimizing the structure of the logistics network.

1.2 Research Objectives

This study aims to construct and optimize a three-tier structure for the municipal solid waste (MSW) reverse logistics network, investigating its structural role in enhancing processing efficiency and controlling environmental risks. Through modern optimization modeling approaches, particularly genetic algorithms and fuzzy parameter handling, the comprehensive costs and operational effectiveness of the network design are evaluated. Although the three-tier network has been theoretically recognized as a foundation for process optimization, this paper delves into the precise coverage of waste generation sources, the scientific layout of transfer facilities, the synergistic matching of disposal terminals, and the system's stability in responding to fluctuations in waste volume. Ultimately, this study seeks to provide a clearer and more quantifiable planning solution, enabling decision-makers to understand the fundamental value of the reverse logistics network structure in achieving the "reduction, recycling, and harmless treatment" of waste, while offering new implementation pathways for advancing the modernization of urban environmental governance systems.

1.3 Data Source Description

This study obtained data on municipal solid waste from the Hefei Municipal Bureau of Ecology and Environment (http://zwgk.hefei.gov.cn/public/14011/106651511.html), administrative division data from the China National Geographic Information Resource Directory Service System (https://www.webmap.cn), and population density data from the Hefei Municipal People's Government Seventh National Population Census Bulletin (http://www.hefei.gov.cn/xxgk/gsgg/106488113.html).

2.Design Principles

2.1 Hierarchical Structure

The nodal structure of the municipal solid waste (MSW) reverse logistics network primarily consists of the generation tier (households), the transfer tier, and the processing tier (incineration plants and landfills).[8] The main process flow involves waste separation and disposal by residents, followed by the transfer stations transporting different categories of waste to corresponding treatment facilities. The critical linkages in this hierarchy are between the generation tier and the transfer tier, and between the transfer tier and the processing tier.[9]

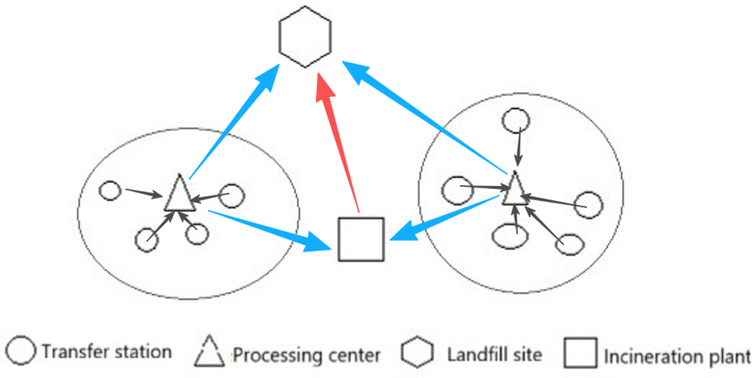
2.2 Primary Functions across Tiers

Generation Tier: This tier primarily consists of households that generate waste through daily activities. The waste is either collected regularly by waste collection vehicles or transported by residents to designated drop-off points, after which it is forwarded to the transfer tier.[10]

Transfer Tier: The transfer tier receives waste from households and other sources, sorts it based on its characteristics, and dispatches different categories of waste to corresponding processing centers.[11-12]

Processing Tier: This tier mainly includes waste incineration plants and landfills. Combustible waste is sent to incineration plants, where it is converted into thermal energy or electricity for residential use. Non-combustible waste is compacted and transported to landfills for natural restoration. Staff working at landfills or incineration facilities must possess relevant qualifications to prevent improper handling that could harm the environment and human health.[13-14]

Figure1: Topology of reverse logistics network for municipal solid waste



3.Network Model and Algorithm Design

3.1 Model Assumptions

Given the inherent difficulty in quantifying real-world waste generation volumes, this study develops a municipal solid waste reverse logistics network model that treats waste quantity as a fuzzy parameter. The model's framework is built around a three-tier structure comprising generation, transfer, and processing layers, with the following operational sequence: At the transfer tier, collected municipal solid waste undergoes detailed classification and documentation. In compliance with national regulations, this tier then conducts harmless treatment and usability assessment, directing recyclable materials to appropriate treatment facilities while transporting non-recyclable waste to either incineration plants or landfills. The processing tier operates under strict regulatory requirements, where specialized facilities manage recyclable materials through formal treatment and reprocessing channels. Meanwhile, non-recyclable waste sent to incineration plants and landfills receives segregated handling based on its characteristics and environmental impact.

