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Supply Chain Design and Optimization of the Municipal Solid Waste Considering Waste Classification

Chaoliang Xie [a,b], Yinghua Jiang [c], Le Wu [a,b,*]

[a]School of Chemical Engineering, Northwest University, Xi'an 710069, China
[b]Shanghai Engineering Research Center of Solid Waste Treatment and Resource Recovery, Shanghai Jiao Tong University, Shanghai 200240, China
[c]Guangxi Key Laboratory of Petrochemical Resource Processing and Process Intensification Technology, School of Chemistry and Chemical Engineering, Guangxi University, Nanning 530004, China
lewu@nwu.edu.cn

Waste supply chain is one of the key methods to lower the negative effects of municipal solid waste (MSW) due to its larger production. The supply chain of MSW mainly contains four processes: collection, classification, transportation and treatment. MSW can be divided into four categories: kitchen waste, recyclable waste, harmful waste and other waste. A mathematical model for the design and optimization of the MSW supply chain is built to obtain the optimal supply chain network, including the optimal MSW collection and classification site, the classified MSW collection site location and its capability as well as the classified MSW transportation way. The total annual cost (TAC) is 5.73×10^{8} CNY·y^{-1}, including the total transportation cost is 4.42×10^{10} CNY·y^{-1} and the total treatment cost is -4.36×10^{10} CNY·y^{-1}. The transportation cost takes a large proportion of the TAC. The most efficient way to lower the TAC is to decrease the transportation cost. The proposed model can be used for the waste supply chain design considering the further treatment and utilization of different waste categories.

1. Introduction

The acceleration of urbanization has led to a sharp increase in municipal solid waste (MSW) production. At present, a large amount of MSW is produced every day. If it is not treated in time, it will affect the normal life of residents. Therefore, how to effectively deal with MSW has become a major problem that must be solved. Waste classification can greatly improve the efficiency of waste treatment and ensure the healthy development of cities. The proposal of waste classification provides the ideas for the effective treatment of MSW. Liu et al. (2022) studies the factors affecting waste classification and puts forward some suggestions on waste management. Residents' awareness of classification is an important factor affecting waste classification and treatment and a new fashionable social atmosphere for waste sorting needs to be formed. Li (2021) analyzed the urban garbage recycling system and existing problems in China, and gave relevant suggestions for further improvement of China's current policies, and suggested to guide third-party companies to integrate the waste sorting industry chain, so that waste classification can truly form a complete closed-loop system of the entire industry chain. Zhang et al. (2022) found transport link of municipal solid waste is an important part of the waste treatment system. In the cost of waste treatment, the cost of the collection and transportation accounts for a considerable proportion. So transportation routes can be optimized. Yang et al. (2021) had classified MSW into two categories: kitchen waste and recyclable waste. Considering the infrastructure, the supply chain of MSW had been redesigned. The specific method of redesign is to change mixed transportation to the exclusive transportation. Zhang et al. (2021) had pointed out that a more refined classification can effectively improve many aspects of MSW management, especially regarding economic and environmental benefits. Effective MSW management can reduce the cost of waste disposal by 69.4% and greenhouse gas and acidic substance emissions and increase the energy utilisation rate four fold.
However, previous studies of the MSW supply chain ignored the delicacy management or treatment of MSW. Despite that Yang et al. (2021) divided waste into two categories, which are different from the current waste classification. It is urgent to propose a new supply chain model that considers the current waste classification.

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In this work, on the basis of considering waste classification, the MSW is divided into four categories: kitchen waste, recyclable waste, harmful waste and other waste. A mathematical model of waste classification, transportation and treatment is proposed by using the existing waste collection sites, transfer centres and treatment plants to obtain the optimal supply chain network including the MSW transportation style and MSW treatment technology.

2. Problem statement

The MSW treatment divided into three parts: collection, transportation, and treatment processes. The supply chain mainly contains waste collection, waste classification, classified waste transportation from collection sites to transfer centers, classified waste transportation from transfer centers to treatment plants. The optimal transportation route and style for classified treatment of MSW can be obtained, if the following parameters are known: the classified waste supplies around the collection sites, the distances among the collection sites, transfer centers and treatment plants, the capacities of transfer centers and unit transportation prices of different transportation styles.

