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The Dynamic Two-echelon MSW Disposal System Study under Uncertainty in Smart City

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Abstract. The municipal solid waste (MSW) disposal system is the key for building the smart city. In the MSW disposal system, the MSW is allocated among the disposal plants in the first echelon, and then the derivatives (incineration residues and RDF) are allocated between residues disposal plants and markets in the second echelon. In the two-echelon optimal allocation of MSW disposal system, two objectives, cost and environmental impact, should be considered. Considering the uncertainty in the MSW disposal system, this paper constructs a grey fuzzy multi-objective two-echelon MSW allocation model. The model is divided into two sub models and the expected value sorting method is applied to solve the model. The proposed model successfully was applied to a real case in Huangshi, China. The numerical experiments showed RDF technology has advantages on both cost and environmental impact comparing to other disposal technology on disposing MSW.

Keywords: smart city, Two-echelon allocation, MSW, uncertainty.

1. Introduction

With population increasing in the city, the municipal solid waste (MSW) generation grows fast, which causes many issues such as public health, resource utilization and environment. Therefore, MSW management has become an urgent problem in the smart city management. And the MSW disposal is critical to the sustainable development of MSW management.

In the MSW disposal system, the two-echelon optimal allocation model consists of MSW allocation and residues allocation. Sustainable MSW management system requires the incorporation of economic, environmental, and social aspects. Since the social aspect is difficult to measure with data, the economy and environment will be considered into the allocation model.

This paper aims at establishing a dynamic two-echelon MSW optimal allocation model for enhancing MSW management. Generally, the MSW generation is stochastic and unplanned [1]. And it is influenced by many factors, such as people's living habits, consumption pattern and resident income and so on. As a result, the optimal allocation mode is under uncertainty.

The present study area is Huangshi, a city of Hubei Province, China, which consists three administrative districts with a total population of 537,733. Household waste is the major source of MSW. In Huangshi, the MSW generation rate per capita in the study area is about 1.31 kg/day. Currently, MSW incineration is the main technology to dispose the MSW. And there is only one waste incineration power plant located in Huangjinshan. All the MSW of the 3 administrative districts are transported to the waste incineration power plant to be disposed. And in the near future, Refuse Derived Fuel (RDF) disposal technology will be introduced into the MSW disposal system in Huangshi.

The rest of this paper is organized as follows: Section 2 presents a review of the relevant literature and clarifies how we bridge a research gap. A description of the two-echelon allocation of MSW disposal system and the formulation of the mathematical model are presented in Section 3. The computational experiments' results from the case are examined in Section 4. The sensitivity analysis is discussed in Section 5. Finally, Section 6 presents a conclusion, along with suggestions for future research directions.

2. Literature review

The MSW disposal is a complex system. Scholars usually apply mathematical programming models to analyze many MSW management problems, especially the optimal MSW allocation solution. Huang et al. [2] proposed the mathematical programming model, line programming, to obtain the optimal MSW allocation solutions by minimizing the MSW disposal cost. Then, Chang and Wang [3] developed a multi-objective integer programming model based on the model proposed by Huang et al. They took economy and environment into account, and constructed a fuzzy multi-objective integer programming model to seek the optimal allocation solutions of MSW and the capacity expansion solutions of MSW disposal plants. Fiorucci et al. [4] developed a non-linear optimization model to determine the optimal amount and types of MSW transported to landfill, incineration and recycling. Rathi [5] proposed a linear programming model, and took into account the economic and environmental factors in the MSW system to optimize the allocation of MSW in Mumbai.

Many scholars also apply Mixed-Integer Linear Programming (MILP) to find the optimal allocation solution. For example, a MILP model is applied to find the optimal MSW allocation solution in Port Said, Egypt with the goal of minimize transportation cost [6]. Considering the minimize MSW system cost, Dai, Li, and Huang [7] applied the MILP model to obtain the optimal MSW allocation solution in Beijing, China. Chatzouridis and Komilis [8] proposed an MILP model to find the optimal location of MSW transfer stations. Lee et al. [9] proposed a MILP model to find the optimal decision of MSW management system. Tan et al. [10] utilized a MILP model to obtain the optimal MSW disposal facilities capacity and MSW allocation solution by minimizing MSW system cost in Iskandar, Malaysia. The MILP model is developed by Harijani et al. [11]to decide optimal solution of the MSW facilities location and MSW allocation by maximizing the system profit.

There are many uncertain variables in the system, such as MSW generation, MSW recycle rate, transportation and disposal cost, residue conversion rate, etc. Usually, three approaches are applied to represent the uncertain variables: Interval value, Fuzzy and Stochastic programming [12, 13]. Xu et al. [14] optimized the MSW allocation solution by establishing a fuzzy-stochastic programming. Later, an interval-stochastic programming was developed to minimize the MSW system cost by a combination of interval, fuzzy and stochastic programming model [15].

Recently, MSW optimal allocation models have been developed to incorporate multiple disposal technology, especially waste-to-energy (WTE) technology [16,17]. Considering several WTE technologies, Santibañez Aguilar et al. [18] proposed an optimization model to achieve the optimal MSW allocation. Xiong et al. [19] took into account a hybrid WTE system and found that an optimal incorporation of WTE technologies is more economically advantageous. Some scholars took MSW logistics planning and transportation costs into account, applying Location-Routing Problem (LRP) models to find the optimal MSW allocation. Asefi, Lim, Maghrebi, and Shahparvari [20] took minimize MSW transportation and disposal cost as the objectives to optimize the MSW transportation route and allocation solutions. Khattak [21] et al designed a Cross-layer and optimization techniques in wireless multimedia sensor networks for smart cities.

In the previous studies, waste incineration and landfill are considered as the main disposal technology, and refuse derived fuel (RDF) is less involved in the MSW disposal system. Besides, only the MSW allocation is considered in the MSW management system, the residues allocation after MSW disposal is neglected.

In this paper, considering the dynamic and uncertainty of the MSW generation and multiple MSW disposal technologies in the MSW disposal system, a dynamic two-echelon MSW optimal allocation model under uncertainty is established to minimize the economic cost and environmental impact.

3. Methodology

As is mentioned above, many scholars only concern MSW optimal allocation in MSW disposal system. In fact, MSW residues produced during MSW disposal process need to be allocated too. So, in this section, MSW and residues allocation are all considered into the MSW disposal system. Since the MSW generation is uncertain and dynamic, in this paper, the uncertain data or the missing data will be described by grey number and fuzzy number [22, 23], and three periods will be considered. So, a dynamic two-echelon MSW optimal allocation model under uncertainty will be established.

3.1. Problem description

There is two-echelon allocation in the MSW disposal system. The first echelon allocation is the MSW allocation from the MSW transfer stations to the MSW disposal plants. After simple compression and compaction in the MSW transfer stations, the MSW is transported from the transfer station to the each MSW disposal plant (incineration plant, composting plant, RDF plant and sanitary landfill).