3.2 Definition of Parameters and Variables

Table 1. Relevant definitions of variables and symbols

Category	Symbol	Meaning
Superscript and subscript	a	Collection point
	b	Transfer station
	c	Processing center
	d	Landfill
	e	Incineration plant
	I	Number of candidate collection points
	J	Number of candidate transfer stations
	K	Number of candidate processing centers
	H	Number of candidate landfills
	L	Number of candidate incineration plants
Parameter	Q_l^a	Fuzzy waste generation quantity
	C_j^b	Maximum transport capacity of transfer point
	C_k^c	Maximum processing capacity of processing point
	G_j^a	Fixed costs of transit
	G_j^b	Fixed cost of processing center
	G_k^c	Fixed costs of landfills
	G_d^h	Fixed cost of waste incineration plant
	G_l^e	Fixed cost of power plant
	Y_j^a	Unit operating cost of transfer point
	Y_j^b	Unit operating cost of processing point
	Y_k^c	Unit operating cost of landfill site
	Y_h^d	Unit operating cost of waste incineration plant
	D_{ij}^{ab}	Distance from generation point to transfer point
	D_{jk}^{bc}	Distance from transfer point to processing point
	D_{jh}^{bc}	Distance from transfer point to landfill site
	D_{jl}^{bc}	Distance from transfer point to waste incineration plant
	S_{ij}^{ab}	Unit transportation cost from transfer point to processing point
	S_{jk}^{bc}	Unit transportation cost from transfer point to landfill site

Category	Symbol	Meaning
	S_{jh}^{bd}	Unit transportation cost from transfer point to waste incineration plant
	β	Proportion of hazardous waste at transfer point
	t	Treatment cost of hazardous waste at treatment point
	α	Ratio of waste available at transfer point
Decision variable	q_{ij}^{ab}	Quantity of waste transported from generation point to transfer point
	q_{jk}^{bc}	Quantity of waste from transfer point to disposal point
	q_{jh}^{bd}	Quantity of waste from transfer point to landfill site
	q_{jl}^{be}	Quantity of waste from transfer point to waste incineration plant
	x_i^a	1 if location j is selected for a transfer station; 0 otherwise
	x_j^b	1 if location k is selected for a processing center; 0 otherwise
	x_k^c	1 if location h is selected for a landfill; 0 otherwise
	x_l^e	1 if location l is selected for an incineration plant; 0 otherwise

3.3 Model Formulation

A reverse logistics network model for municipal solid waste (MSW) is developed with the objective of minimizing total costs, incorporating waste quantity as a fuzzy parameter. Taking Hefei City as a case study and based on the actual local conditions of MSW management, the primary cost components considered in the operation of the reverse logistics network include: ① infrastructure construction cost, ② facility maintenance cost, ③ transportation cost for MSW between different tiers, and ④ treatment cost for non-recyclable waste. As assumed in this study, the recyclable waste is fully utilized, meaning its residual value offsets the processing costs incurred.

Infrastructure Construction Cost for Reverse Logistics: This refers to the expenses required for building the fundamental facilities necessary for the normal operation of the reverse logistics network. These facilities include collection points, transfer stations, processing centers, waste incineration plants, and landfills.

$$z_1=\sum_{i=1}^{l} G_i^a+\sum_{j=1}^{l} G_i^b x_j^b+\sum_{k=1}^{k} G_k^c x_k^c+\sum_{h=1}^{h} G_h^d x_h^d+\sum_{l=1}^{l} G_l^e x_l^e$$

Facility Maintenance Cost: This refers to the expenses incurred to maintain equipment in proper working condition and ensure its normal operation.

$$z_2=\sum_{i=1}^{l} Y_i^a Q_i^a x_i^a+\sum_{i=1}^{i}\sum_{j=1}^{l} q_{ij}^{ab} Y_j^b x_j^b+\sum_{i=1}^{h}\sum_{j=1}^{j} q_{gh}^{bd} Y_h^d x_h^d+\sum_{l=1}^{l}\sum_{j=1}^{j} q_{jl}^{be} Y_l^e x_l^e+\sum_{j=1}^{j}\sum_{k=1}^{k} q_{jk}^{bc} Y_k^c x_k^c$$