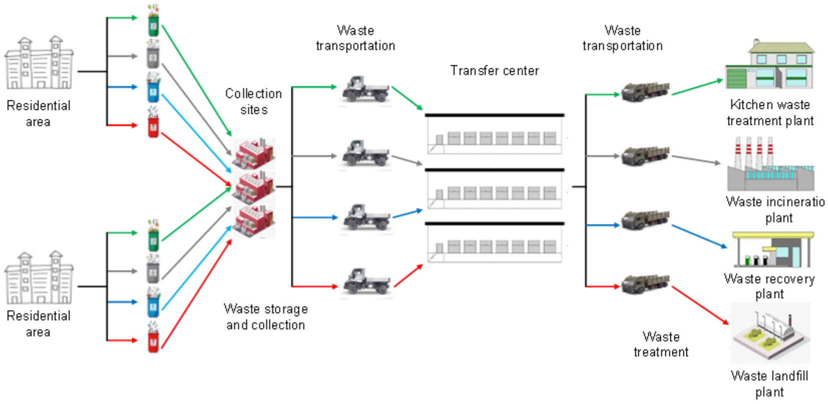

Figure 1: Supply chain of waste classification, transportation and treatment

3. Mathematical model

3.1 Objective function

The total annual cost (TAC) is chosen as the objective function in the design and optimization of the supply chain. It contains the operating cost and the treatment cost. The operating cost is mainly the transportation cost of MSW while the treatment cost consists of the MSW treatment cost and the residents' sanitation cost. The calculation formula is shown in Eq(1).

$$TAC = TOC + TTC \tag{1}$$

where *TAC* denotes the total annual cost, in CNY·y^{-1}. CNY is the abbreviation of China Yuan. *TOC* represents the annualized operating cost, in CNY·y^{-1}; *TTC* is the annualized treatment cost, in CNY·y^{-1}.
Transportation is mainly considered in calculating the *TOC*. The transportation cost consists of the transportation from collection sites to the transfer centers and classified waste transportation from transfer centers to treatment plants. The transportation cost from the collection site to the transfer center is calculated by Eq(2).

$$C^{tc,ab}_{a,b,te} = A d^{ab}_{a,b} p_{te} \tag{2}$$

where *C* denotes the cost, in CNY·day^{-1}; *A* denotes the MSW amount, in t·day^{-1}; *d* is the distance, in km; *p* represents the prices of different transportation styles, in CNY·t^{-1}·km^{-1}; Superscripts *tc* and *ab* are transportation cost and collection site to transfer center; Subscripts *a* and *b* are the sets for the collection sites, transfer center respectively, and *te* means the transportation style of electric truck.
The transportation cost from the transfer center to the treatment plant is calculated by Eq(3).

$$C^{tc,bc}_{b,c,th} = A d^{bc}_{b,c} p_{th} \tag{3}$$

where superscript *bc* denotes the connection between transfer center and treatment plant; Subscripts *th* is the transportation style of heavy truck.
The total transportation cost can be obtained by the following Eq(4) and Eq(5).

$$C^{tc} = \sum_{a,b} z_{a,b}^{ab} C_{a,b,te}^{tc,ab} + \sum_{b,c,t} z_{b,c}^{bc} C_{b,c,th}^{tc,bc} \quad (4)$$

Where C^{tc} is the total transportation cost, in CNY·day^{-1}; *z* is the binary variable to determine the existence of the transportation route, 0 or 1.

$$TOC = C^{tc} AOT \quad (5)$$

where *AOT* is the annual operating time, in day·y^{-1}.
The treatment cost consists of the kitchen waste treatment costs, incineration cost, landfill cost, recovery cost and resident' sanitation cost. These costs can be calculated by the following Eq(6).

$$TC^{i} = A^{i} p^{i} \quad (6)$$

where superscript *i* is the sets for the treatment way.
The total treatment cost can be obtained by the following Eq. (7).

$$TTC = (TC^{kit} + TC^{inc} + TC^{lan} - TC^{rec})\ AOT - TC^{res} \quad (7)$$

where superscript *kit*, *inc*, *lan* and *rec* are the treatment ways of kitchen waste, other waste, recyclable waste and harmful waste, respectively; Superscript *res* denotes resident' sanitation cost.

3.2 Mass balance

The mass balances of the collection sites, transfer centers and treatment plants are shown in Eq(8) ~ Eq(10).

$$\sum_{a} S_a = \sum_{b} Cap_b \quad (8)$$

$$\sum_{ba} Cap_b = \sum_{c} Tre_c \quad (9)$$

$$\sum_{c} Tre_c = A^{kit} + A^{inc} + A^{lan} + A^{rec} \quad (10)$$

where *S* denotes the waste supply, in t; *Cap* is the capacity, in t; *Tre* represents the amount of waste treatment, in t; Superscript *a*, *b* and *c* are the sets for the collection site, transfer center and treatment plant.