The second echelon allocation is the residues allocation. The MSW residues include MSW incineration residues and RDF. During the MSW incineration process, residues, fly ash and bottom ash, will be produced. In the RDF plant, MSW can be converted into RDF. So, residues and RDF need to be redistributed. There are two main disposal methods of residues: landfill and co-disposal in cement kiln. RDF, an alternative fuel for cement plant, can be transported to cement plant to dispose. In addition, RDF can be sold on the market. In summary, the two-echelon allocation of MSW disposal system is shown in Figure.1.

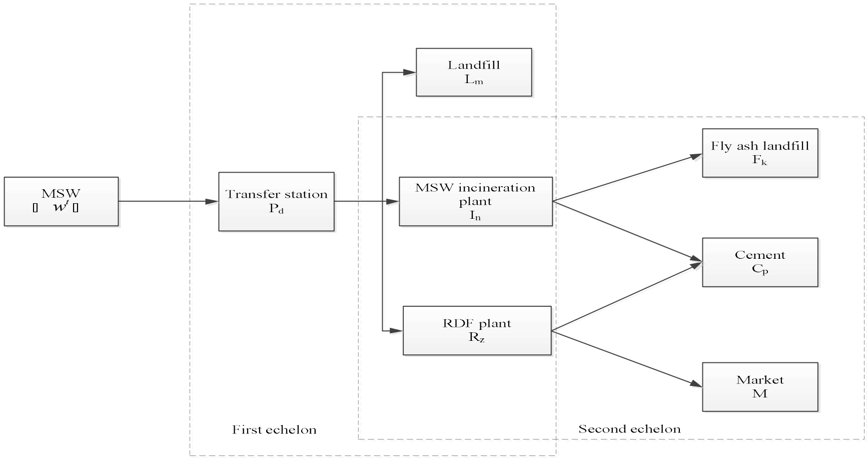

Fig. 1. The two-echelon allocation diagram of MSW disposal system

3.2. Model description

The model built in this paper is based on the following assumptions:

(1) All MSW disposal plants and residues plants applying the same technology have the same disposal efficiency;

(2) In the MSW disposal plant, if the MSW received exceeds its maximum capacity, the capacity expansion will be considered;

(3) The operation cost of each enterprise is only considered;

(4) The transportation cost is only related to the transportation distance.

The parameters involved in the model are as follows:

w^t : The MSW quantity in t period

λ : Converted ratio after pretreatment in transfer station

P_d^t : There are d transfer stations to collect and pre-treat the MSW in period t, $d = 1,\ldots,D$

R_z^t : There are z RDF plants to dispose the MSW in period t, $z = 1,\ldots,Z$

I_n^t : There are n incineration plants to dispose the MSW in period t, $n = 1,\ldots,N$

L_m^t : There are m landfills to dispose the MSW in period t, $m = 1,\ldots,M$

C_p^t : There are p cement plants to dispose the RDF and fly ash in period t, $p = 1,\ldots,P$

F_g^t : There are g fly ash landfills to dispose fly ash in period t, $g = 1,\cdots,G$

$Q_{p_d,I}^t$: The amount of MSW from transfer station P_d^t to incineration plant I_n^t in period t (thousand ton)

Q_{P_d,R_z}^t : The amount of MSW from transfer station P_d^t to RDF plant R_z^t in period t (thousand ton)

Q_{P_d,L_m}^t : The amount of MSW from transfer station P_d^t to landfill L_m^t in period t (thousand ton)

σ : The RDF conversion rate

Q_{R_z,C_q}^t : The amount of MSW from RDF plant R_z^t to cement plant C_p^t in period t (thousand ton)

$Q_{R_z,M}^t$: The amount of MSW from RDF plant R_z^t to market in period t (thousand ton)

ε : Electric generated by incinerating 1 ton MSW (kw*h)

μ : The fly ash conversion rate

Q_{I_n,F_g}^t : The amount of fly ash from incineration plant I_n^t to fly ash landfill F_g^t in period t (thousand ton)

Q_{I_n,C_p}^t : The amount of fly ash from incineration plant I_n^t to cement plant C_p^t in period t (thousand ton)

$Q_{a,b}^t$: The amount of MSW from a to b in period t (thousand ton)

$D_{a,b}$: The distance from a to b

C_T^t : Transport cost in period t

C_m^t : The operation cost of each enterprises in period t

$C_{R_z}^t$: The operation cost of RDF plant in period t

$C_{I_n}^t$: The operation cost of incineration plant in period t

$C_{L_m}^t$: The operation cost of landfill in period t

$C_{C_p}^t$: The operation cost of disposing MSW in cement plant in period t

$C_{CF_p}^t$: The operation cost of disposing fly ash in cement plant in period t

$C_{F_g}^t$: The operation cost of disposing fly ash in fly ash landfill in period t

P_{RDF}^{t} : The price of RDF in period t

S_{RDF}^{t} : The subsidy of disposing MSW in RDF plant in period t

B_{RDF}^{t} : The revenue of RDF plant in period t

S_{I}^{t} : The subsidy of disposing MSW in incineration plant in period t

E_{n}^{t} : The electricity on grid power from MSW incineration plant n in period t

P_{I}^{t} : The price of the electricity on grid power from MSW incineration plant in period t

ν : The substitution rate of RDF for fossil fuel

P_{C}^{t} : The price of fossil fuel

B_{C}^{t} : The revenue of cement plant in period t

$M_{I_n,a}$: The minimum MSW disposal requirement of incineration plant

$M_{I_n,b}$: The maximum MSW disposal capacity of incineration plant

α^{t} : Binary variable, if the MSW incineration plant expands in t period, $\alpha^{t} = 1$, otherwise 0

M_{I_nE} : The expanded capacity of incineration plant

$M_{R_z,a}$: The minimum MSW disposal requirement of RDF plant

$M_{R_z,b}$: The maximum MSW disposal capacity of RDF plant

β^{t} : Binary variable, if the MSW incineration plant expands in t period, $\beta^{t} = 1$, otherwise 0

M_{R_zE} : The expanded capacity of RDF plant

C_{ER_z} : The unit expansion cost of RDF plant

C_{EI_n} : The unit expansion cost of incineration plant

C_{E}^{t} : The total expansion cost of all the plants

M_{L_m} : The maximum MSW disposal capacity of landfill

M_{C_p} : The maximum RDF disposal capacity of cement

M_{F_g} : The maximum fly ash disposal capacity of fly ash landfill

Z_{1}^{t} : The total cost of MSW disposal system

GWP_{L} : The greenhouse gas emission of disposing MSW in landfill

GWP_{I} : The greenhouse gas emission of disposing MSW in incineration plant

GWP_{R} : The greenhouse gas emission of disposing MSW in RDF plant

GWP_{FL} : The greenhouse gas emission of disposing fly ash in fly ash landfill

GWP_{FC} : The greenhouse gas emission of disposing fly ash in cement

GWP_{C} : The greenhouse gas emission of disposing RDF in cement

GWP_{TC} : The greenhouse gas emission of transportation vehicle fleet

Z_{2}^{t} : The total greenhouse gas emission of MSW disposal system

W_1: The cost weight of MSW disposal system

W_2: The greenhouse gas emission weight of MSW disposal system

Z^t: The comprehensive evaluation value (GEV) of MSW disposal system

3.3. Mathematical model

The MSW disposal system mainly considers two objectives (cost and environment). The objective function is as follows:

$$\min Z^t = W_1 Z_1^t + W_2 Z_2^t \tag{1}$$

Where Z^t represents total comprehensive evaluation index, Z_1^t represents total system cost, and Z_2^t represents total environmental impact.