Transportation Cost between Tiers: This refers to the expenses incurred during the transportation of municipal solid waste between different tiers of the network.

$$z_3=\sum_{i=1}^{i}\sum_{j=1}^{l} q_{ij}^{ab} D_{ij}^{ab} S_{ij}^{ab}+\sum_{j=1}^{j}\sum_{k=1}^{k} q_{jk}^{bc} D_{jk}^{bc} S_{jk}^{bc}+\sum_{h=1}^{h}\sum_{j=1}^{j} q_{gh}^{bd} D_{jh}^{bd} S_{jh}^{bd}+\sum_{l=1}^{l}\sum_{j=1}^{j} q_{jl}^{be} D_{jl}^{be} S_{jl}^{be}$$

Treatment Cost for Non-Recyclable Waste: This refers to the expenses associated with the landfilling or incineration of non-recyclable waste.

$$z_4=\sum_{i=1}^{l} G_i^a+\sum_{j=1}^{l} G_i^b x_j^b+\sum_{k=1}^{k} G_k^c x_k^c+\sum_{h=1}^{h} G_h^d x_h^d+\sum_{l=1}^{l} G_l^e x_l^e$$

In summary, the objective function for minimizing the total cost in the municipal solid waste reverse logistics network is formulated as follows:

$$\min z=z_1+z_2+z_3+z_4$$

4.Case analysis

4.1 Fuzzy output of domestic waste in Hefei

Taking Hefei City as an example, by the end of 2020, its permanent resident population had exceeded 9 million, with a total municipal solid waste generation of 2.7091 million tons—ten times higher than a decade ago. This massive volume of waste has placed a heavy burden on the disposal system. The Hefei Longquanshan Landfill covers an area of approximately 1 million square meters. The first phase of the project commenced in 2002 and was officially put into operation in June 2004.

By the end of 2013, the first-phase landfill reached capacity and underwent transitional closure, filling up half a year earlier than originally planned. The second phase was put into use in December 2013 and currently processes over 2,000 tons of waste per day. The environmental quality of the Longquanshan Landfill is suboptimal, with existing issues of pollution and potential safety hazards. To address this situation, it is particularly important to optimize the location of landfills in Hefei and to design and improve the reverse logistics network for municipal solid waste.

4.2 Infrastructure construction cost and operation and maintenance cost

Since the municipal solid waste generation data for each district (county) of Hefei City has not been officially reported, and given that local population size significantly influences waste generation, the waste quantities for these areas were estimated based on their respective population proportions. Furthermore, to account for potential fluctuations due to various influencing factors, deviation ranges were incorporated into the model, with a lower limit of -5% and an upper limit of +10%. The population figures and corresponding fuzzy waste generation amounts for each region are presented in the table below.

Table 2. Municipal Solid Waste Generation and Fuzzy Quantities by Region in Hefei (2020)

Regions	Waste Generation Quantity (tons)	Fuzzy Waste Generation Quantity (tons)
Yaohai District	249237	(236775) (249237) (274160)
Luyang District	201557	(191479) (201557) (221713)
Shushan District	302877	(333165) (302877) (287733)
Baohe District	351912	(387103) (351912) (334316)
High-Tech Industrial Development Zone	78022	(85824) (78022) (74121)
Economic Development Zone	161191	(177310) (161191) (153131)
Xinzhan District	134913	(148404) (134913) (128167)
Changfeng County	226752	(249427) (226752) (215414)
Feidong County	255739	(281313) (255739) (242952)
Feixi County	279850	(265858) (279850) (307835)
Lujiang County	256823	(282505) (256823) (243982)
Chaohu City	210226	(199715) (210226) (231249)

4.3 Coordinates of main transfer stations in Hefei

In recent years, China has significantly intensified the construction of environmental protection infrastructure, leading to the establishment of numerous waste treatment enterprises across various provinces and municipalities. Through an investigation into the fixed facility construction costs and relevant transportation and management expenses of waste treatment enterprises in Hefei, and by integrating the reverse logistics planning model for municipal solid waste developed in this study, the fixed and operational costs for the nodes within the reverse logistics network have been derived, as summarized in Table 3. It should be noted that, since transfer stations, waste incineration plants, and landfills rely on existing local institutions, their capital construction costs are considered zero and are thus excluded from this reverse logistics network analysis. Consequently, the operational costs primarily reflect the expenses associated with the treatment of municipal solid waste.