3.3 Constraints

Determination of daily waste supply and limitation on the capacity of the transfer center can be calculated by Eq. (11) and Eq. (12).

$$\sum_{a} S_a = A \quad (11)$$

$$Cap_b \le Cap_b^{\max} \quad (12)$$

4. Case study

4.1 Base parameters

In this work, taking Xi'an, located in middle of China, as an example, there are 12 waste classification collection sites (a1 - a12), 8 waste treatment transfer centers (b1 - b8) and 6 waste treatment plants (c1 – c6). The proportion of various types MSW are shown in Table 1(Yang et al., 2021). The prices of treating various types MSW and transportation are listed in Table 2 (Deppon Express, 2022). The supply of various types MSW in each waste collection site is listed in Table 3. The distances among the collection sites, transfer centers and treatment plants are presented in Table 4 and Table 5 (Gaode map, 2022). MSW need pass through collection sites, transfer centers and before they enter the treatment plants.

Table 1: Proportion of waste type

Type	Kitchen waste	Other waste	Recyclable waste	Harmful waste
Proportion/%	52.2	20.7	17.2	9.9

Table 2: Price of waste treatment and transportation

	Waste treatment				Transportation[a)]	
	Kitchen	Other	Recyclable	Harmful	Electric truck	Heavy truck
Price/CNY·t^{-1}	52.2	20.7	17.2	9.9	3.7	3

Note: a) The unit for transportation price is CNY·t^{-1}·km^{-1}.

Table 3: Waste supply of the 12 collection sites

Supply/t·day^{-1}	Kitchen waste	Other waste	Recyclable waste	Harmful waste
a1	68,990.1	27,358.2	22,732.4	13,084.3
a2	77,235.1	30,627.7	25,449.1	14,648
a3	98,376.1	39,011.2	32,415.1	18,657.6
a4	86,349.2	34,242	28,452.2	16,376.6
a5	48,060.5	19,058.5	15,836	9,115
a6	23,161.1	9,184.6	7,631.6	4,392.7
a7	10,1758.7	40,352.6	33,529.7	19,299
a8	48,389.4	19,189.9	15,944.4	9,177.3
a9	98,564	39,085.8	32,477	18,693.2
a10	10,1946.6	40,427.1	33,591.6	19,334.7
a11	46,181.3	18,313.3	15,216.8	8,758.6
a12	45,387.7	17,996.6	14,953.7	8,607

Table 4: Distances among 12 collection sites and 8 transfer centers

Distance/km		Transfer centers							
		b1	b2	b3	b4	b5	b6	b7	b8
	a1	11.2	4.5	5.2	4.5	3.3	14.6	8.9	6.3
	a2	11.7	3.7	4.9	5.3	4.1	14	9.3	6.8
	a3	20.1	11.6	14.3	15.5	15.4	18.2	23.8	18.4
	a4	37.8	31.9	29.4	31.1	29.7	42	21.9	29.1
	a5	8.3	6.5	8.7	3.3	0.28	14.2	11.3	3.5
Collection site	a6	36	30.1	27.6	29.3	27.9	40.2	20	27.3
	a7	8.1	8	11.4	9.9	11.1	5.9	20.1	14
	a8	23.6	14.8	17.5	19.4	18.7	21.4	27.1	21.7
	a9	12.2	9.2	12.4	11.8	13	9.9	22.1	16.1
	a10	14	4.2	6.3	9.2	8	12.3	15.8	11.1
	a11	12.3	5.8	8.5	9.4	9.7	10.2	18.1	14
	a12	12.1	5.6	8.3	9.3	9.5	10	17.9	12.5

Table 5: Distances among 8 transfer centers and 6 treatment plants

Distance/km	Treatment plant						
		c1	c2	c3	c4	c5	c6
	b1	29.3	46.5	16.8	8.6	10.2	25.1
	b2	16.5	32.5	2.7	18.8	6.7	14.4
	b3	13.6	29.9	3.3	21.2	8	17.3
Transfer center	b4	22.3	40.7	11	11.5	3.8	19.9
	b5	20.3	38.8	9.1	12.8	0.6	18.4
	b6	27.8	43.3	13.5	12.4	13.6	21.5
	b7	11.5	30.7	11.9	21.7	10.5	25.2
	b8	21.4	40.6	10.9	11.8	3.9	21.2

4.2 Optimal supply chain

According to the relevant data shown in Table 1 to Table 5, the proposed model is solved in GAMS 24.1.3 with solver SCIP. Then the optimal solution is obtained. The optimal waste flowrates among the collection sites, the transfer centers and the treatments are presented in Figure 2 and Figure 3.