The total system cost Z_1^t mainly consists of four parts: transportation cost, operation cost, expansion cost and economic revenue. The details are as follows:

(1) Transportation cost

Let X be the set of all transportation routes, and $(a,b) \in X$ denotes the route from a to b. $C_{a,b}^t$ represents the transportation cost per kilometer from a to b in period t, and $D_{a,b}$ represents the distance from a to place b. Then the total transportation cost in period t is:

$$C_T^t = \sum_{(a,b)\in X} C_{a,b}^t \cdot D_{a,b} \tag{2}$$

(2) Operation cost

Suppose $C_{R_z}^t$, $C_{I_n}^t$, $C_{L_m}^t$, $C_{C_p}^t$, $C_{CF_p}^t$, $C_{F_g}^t$ represent the MSW operating cost of RDF plant, MSW incineration plant, landfill, and the residues operating cost of cement plant and fly ash, fly ash landfill respectively in period t. Then the total operating cost in period t is

$$\begin{aligned} C_m^t = {} & \sum_{d=1}^{D}\sum_{z=1}^{Z} Q_{P_d,R_z}^t C_{R_z}^t + \sum_{d=1}^{D}\sum_{n=1}^{N} Q_{P_d,I_n}^t C_{I_n}^t + \sum_{d=1}^{D}\sum_{m=1}^{M} Q_{P_d,L_m}^t C_{L_m}^t \\ & + \sum_{p=1}^{P}(\sum_{z=1}^{Z} Q_{R_z,C_p}^t C_{C_p}^t + \sum_{n=1}^{N} Q_{I_n,C_p}^t C_{CF_p}^t) + \sum_{n=1}^{N}\sum_{g=1}^{G} Q_{I_n,F_g}^t C_{F_g}^t \end{aligned} \tag{3}$$

(3) The expansion cost

When the MSW transported to the disposal plants exceeds their disposal capacity, the expansion decision will be considered. This paper only considers the expansion of MSW incineration plant and RDF plant. The total expansion cost in period t is

$$C_E^t = \alpha^t \sum_{n=1}^{N} C_{EI_n}^t + \beta^t \sum_{z=1}^{Z} C_{ER_z}^t \tag{4}$$

(4) The RDF plant revenue

The revenue of RDF plant in period t mainly consists of two parts: the sales revenue in the market and the subsidy revenue. The revenue of RDF plant can be expressed as follows:

$$B^t_{RDF} = \sum_{z=1}^{Z} P^t_{RDF} Q^t_{R_z,M} + S^t_{RDF} \sum_{d=1}^{D} \sum_{z=1}^{Z} Q^t_{P_d,R_z} \quad \textbf{(5)}$$

(5) The incineration plant revenue

It is assumed that the electricity price on grid converted from MSW is 0.65 yuan per kilowatt hour. In addition, the MSW incineration plant can also obtain the subsidy S^t_n for disposing MSW. The ε kW electricity can be obtained by disposing 1 ton MSW. Then the incineration plant revenue in period t is

$$B^t_E = \sum_{n=1}^{N} P^t_I E^t_n + \sum_{d=1}^{D} \sum_{n=1}^{N} Q^t_{P_d,I_n} S^t_n \quad \textbf{(6)}$$

where $E^t_n = \sum_{d=1}^{D} \sum_{n=1}^{N} Q^t_{P_d,I_n} \varepsilon$.

(6) The cement plant revenue

RDF can be disposed in cement plant, which can replace fossil fuel. So, disposing RDF can be regarded as the revenue of cement plant. Then the revenue of cement plant in period t is

$$B^t_C = P^t_C \sum_{p=1}^{P} \sum_{z=1}^{Z} v Q^t_{R_z,C_p} \quad \textbf{(7)}$$

Above all, the objective function of total cost of MSW disposal system in period t is

$$\min Z^t_1 = C^t_T + C^t_m + C^t_E - B^t_{RDF} - B^t_E - B^t_C \quad \textbf{(8)}$$

(7) Constraints

Capacity constraint of incineration plant: The amount of MSW transported to the incineration plant in period t should be between the minimum and maximum disposal capacity and expansion capacity. Then the constrain is:

$$M_{I_n,a} \le \sum_{n=1}^{N} \sum_{d=1}^{D} Q^t_{P_d,I_n} \le M_{I_n,b} + \alpha^t M_{I_nE} \quad \textbf{(9)}$$

Capacity constraint of RDF plant: The amount of MSW transported to the RDF plant in period t should be between its minimum and maximum disposal capacity and expansion capacity. Then the constrain is:

$$M_{R_z,a} \le \sum_{d=1}^{D} \sum_{z=1}^{Z} Q^t_{P_d,R_z} \le M_{R_z,b} + \beta^t M_{R_zE} \quad \textbf{(10)}$$

Capacity constraint of landfill: The amount of MSW transported to the landfill should be no more than the landfill capacity. Then the constrain is:

$$\sum_{t=1}^{T} \sum_{d=1}^{D} \sum_{m=1}^{M} Q^t_{P_d,L_m} \le M_{L_m} \quad \textbf{(11)}$$

Capacity constraint of cement plant: The RDF and fly ash transported to the cement plant in period t should be no more than the cement plant capacity respectively. Then the constrain is:

$$\sum_{z=1}^{Z} \sum_{p=1}^{P} Q^t_{R_z,C_p} \le M_{C_p} \quad \textbf{(12)}$$

$$\sum_{n=1}^{N} \sum_{p=1}^{P} Q^t_{I_n,C_p} \le M_{C_{p,F}} \quad \textbf{(13)}$$

Capacity constraint of fly ash landfill: The amount of fly ash transported to the landfill should be no more than the landfill capacity. Then the constrain is:

$$\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{g=1}^{G} Q_{I_n,F_g}^{t} \le M_{F_g} \tag{14}$$

Material balance constraint: The material balance constraints of MSW transfer station, incineration plant, RDF plant and landfill are as follows.

$$\sum_{z=1}^{Z} Q_{P_d,R_z}^{t} + \sum_{n=1}^{N} Q_{P_d,I_n}^{t} + \sum_{m=1}^{M} Q_{P_d,L_m}^{t} = \lambda w^{t} \quad d = 1,\dots,D \tag{15}$$

$$\sum_{p=1}^{P} Q_{R_z,C_p}^{t} + Q_{R_z,M}^{t} = \sigma \sum_{d=1}^{D} Q_{P_d,R_z}^{t} \quad z = 1,\dots,Z \tag{16}$$

$$\sum_{g=1}^{G} Q_{I_n,F_g}^{t} + \sum_{p=1}^{P} Q_{I_n,C_p}^{t} = \mu \sum_{d=1}^{D} Q_{P_d,I_n}^{t} \quad n = 1,\dots,N \tag{17}$$

In this paper, all decision variables are nonnegative.