Table 3. Municipal Solid Waste Generation and Fuzzy Quantities by Region in Hefei (2020)

Facility Type	Construction Cost (10,000 CNY)	Maintenance Cost (10,000 CNY)
Transfer Station	500	100
Processing Center	500	200
Waste Incineration Plant	100	10
Landfill	100	10

4.4 Other relevant parameters

First, Transportation Cost for Collection Vehicles. Based on surveys, the transportation cost for municipal solid waste in Hefei is approximately 5 CNY/ton. The costs for transporting waste from transfer stations to landfills and power plants are classified as municipal solid waste transportation expenses. Therefore, the final transportation costs between respective tiers are defined as $S_{ij}^{ab}=S_{jk}^{bc}=S_{jh}^{bd}$==5 CNY/ton/km.

Second, Recyclable Proportion of Municipal Solid Waste. As the recyclable proportion of municipal solid waste varies across periods, relevant data indicate that the waste recovery rate in Hefei is 20%, i.e., α=20%.

Third, Processing Capacity of Facilities at Each Tier in the Reverse Logistics Network. According to investigations, the average daily processing capacity of transfer stations in Hefei is 50 tons/day, i.e., $C_g^b=C_k^c$=50 tons.

4.5 Operation results

By applying genetic algorithm encoding and MATLAB (2018) software to solve and analyze the model, optimized data regarding the location, routing, and flow volume of infrastructure at each level were obtained. The selected parameters included a population size of n = 30, a chromosome crossover rate of 0.7, a mutation probability of 0.1, and 400 iterations, resulting in a final objective function value of z = 62,770 million CNY.

The iteration curve of the algorithm is shown in Figure 2. As the genetic algorithm progressively optimized the model, the objective function value gradually decreased and eventually stabilized. Figure 3 illustrates the optimized reverse logistics network structure for municipal solid waste in Hefei, while Table 4 presents the corresponding relationships among the different layers of the reverse logistics network, which includes 10 transfer stations, 2 treatment centers, 1 incineration plant, and 1 landfill site. Tables 5 and 6 provide the distances between transfer stations and treatment centers in the reverse logistics network and the corresponding transportation instruction matrix, respectively.