Figure 2: The optimal supply chain network of kitchen waste, other waste, recovery waste and harmful waste (a denotes collection site; b is transfer center; c represents treatment plant.)

According to Figure 2, there are 12 collection sites, 6 transfer centers and 4 treatment plants. The transportation styles from the collection sites to the transfer centers and the transfer centers to the treatment plants are electric truck and heavy truck, respectively. It is worth noting that there are 8 transfer stations and 6 treatment plants in the original plan. However, when the maximum capacity of waste transfer center is 300,000.015t and the waste treatment plant is unlimited, only 6 transfer centers and 4 treatment plants are selected.

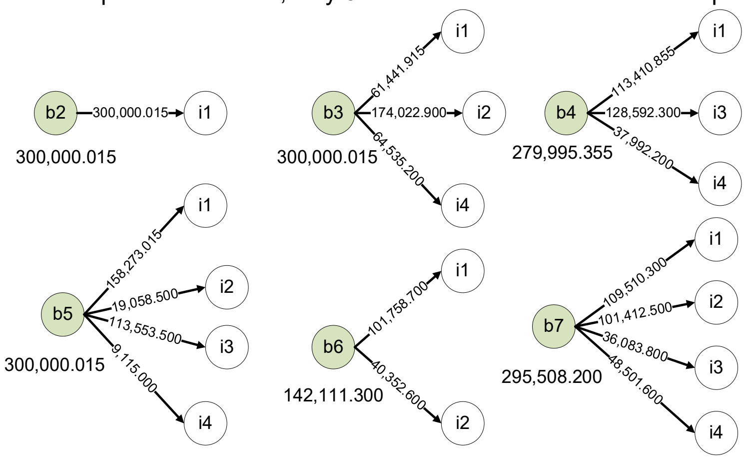

Figure 3: Amount and type of MSW contained in each transfer center (i denotes the waste type)

The specific flowrates of various types MSW in 6 waste transfer centers are shown in Figure 3. The b2, b3, b4, b5 and b7 are close or even reach to their maximum capacity. In b5 and b7, there are all kinds of MSW, so in order to improve the efficiency and total amount of waste treatment, it can be considered to expand their scale.

Table 6: The details of the total annual cost

Cost	Transportation from collection site to transfer center	Transportation from transfer center to treatment plant	Recyclable waste	TAC
Value/CNY·y^{-1}	2.17×10^{10}	2.25×10^{10}	-4.36×10^{10}	5.73×10^{8}

According to Table 6, the transportation cost from the collection sites to the transfer centers is 2.17×10^{10} CNY·y^{-1}, and transportation cost from the transfer centers to the treatment plants is 2.25×10^{10} CNY·y^{-1}. The treatment cost is -4.36×10^{10} CNY·y^{-1}. That is to say, there are economic benefits in waste treatment considering classification, which is one of the reasons why waste classification is necessary. The TAC is 5.73×10^{8} CNY·y^{-1}. The supply chain proposed in this work makes full use of the existing infrastructure and further improves the waste treatment effect through more detailed division of waste. Through intuitive data, it is proved that our conclusion is the same as Yang et al. (2021)' conclusion that waste classification improves the treatment effect of MSW. Furthermore, more classifications of MSW can enhance the economic performance of the system according to the comparison with Yang et al. (2021)' work.

5. Conclusion

A mixed integer programming is proposed to optimize the supply chain of MSW transportation and treatment by considering the waste classification. The supply chain can be optimized by solving the proposed model. After the waste is classified for treatment, the waste treatment effect is apparently improved. The results show that it has benefits in the link of waste classification and treatment. Considering the higher MSW transportation cost and relatively lower investments of collection site and transfer center, the most effective way to lower the total cost of the supply chain is to build the new waste collection sites and transfer centers in appropriate locations based on the waste classifications in order to decrease the distances between transportation routes. Future research should focus on the impact of seasonal changes and the uncertainty of supply of various waste collection.

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