The environmental impact is measured by greenhouse gas emissions (GHG). The environmental impact Z_2^t in period t is:

$$\begin{aligned}\min Z_2^t = {} & \Big(\sum_{d=1}^{D}\sum_{m=1}^{M} Q_{P_d,L_m}^{t} \cdot d_{P_d,L_m} + \sum_{d=1}^{D}\sum_{n=1}^{N} Q_{P_d,I_n}^{t} \cdot d_{P_d,I_n} + \sum_{d=1}^{D}\sum_{z=1}^{Z} Q_{P_d,R_z}^{t} \cdot d_{P_d,R_z} \\ & + \sum_{z=1}^{Z}\sum_{p=1}^{P} Q_{R_z,C_p}^{t} \cdot d_{R_z,C_p} + \sum_{n=1}^{N}\sum_{g=1}^{G} Q_{I_n,F_g}^{t} \cdot d_{I_n,F_g} + \sum_{n=1}^{N}\sum_{p=1}^{P} Q_{I_n,C_p}^{t} \cdot d_{I_n,C_p}\Big) \cdot GWP_{TC} \\ & + \sum_{d=1}^{D}\sum_{m=1}^{M} Q_{P_d,L_m}^{t} \cdot GWP_{L} + \sum_{d=1}^{D}\sum_{n=1}^{N} Q_{P_d,I_n}^{t} \cdot GWP_{I} + \sum_{d=1}^{D}\sum_{z=1}^{Z} Q_{P_d,R_z}^{t} \cdot GWP_{R} \\ & + \sum_{z=1}^{Z}\sum_{p=1}^{P} Q_{R_z,C_p}^{t} \cdot GWP_{C} + \sum_{g=1}^{G} Q_{I_n,F_g}^{t} \cdot GWP_{FL} + \sum_{n=1}^{N}\sum_{p=1}^{P} Q_{I_n,C_p}^{t} \cdot GWP_{FC}\end{aligned} \tag{18}$$

Where the first three terms represent the greenhouse gas emissions of MSW transportation from the waste transfer station to the landfill, incineration plant and RDF Plant respectively; the fourth term represents the greenhouse gas emissions of the RDF transportation from RDF plant to the cement plant, the fifth and sixth terms represent the greenhouse gas emissions of the fly ash transportation from incineration plant to the fly ash landfill and the cement plant respectively; the seventh, eighth and ninth terms represent the greenhouse gas emissions of disposing MSW in landfill, incineration plant and RDF plant respectively; Since RDF can replace the fossil fuel, disposing the RDF can reduce the greenhouse gas emission the tenth term represents the greenhouse gas emissions of disposing RDF in cement plant; the eleventh and twelfth terms represent the greenhouse gas emissions of disposing the fly ash in fly ash landfill and cement plant respectively.

3.4. The uncertain multi-objective two-echelon optimal MSW allocation model

Since there are many uncertain factors in the MSW disposal system, considering the uncertain factors, the above model is transformed into gray fuzzy multi-objective programming model. The grey fuzzy minimum system cost function is:

$$\min \otimes \tilde{Z}_1^t = \otimes \tilde{C}_T^t + \otimes \tilde{C}_m^t + \otimes \tilde{C}_E^t - \otimes \tilde{B}_{RDF}^t - \otimes \tilde{B}_E^t - \otimes \tilde{B}_C^t \qquad \textbf{(19)}$$

Where $\otimes \tilde{C}_T^t$ represents the fuzzy grey value of transportation cost in period t, $\otimes C_m^t$ represents the operation cost in period t, $\otimes C_E^t$ represents the expansion cost in period t, $\otimes \tilde{B}_{RDF}^t$ represents the RDF plant revenue in period t, $\otimes \tilde{B}_E^t$ represents the electric revenue in period t and $\otimes \tilde{B}_C^t$ represents the cement plant revenue in period t.

$\tilde{GWP}_{TC}$, $\tilde{GWP}_{L}$, $\tilde{GWP}_{I}$, $\tilde{GWP}_{R}$, $\tilde{GWP}_{C}$, $\tilde{GWP}_{FL}$, $\tilde{GWP}_{FC}$ represent the fuzzy greenhouse gas emissions value of transportation, landfill, incineration plant, RDF plant, disposing RDF in cement plant , fly ash landfill and disposing fly ash in cement plant respectively. The fuzzy function of environmental impact in period t is

$$\begin{aligned}\min \tilde{Z}_2^t = (&\sum_{d=1}^{D}\sum_{m=1}^{M} Q_{P_d,L_m}^t \square d_{P_d,L_m} + \sum_{d=1}^{D}\sum_{n=1}^{N} Q_{P_d,I_n}^t \square d_{P_d,I_n} + \sum_{d=1}^{D}\sum_{z=1}^{Z} Q_{P_d,R_z}^t \square d_{P_d,R_z} \\ &+ \sum_{z=1}^{Z}\sum_{p=1}^{P} Q_{R_z,C_p}^t \square d_{R_z,C_p} + \sum_{n=1}^{N}\sum_{g=1}^{G} Q_{I_n,F_g}^t \square d_{I_n,F_g} + \sum_{n=1}^{N}\sum_{p=1}^{P} Q_{I_n,C_p}^t \square d_{I_n,C_p}) \square \tilde{GWP}_{TC} \\ &+ \sum_{d=1}^{D}\sum_{m=1}^{M} Q_{P_d,L_m}^t \square \tilde{GWP}_{L} + \sum_{d=1}^{D}\sum_{m=1}^{M} Q_{P_d,I_n}^t \square \tilde{GWP}_{I} + \sum_{d=1}^{D}\sum_{z=1}^{Z} Q_{P_d,R_z}^t \square \tilde{GWP}_{R} \\ &+ \sum_{z=1}^{Z}\sum_{p=1}^{P} Q_{R_z,C_p}^t \square \tilde{GWP}_{C} + \sum_{g=1}^{G} Q_{I_n,F_g}^t \square \tilde{GWP}_{FL} + \sum_{n=1}^{N}\sum_{p=1}^{P} Q_{I_n,C_p}^t \square \tilde{GWP}_{FC}\end{aligned} \qquad \textbf{(20)}$$

The grey fuzzy comprehensive evaluation function of two-echelon allocation model is

$$\min \otimes \tilde{Z}^t = W_1 \otimes \tilde{Z}_1^t + W_2 \otimes \tilde{Z}_2^t \qquad \textbf{(21)}$$