Figure2: Iterative graph of genetic algorithm

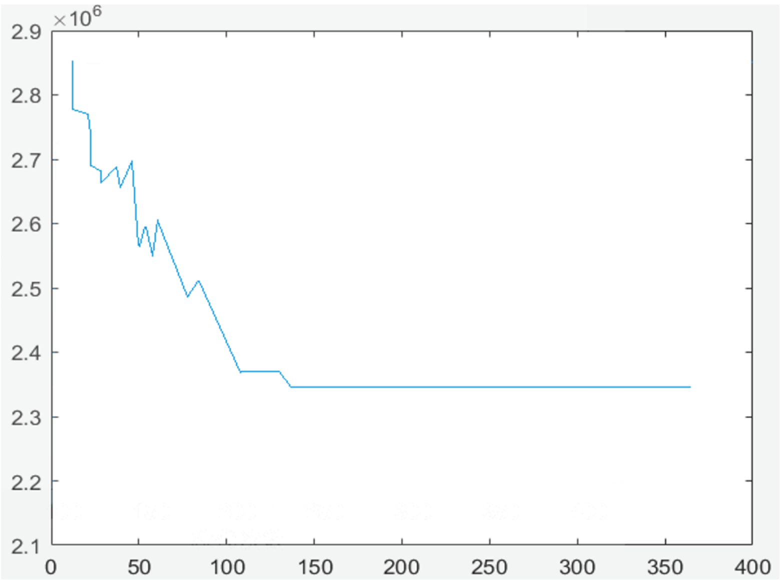


Figure3: Site selection of domestic waste reverse logistics network in Hefei

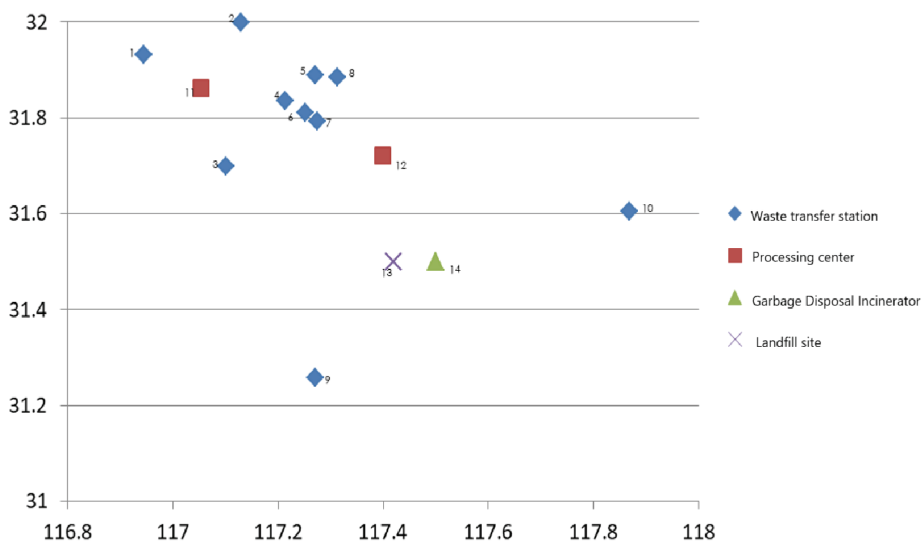


Table 4. Municipal Solid Waste Generation and Fuzzy Quantities by Region in Hefei (2020)

Transfer station	Disposal center	Landfill site	Garbage Disposal Incinerator
1，2，3，4	11	13	14
5，6，7，8，9，10	12	13	14

Table 5. Transportation distance from waste transfer station to waste treatment center (km)

	Processing center 11	Processing center 12
Waste transfer station 1	13.073	
Waste transfer station 2	18.400	
Waste transfer station 3	16.876	
Waste transfer station 4	15.142	
Waste transfer station 5		17.289
Waste transfer station 6		52.862
Waste transfer station 7		22.314
Waste transfer station 8		20.059
Waste transfer station 9		57.620
Waste transfer station 10		45.994

Table 6. Transportation instruction matrix: recycle bin to processing center

node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	0	0	0	0	0	0	0	0	0	1	0	1	1
2	0	0	0	0	0	0	0	0	0	0	1	0	1	1
3	0	0	0	0	0	0	0	0	0	0	1	0	1	1
4	0	0	0	0	0	0	0	0	0	0	1	0	1	1
5	0	0	0	0	0	0	0	0	0	0	0	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	1	1	1
7	0	0	0	0	0	0	0	0	0	0	0	1	1	1
8	0	0	0	0	0	0	0	0	0	0	0	1	1	1
9	0	0	0	0	0	0	0	0	0	0	0	1	1	1
10	0	0	0	0	0	0	0	0	0	0	0	1	1	1
11	1	1	1	1	0	0	0	0	0	0	0	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	1	1
13	0	0	0	0	0	0	0	0	0	0	1	1	0	0
14	0	0	0	0	0	0	0	0	0	0	1	1	0	0

Conclusion

This study constructs a three-layer reverse logistics network structure for municipal solid waste (MSW), comprising the generation layer, transfer layer, and disposal layer, which refines the waste treatment process and helps improve processing efficiency while reducing environmental pollution. Using Hefei City as a case study, the network model was optimized to address key uncertainties such as waste generation volume, and the genetic algorithm was applied to determine the optimal locations and quantities of recycling centers, treatment centers, and landfills. Based on the findings, it is recommended to enhance multi-department and multi-process collaboration in the development of the reverse logistics system, incorporating uncertainties such as weather and traffic into systematic planning and design to achieve a balance of economic, social, and environmental benefits. Furthermore, there should be an active integration of internet and information technologies, such as cloud management and cloud identification, to innovate the offline waste treatment system, improve resource utilization efficiency, and support sustainable urban development.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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