The constraints of grey fuzzy multi-objective two-echelon allocation model are

$$M_{I_n,a} \le \sum_{n=1}^{N}\sum_{d=1}^{D} \otimes Q_{P_d,I_n}^t \le M_{I_n,b} + \alpha^t M_{I_nE} \qquad \textbf{(22)}$$

$$M_{R_z,a} \le \sum_{d=1}^{D}\sum_{z=1}^{Z} \otimes Q_{P_d,R_z}^t \le M_{R_z,b} + \beta^t M_{R_zE} \qquad \textbf{(23)}$$

$$\sum_{t=1}^{T}\sum_{d=1}^{D}\sum_{m=1}^{M} \otimes Q_{P_d,L_m}^t \le M_{L_m} \qquad \textbf{(24)}$$

$$\sum_{z=1}^{Z}\sum_{p=1}^{P} \otimes Q_{R_z,C_p}^t \le M_{C_p} \qquad \textbf{(25)}$$

$$\sum_{n=1}^{N}\sum_{p=1}^{P} \otimes Q_{I_n,C_p}^t \le M_{C_{p,F}} \qquad \textbf{(26)}$$

$$\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{g=1}^{G} \otimes Q_{I_n,F_g}^t \le M_{F_g} \qquad \textbf{(27)}$$

$$\sum_{z=1}^{Z} \otimes Q_{P_d,R_z}^t + \sum_{n=1}^{N} \otimes Q_{P_d,I_n}^t + \sum_{m=1}^{M} \otimes Q_{P_d,L_m}^t = \lambda \otimes w^t \quad d = 1,\ldots,D \qquad \textbf{(28)}$$

$$\sum_{p=1}^{P} \otimes Q_{R_z,C_p}^t + \otimes Q_{R_z,M}^t = \sigma \sum_{d=1}^{D} \otimes Q_{P_d,R_z}^t \quad z = 1,\ldots,Z \qquad \textbf{(29)}$$

$$\sum_{g=1}^{G} \otimes Q^{t}_{I_n,F_g} + \sum_{p=1}^{P} \otimes Q^{t}_{I_n,C_p} = \mu \sum_{d=1}^{D} \otimes Q^{t}_{P_d,I_n} \quad n = 1,\ldots,N \tag{30}$$

4. Case study

4.1. Experimental Design and Environment

Huangshi is located in the southeast of Hubei Province, China. Huangshi consists of three administrative districts (Huangshigang, Xisaishan, Xialu). This section first forecasts the MSW generation per capita in the three administrative districts, and then combines the population data in each administrative region with the MSW generation per capita prediction data to obtain the MSW generation allocation in Huangshi. There are 76 communities in the three administrative districts, where 30 communities are located in Huangshigang, 19 communities are located in Xisaishan and 27 communities are located in Xialu. In this paper, the community is regarded as collection point.

This paper will study the two-echelon optimal allocation in MSW disposal system in three periods. The system includes two parts: (1) the allocation of MSW among waste disposal plants; (2) the allocation of residues between residues disposal plants and the market. There are 18 waste transfer stations (TS) in Huangshi, the longitude and latitude coordinates of 18 waste transfer stations and the amount of MSW are shown in Table 1.

Table 1. The received waste amount of waste transfer station (thousand ton)

No	T1		T2		T3	
	Low	Up	Low	Up	Low	Up
1	15.9	16.2	16.4	16.6	16.4	16.6
2	10.1	10.2	10.3	10.4	10.3	10.4
3	16.9	17.1	17.3	17.5	17.3	17.5
4	46.1	46.6	47	47.5	47	47.5
5	6.6	6.8	7	7.2	7	7.2
6	14.5	14.9	15.3	15.8	15.4	15.8
7	10.7	11.1	11.4	11.7	11.4	11.7
8	17.4	17.9	18.4	19.0	18.4	19.0
9	15.9	16.4	16.9	17.4	16.9	17.4
10	15.6	16.1	16.6	17.1	16.6	17.1
11	11.5	11.8	12	12.3	12.0	12.3
12	11.2	11.4	11.7	11.9	11.7	11.9
13	33.3	34	34.7	35.5	34.7	35.5
14	27.3	27.9	28.5	29.1	28.5	29.1
15	11.7	11.8	11.9	12	11.9	12
16	12.2	12.3	12.4	12.5	12.4	12.5
17	3.1	3.1	3.2	3.3	3.2	3.3
18	28.4	29	29.6	30.3	29.6	30.3

Based on the MSW management system in Huangshi, this paper will consider three MSW disposal technologies, namely landfill, MSW incineration and RDF. The disposal capacity of each disposal plant is shown in Table 2. The transportation distance between each disposal plant is shown in Table 3. The operating cost of each plant in three periods is shown in Table 4. The subsidy for MSW disposal is shown in Table 5.

Table 2. The disposal capacity of each disposal plant

Disposal plant	Disposal object	Disposal capacity	Unit
Incineration plant （$M_{I_n,a}$，$M_{I_n,b}$）	MSW	[63.4，190.4]	Thousand ton/year
RDF plant （$M_{R_q,a}$，$M_{R_q,b}$）	MSW	[47.4，158.7]	Thousand ton/year
Cement plant	RDF（M_{C_p}）	≤328.5	Thousand ton/year
	Fly ash （$M_{C_{p,F}}$）	[15.8，19]	Thousand ton/year
Fly ash landfill （M_{F_g}）	Fly ash	≤120.45	Thousand ton/year

Table 3. The transportation distances between each disposal plant Unit:km

To From	RDF plant	Incineration plant	Fly ash landfill	Cement plant
Transfer station 1	17.2	13.1	9.5	-
Transfer station 2	18.7	14.2	7.5	-
Transfer station 3	20.0	15.3	5.8	-
Transfer station 4	14.3	10.6	12.2	-
Transfer station 5	5.1	7	22.5	-
Transfer station 6	4.5	8.3	24.8	-
Transfer station 7	6.5	11.3	27.9	-
Transfer station 8	4.4	8.7	25.5	-
Transfer station 9	7.5	6.8	19.5	-
Transfer station 10	10.0	7.4	16.5	-
Transfer station 11	16.3	13.2	12.5	-
Transfer station 12	14.0	11.6	15.0	-
Transfer station 13	15.7	13.5	15.2	-
Transfer station 14	14.5	12.9	16.9	
Transfer station 15	15.2	11.3	11.3	
Transfer station 16	17.1	12.7	9.0	
Transfer station 17	7.4	8.8	22.3	
Transfer station 18	16.0	12.3	11.3	
RDF plant	-	-	-	3.94
Incineration plant	-	-	19.6	9.4

Table 4. The operating costs of each plant in three periods

Disposal plant	Operation cost					
	T1		T2		T3	
	Low	Up	Low	Up	Low	Up
RDF plant (yuan/ton)	135.0	137.7	140.4	143.2	146.0	148.9
Incineration plant (yuan/ton)	90	91.9	93.9	96.1	98.4	100.8
Landfill (yuan/ton)	89.0	90.9	92.9	95.0	97.3	99.7
Fly ash landfill (yuan/ton)	446.1	455	463.9	473.2	482.5	492.1
Cement plant (yuan/ton)	1500	1531.5	1565.2	1601.2	1639.6	1680.6

Table 5. The subsidy for MSW disposal

Disposal technology	Subsidy form	Subsidy standard
Incineration	Disposal （S_I^t）	150 yuan/ton
Incineration	Electricity price on grid （P_I^t）	0.65 yuan/kwh
RDF	Disposal （S_{RDF}^t）	80 yuan/ton

There is some fuzzy data in MSW disposal system, such as expansion capacity, expansion cost, conversion rate, greenhouse gas emissions and so on. For the fuzzy data, the lower limit of the fuzzy data is based on 90% of the original data, the upper limit of the fuzzy data is based on 120% of the original data, and the de-fuzzy data is obtained according to the expected value sorting method. The de-fuzzy data of related parameters is shown in Table 6. The de-fuzzy greenhouse gas emissions of each disposal plant are shown in Table 7.

Table 6. The de-fuzzy data of related parameters

Disposal plant	Parameter	Value
Transfer station	The rest rate after pretreatment（λ）	96.58%
Incineration plant	The electricity on grid after disposing MSW （$E_n^t - E_{c,n}^t$）	325.33 kwh/ton
	Production rate of fly ash（μ）	3.05%
	Expansion capacity（M_{I_nE}）	100 thousand ton
	Expansion cost（C_{EI_n}）	50.83 yuan/ton
RDF plant	RDF conversion rate（σ）	50.83%
	Expansion capacity（M_{I_nE}）	100 thousand ton
	Expansion cost（C_{ER_z}）	40.67 yuan/ton
	Price（P_{RDF}^t）	203.33yuan/ton
Cement plant	Substitution rate of RDF for coal（ν）	50.83%
	Coal rice（P_C^t）	610 yuan/ton

Table 7. The de-fuzzy data of greenhouse gas emissions of each disposal plant

Emission source	GWP（t CO_2 eqv. t^{-1} MSW）
Landfill（GWP_L）	2.755
Incineration plant（GWP_I）	0.464
RDF plant（GWP_R）	0.203
Fly ash landfill（GWP_{FL}）	0.015
Disposal fly ash（GWP_{FC}）	0
Disposal RDF（GWP_C）	-1.169

4.2. Results and discussion

The uncertain multi-objective two-echelon optimal MSW allocation model is divided into two sub models, the weight of cost objective function (W_1) is 0.6, the weight of environment objective function (W_2) is 0.4, and then it is solved by matlab2016a.

It can be seen from Table 8-10 that in the next three periods, the annual MSW is mainly allocated to RDF plant and incineration plant. During the MSW allocation process, the transportation distance is fully considered. When the transfer station is close to the RDF plant, the MSW is prior to be allocated to the RDF plant (such as transfer station 8), otherwise, it is prior to be allocated to the incineration plant (such as transfer station 4). Since RDF plant has environmental advantages in MSW disposal, MSW is prior to be allocated to the RDF plant. So the MSW allocated to RDF plant reaches its maximum disposal capacity. The MSW allocated to landfill is zero in the three periods.

In addition, all RDF produced in RDF plant is disposed in cement plants, and there is no market sale for RDF. Due to the high cost of disposing fly ash in cement plant, all fly ashes are transported to fly ash landfill to be disposed. The system revenue increases from T1 to T2, mainly due to the MSW growth. The system revenue decrease from T2 to T3, mainly because the MSW growth slows down and the operating cost of the MSW disposal plants increases. The revenue of MSW disposal plants mainly comes from the subsidy and the MSW recycle income.

It also can be seen that the environmental impact is proportional to the MSW amount. When the MSW increases, the environmental pressure increases. According to the comprehensive evaluation index, the operation effect of the above-mentioned system is decreasing, mainly because the MSW amount can't meet the demand of all the MSW disposal plant.

5. Sensitivity analysis

In this part, two sensitivity analysis cases will be discussed:

(1) Adjust the weight of cost and environment in the comprehensive evaluation, and compare the difference of the optimal solutions.

(2) Don't consider the landfill disposal technology, and assume that the MSW generation increases by 30% in T4 period, then the capacity expansion of the MSW disposal plant will be discussed.

5.1. Weight adjustment of cost and environmental

The weight of cost and environment is adjusted to $W_1=0.4$, $W_2=0.6$, which means policy makers pay more attention to environmental impact. The result is shown in Table11-13. Comparing the data in Table 8-10 with the data in Table 11-13, the MSW allocation in each transfer station has little change and MSW is still allocated to RDF plant preferentially. The amount of fly ash allocated to cement kiln collaborative disposal technology is still 0. The reason is that although the cement kiln collaborative disposal technology has environmental advantages, due to the high cost of fly ash collaborative disposal, the MSW disposal system still cannot apply this technology. Considering comprehensive evaluation, the overall effect of this case is worse compared with the previous case. The main reason is that the MSW allocated to RDF plant is not sufficient, so the environmental advantage of RDF technology is difficult to present.

5.2. The capacity expansion of the MSW disposal plant

In order to discuss the capacity expansion of the MSW disposal plant, T4 period is added. In this period, it is assumed that the MSW in each transfer station increases by 30%, and the landfill technology is not considered, the operation cost of each MSW disposal plant is the same as that of the T3 period, the weight of cost and environment is 0.6 and 0.4, the result is shown in Table 14. According to the Table 14, it can be found that when the MSW exceeds the maximum disposal capacity of the plant, the capacity expansion of the RDF plant is considered preferentially. Only the minimum MSW disposal requirement of the incineration plant is satisfied, and the rest MSW is allocated to the RDF plant. Comparing the data in T4 period with the data in T3 period of the previous two cases, it is found that the system revenue decreases, but the environmental impact significantly increase. It also can be seen that when the MSW is sufficient, the environmental advantage of RDF technology can be reflected, and the whole system runs better.

Table 8. The result of uncertain multi-objective two-echelon optimal MSW allocation model in period T1 (W_1=0.6， W_2=0.4)

To From	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement
	Lower amount of collected MSW （297.9 thousand ton）					Upper amount of collected MSW（303.8 thousand ton）				
TS 1	0.79	0.75	0	-	-	0.86	0.66	0	-	-
TS 2	0.48	0.50	0	-	-	0.58	0.39	0	-	-
TS 3	0.83	0.81	0	-	-	0.84	0.80	0	-	-
TS 4	1.95	2.50	0	-	-	1.97	2.54	0	-	-
TS 5	0.36	0.28	0	-	-	0.42	0.23	0	-	-
TS 6	0.89	0.51	0	-	-	0.85	0.60	0	-	-
TS 7	0.65	0.39	0	-	-	0.58	0.49	0	-	-
TS 8	1.12	0.56	0	-	-	1.06	0.68	0	-	-
TS 9	0.85	0.68	0	-	-	0.97	0.63	0	-	-
TS 10	0.82	0.69	0	-	-	0.90	0.67	0	-	-
TS 11	0.57	0.54	0	-	-	0.62	0.51	0	-	-
TS 12	0.57	0.51	0	-	-	0.48	0.62	0	-	-
TS 13	1.78	1.44	0	-	-	1.48	1.84	0	-	-
TS 14	1.49	1.15	0	-	-	1.31	1.41	0	-	-
TS 15	0.57	0.56	0	-	-	0.57	0.54	0	-	-
TS 16	0.58	0.59	0	-	-	0.61	0.55	0	-	-
TS 17	0.17	0.13	0	-	-	0.13	0.15	0	-	-
TS 18	1.41	1.33	0	-	-	1.64	1.19	0	-	-
Incineration plant	-	-	-	0.42	0	-	-	-	0.44	0
RDF plant	-	-	-	-	8.07	-	-	-	-	8.07
Revenue			51.77					52.53		
GHG			2.75					5.53		
GEV			-2.00					-0.94		

Table 9. The result of uncertain multi-objective two-echelon optimal MSW allocation model in period T2 (W_1=0.6，W_2=0.4)

To From	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement
	Lower amount of collected MSW（297.9 thousand ton）					Upper amount of collected MSW（303.8 thousand ton）				
TS 1	0.79	0.80	0	-	-	0.26	1.34	0	-	-
TS 2	0.29	0.71	0	-	-	0.31	0.70	0	-	-
TS 3	0.94	0.70	0	-	-	0.36	1.33	0	-	-
TS 4	1.58	2.96	0	-	-	1.19	3.40	0	-	-
TS 5	0.41	0.27	0	-	-	0.59	0.11	0	-	-
TS 6	1.11	0.38	0	-	-	1.49	0.04	0	-	-
TS 7	0.81	0.30	0	-	-	0.97	0.16	0	-	-
TS 8	1.05	0.73	0	-	-	1.71	0.12	0	-	-
TS 9	0.85	0.79	0	-	-	1.25	0.43	0	-	-
TS 10	0.98	0.62	0	-	-	1.02	0.63	0	-	-
TS 11	0.72	0.44	0	-	-	0.52	0.67	0	-	-
TS 12	0.52	0.61	0	-	-	0.56	0.59	0	-	-
TS 13	1.52	1.83	0	-	-	2.02	1.40	0	-	-
TS 14	1.58	1.18	0	-	-	1.84	0.97	0	-	-
TS 15	0.51	0.65	0	-	-	0.41	0.75	0	-	-
TS 16	0.51	0.70	0	-	-	0.24	0.97	0	-	-
TS 17	0.20	0.11	0	-	-	0.24	0.08	0	-	-
TS 18	1.52	1.34	0	-	-	0.88	2.04	0	-	-
Incineration plant	-	-	-	0.46	0	-	-	-	0.48	0
RDF plant	-	-	-	-	8.07	-	-	-	-	8.07
Revenue			53.29					54.04		
GHG			8.23					11.12		
GEV			0.095					1.21		

Table10． The result of uncertain multi-objective two-echelon optimal MSW allocation model in period T3 (W_1 =0.6， W_2 =0.4)

To From	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement
	Lower amount of collected MSW （297.9 thousand ton）					Upper amount of collected MSW（303.8 thousand ton）				
TS 1	0.80	0.78	0	-	-	0.29	1.31	0	-	-
TS 2	0.47	0.53	0	-	-	0.26	0.75	0	-	-
TS 3	0.86	0.81	0	-	-	0.14	1.55	0	-	-
TS 4	2.42	2.12	0	-	-	1.67	2.92	0	-	-
TS 5	0.35	0.33	0	-	-	0.61	0.09	0	-	-
TS 6	0.78	0.70	0	-	-	1.46	0.07	0	-	-
TS 7	0.56	0.55	0	-	-	1.06	0.07	0	-	-
TS 8	0.94	0.84	0	-	-	1.76	0.07	0	-	-
TS 9	0.85	0.79	0	-	-	1.32	0.36	0	-	-
TS 10	0.83	0.78	0	-	-	0.76	0.89	0	-	-
TS 11	0.59	0.57	0	-	-	0.60	0.59	0	-	-
TS 12	0.56	0.57	0	-	-	0.60	0.55	0	-	-
TS 13	1.72	1.63	0	-	-	1.72	1.70	0	-	-
TS 14	1.37	1.38	0	-	-	1.67	1.14	0	-	-
TS 15	0.57	0.58	0	-	-	0.40	0.76	0	-	-
TS 16	0.55	0.66	0	-	-	0.33	0.88	0	-	-
TS 17	0.16	0.15	0	-	-	0.24	0.08	0	-	-
TS 18	1.50	1.36	0	-	-	0.98	1.94	0	-	-
Incineration plant	-	-	-	0.46	0	-	-	-	0.48	0
RDF plant	-	-	-	-	8.07	-	-	-	-	8.07
Revenue			51.66					52.28		
GHG			8.29					11.08		
GEV			0.22					1.29		

Table11． The result of uncertain multi-objective two-echelon optimal MSW allocation model in period T1 (W_1=0.4，W_2=0.6)

To From	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement
	Lower amount of collected MSW （297.9 thousand ton）					Upper amount of collected MSW（303.8 thousand ton）				
TS 1	0.78	0.76	0	-	-	0.29	1.27	0	-	-
TS 2	0.42	0.56	0	-	-	0.07	0.92	0	-	-
TS 3	0.78	0.86	0	-	-	0.02	1.63	0	-	-
TS 4	2.50	1.95	0	-	-	1.76	2.74	0	-	-
TS 5	0.45	0.19	0	-	-	0.63	0.03	0	-	-
TS 6	0.88	0.52	0	-	-	1.39	0.05	0	-	-
TS 7	0.68	0.36	0	-	-	1.06	0.01	0	-	-
TS 8	0.96	0.72	0	-	-	1.72	0.01	0	-	-
TS 9	0.84	0.70	0	-	-	1.08	0.50	0	-	-
TS 10	0.72	0.79	0	-	-	0.70	0.85	0	-	-
TS 11	0.51	0.60	0	-	-	0.19	0.95	0	-	-
TS 12	0.59	0.49	0	-	-	0.44	0.66	0	-	-
TS 13	1.90	1.32	0	-	-	2.12	1.17	0	-	-
TS 14	1.30	1.34	0	-	-	2.05	0.64	0	-	-
TS 15	0.48	0.65	0	-	-	0.15	0.99	0	-	-
TS 16	0.57	0.60	0	-	-	0.14	1.05	0	-	-
TS 17	0.19	0.10	0	-	-	0.27	0.03	0	-	-
TS 18	1.33	1.41	0	-	-	1.79	1.01	0	-	-
Incineration plant	-	-	-	0.42	0	-	-	-	0.44	0
RDF plant	-	-	-	-	8.07	-	-	-	-	8.07
Revenue			51.75					52.51		
GHG			2.73					5.49		
GEV			-0.43					1.19		

Table12. The result of uncertain multi-objective two-echelon optimal MSW allocation model in period T2 (W_1 =0.4， W_2 =0.6)

To / From	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement
	Lower amount of collected MSW （297.9 thousand ton）					Upper amount of collected MSW（303.8 thousand ton）				
TS 1	0.85	0.73	0	-	-	0.44	1.16	0	-	-
TS 2	0.50	0.51	0	-	-	0.53	0.48	0	-	-
TS 3	0.86	0.81	0	-	-	0.82	0.87	0	-	-
TS 4	2.44	2.10	0	-	-	2.34	2.25	0	-	-
TS 5	0.34	0.34	0	-	-	0.15	0.55	0	-	-
TS 6	0.76	0.72	0	-	-	1.03	0.50	0	-	-
TS 7	0.58	0.52	0	-	-	0.61	0.52	0	-	-
TS 8	0.90	0.88	0	-	-	1.21	0.63	0	-	-
TS 9	0.84	0.79	0	-	-	0.97	0.71	0	-	-
TS 10	0.84	0.76	0	-	-	0.97	0.68	0	-	-
TS 11	0.60	0.56	0	-	-	0.44	0.75	0	-	-
TS 12	0.57	0.56	0	-	-	0.36	0.79	0	-	-
TS 13	1.72	1.63	0	-	-	1.85	1.57	0	-	-
TS 14	1.28	1.47	0	-	-	1.64	1.17	0	-	-
TS 15	0.60	0.56	0	-	-	0.46	0.70	0	-	-
TS 16	0.59	0.61	0	-	-	0.17	1.04	0	-	-
TS 17	0.15	0.16	0	-	-	0.16	0.17	0	-	-
TS 18	1.44	1.42	0	-	-	1.72	1.20	0	-	-
Incineration plant	-	-	-	0.46	0	-	-	-	0.48	0
RDF plant	-	-	-	-	8.07	-	-	-	-	8.07
Revenue			53.25					54.02		
GHG			8.12					11.05		
GEV			2.74					4.47		

Table13. The result of uncertain multi-objective two-echelon optimal MSW allocation model in period T3 (W_1=0.4， W_2=0.6)

To / From	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement
	Lower amount of collected MSW （297.9 thousand ton）					Upper amount of collected MSW（303.8 thousand ton）				
TS 1	0.87	0.71	0	-	-	0.32	1.28	0	-	-
TS 2	0.50	0.51	0	-	-	0.02	0.99	0	-	-
TS 3	0.94	0.73	0	-	-	0.10	1.59	0	-	-
TS 4	1.24	3.30	0	-	-	2.18	2.41	0	-	-
TS 5	0.38	0.30	0	-	-	0.67	0.03	0	-	-
TS 6	0.95	0.53	0	-	-	1.48	0.05	0	-	-
TS 7	0.69	0.41	0	-	-	1.11	0.02	0	-	-
TS 8	1.23	0.55	0	-	-	1.82	0.01	0	-	-
TS 9	0.98	0.65	0	-	-	1.13	0.55	0	-	-
TS 10	0.93	0.67	0	-	-	0.55	1.10	0	-	-
TS 11	0.60	0.56	0	-	-	0.31	0.88	0	-	-
TS 12	0.61	0.52	0	-	-	0.41	0.74	0	-	-
TS 13	1.42	1.93	0	-	-	2.29	1.13	0	-	-
TS 14	1.28	1.47	0	-	-	1.65	1.16	0	-	-
TS 15	0.62	0.53	0	-	-	0.24	0.92	0	-	-
TS 16	0.63	0.57	0	-	-	0.13	1.08	0	-	-
TS 17	0.17	0.14	0	-	-	0.29	0.03	0	-	-
TS 18	1.82	1.04	0	-	-	1.16	1.76	0	-	-
Incineration plant	-	-	-	0.46	0	-	-	-	0.48	0
RDF plant	-	-	-	-	8.07	-	-	-	-	8.07
Revenue	51.56					52.22				
GHG	8.28					11.04				
GEV	2.91					4.54				

Table14. The result of uncertain multi-objective two-echelon optimal MSW allocation model in period T4 (W_1=0.6，W_2=0.4)

To / From	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement	RDF plant	Incineration plant	Landfill	Fly ash landfill	Cement
	Lower amount of collected MSW（297.9 thousand ton）					Upper amount of collected MSW（303.8 thousand ton）				
TS 1	1.74	0.32	0	-	-	1.76	0.33	0	-	-
TS 2	0.86	0.43	0	-	-	1.01	0.30	0	-	-
TS 3	1.86	0.31	0	-	-	1.86	0.33	0	-	-
TS 4	5.42	0.49	0	-	-	5.32	0.65	0	-	-
TS 5	0.70	0.18	0	-	-	0.65	0.26	0	-	-
TS 6	1.56	0.36	0	-	-	1.65	0.33	0	-	-
TS 7	1.07	0.36	0	-	-	1.15	0.32	0	-	-
TS 8	2.06	0.26	0	-	-	2.08	0.30	0	-	-
TS 9	1.80	0.32	0	-	-	1.84	0.34	0	-	-
TS 10	1.76	0.32	0	-	-	1.63	0.51	0	-	-
TS 11	1.15	0.35	0	-	-	1.19	0.35	0	-	-
TS 12	1.20	0.27	0	-	-	1.17	0.33	0	-	-
TS 13	3.72	0.64	0	-	-	4.00	0.45	0	-	-
TS 14	3.05	0.53	0	-	-	3.30	0.35	0	-	-
TS 15	1.20	0.30	0	-	-	1.18	0.33	0	-	-
TS 16	1.29	0.27	0	-	-	1.23	0.34	0	-	-
TS 17	0.25	0.16	0	-	-	0.25	0.17	0	-	-
TS 18	3.26	0.46	0	-	-	3.43	0.37	0	-	-
Incineration plant	-	-	-	0.19	0	-	-	-	0.19	0
RDF plant	-	-	-	-	17.25	-	-	-	-	17.25
Revenue			45.1					44.6		
GHG			-103					-101		
GEV			-63.671					-62.654		

6. Conclusion and future work

In the MSW disposal system, the MSW is allocated among the disposal plants firstly, and then the residues (incineration residues and RDF) are allocated between the residue disposal plants and market. So there is a two-echelon allocation in the MSW disposal system. In the two-echelon optimal allocation of MSW system, two objectives, cost and environmental impact, should be considered. Considering the uncertainty and dynamic in the MSW disposal system, this paper constructs a grey fuzzy multi-objective two-echelon MSW allocation model. The model is divided into two sub models firstly, and then the expected value sorting method is applied to solve the models. According to the result, the MSW is prior to be allocated to RDF plant and incineration plant. The MSW allocated to landfill is zero in the three periods, because the landfill will cause more environment pollution. Two sensitivity analysis cases are studied, and it is found that RDF technology has greater environmental advantage in all disposal technology. When the MSW is sufficient, the environmental advantage of RDF technology can be reflected, and the whole system runs better.

In the future work, stochastic MSW generation rates can be considered. Besides that, waste classification can be considered into the MSW disposal system. How to allocate the different waste type among the disposal plants can be an interesting research direction in the future.

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