sustainability

MDPI

Article

Redesigning the Municipal Solid Waste Supply Chain Considering the Classified Collection and Disposal: A Case Study of Incinerable Waste in Beijing

Xiaoyu Yang [1], Xiaopeng Guo [1,2,*] and Kun Yang [1]

[1] School of Economics and Management, North China Electric Power University, Beijing 102206, China; yxyxiaoyu2016@163.com (X.Y.); yangkun@ncepu.edu.cn (K.Y.)
[2] Beijing Key Laboratory of New Energy and Low-Carbon Development, North China Electric Power University, Beijing 102206, China
* Correspondence: 13520328997@163.com

Abstract: The output of municipal solid waste is growing rapidly, which has brought tremendous pressure to urban development. The supply chain of municipal solid waste (MSW) in China mainly contains three processes: collection, transportation, and disposal. The waste is sorted at the collection and disposed of according to the classification. However, it is mixed at the transportation stage. Mixed transportation remixes the separately collected waste, which seriously affects the disposal effect. The supply chain of MSW urgently needs to be redesigned to improve the MSW disposal effect. First of all, on the ground of the waste treatment situation, we redesigned the supply chain of MSW in China. Secondly, combined with the redesign of the MSW supply chain, this paper established the function allocation model for collection stations, making a collection station only gather one type of waste, and built the transportation path planning model for vehicles, reducing the impact of waste storage on residents. Finally, based on the data of Xuanwu District in Beijing, the supply chain redesigning practical example of incinerable waste was given. The supply chain redesigning model in this paper not only makes full use of the existing infrastructure but also improves the disposal effect of waste. The supply chain redesigning model has practical application value.

Keywords: waste sorting; supply chain redesigning; function allocation; path planning; incinerable waste

check for updates

Citation: Yang, X.; Guo, X.; Yang, K. Redesigning the Municipal Solid Waste Supply Chain Considering the Classified Collection and Disposal: A Case Study of Incinerable Waste in Beijing. *Sustainability* **2021**, *13*, 9855. https://doi.org/10.3390/su13179855

Academic Editor: Tan Yigitcanlar

Received: 19 July 2021
Accepted: 20 August 2021
Published: 2 September 2021

1. Introduction

The acceleration of urbanization has led to a sharp increase in MSW output. In China, the output of waste has increased at a rate of 8–10% every year, and disposed MSW capacity in 2019 reached 242 million tons (Data from National Bureau of Statistics of China). Effectively dealing with MSW has become a major problem that must be solved in urban development. Waste incineration power generation is the best method of waste disposal under the principle of "reduction, harmlessness, and resource reuse", which has received increased attention. After years of development, waste incineration has achieved significant economic benefits in some developed countries. However, in China, the economic efficiency and emissions of incinerating waste for power are unsatisfactory. Even in large developed cities, such as Beijing and Shanghai, the problem is also serious.

The costs of incinerating waste for power in Beijing Gaoantun Waste to Energy co., Ltd., Beijing Shunyi District Municipal Waste Treatment Plant, Beijing Shougang Bioenergy Science & Technology Co., Ltd., have been analyzed. The results show that the social cost of burning 1 ton of MSW is about 1088.49 yuan, of which 70% comes from the loss of health in society caused by the dioxin generated by waste incineration [1]. It is common knowledge that incomplete waste classification and excessive impurities are the roots of dioxins in waste incineration. Improving the waste incineration effect is an urgent problem for the waste treatment industry.

In China, from generation to disposal, the MSW supply chain mainly contains collection, transportation, and disposal processes. Many cities, such as Beijing and Shanghai, have already realized the sorting collection and disposal of MSW. The MSW is divided into recyclables, hazardous waste, kitchen waste (organic waste), and other waste. In order to improve waste recycling and reduction, since 2019, many local governments have issued strict waste classification policies, such as the “Management Regulations of Shanghai Municipal Solid Waste Classification” and the “Management Regulations of Beijing Municipal Solid Waste”. However, in transportation, MSW is mostly mixed transported, which mixes the sorting waste together, seriously destroying the waste classification results and affecting the waste disposal effect. It is urgent to change the supply chain mode. Therefore, combined with the waste treatment statute, we redesign the MSW supply chain and replan the waste collection and transportation under the existing waste treatment facilities. The specific structure of this paper is shown in Figure 1.

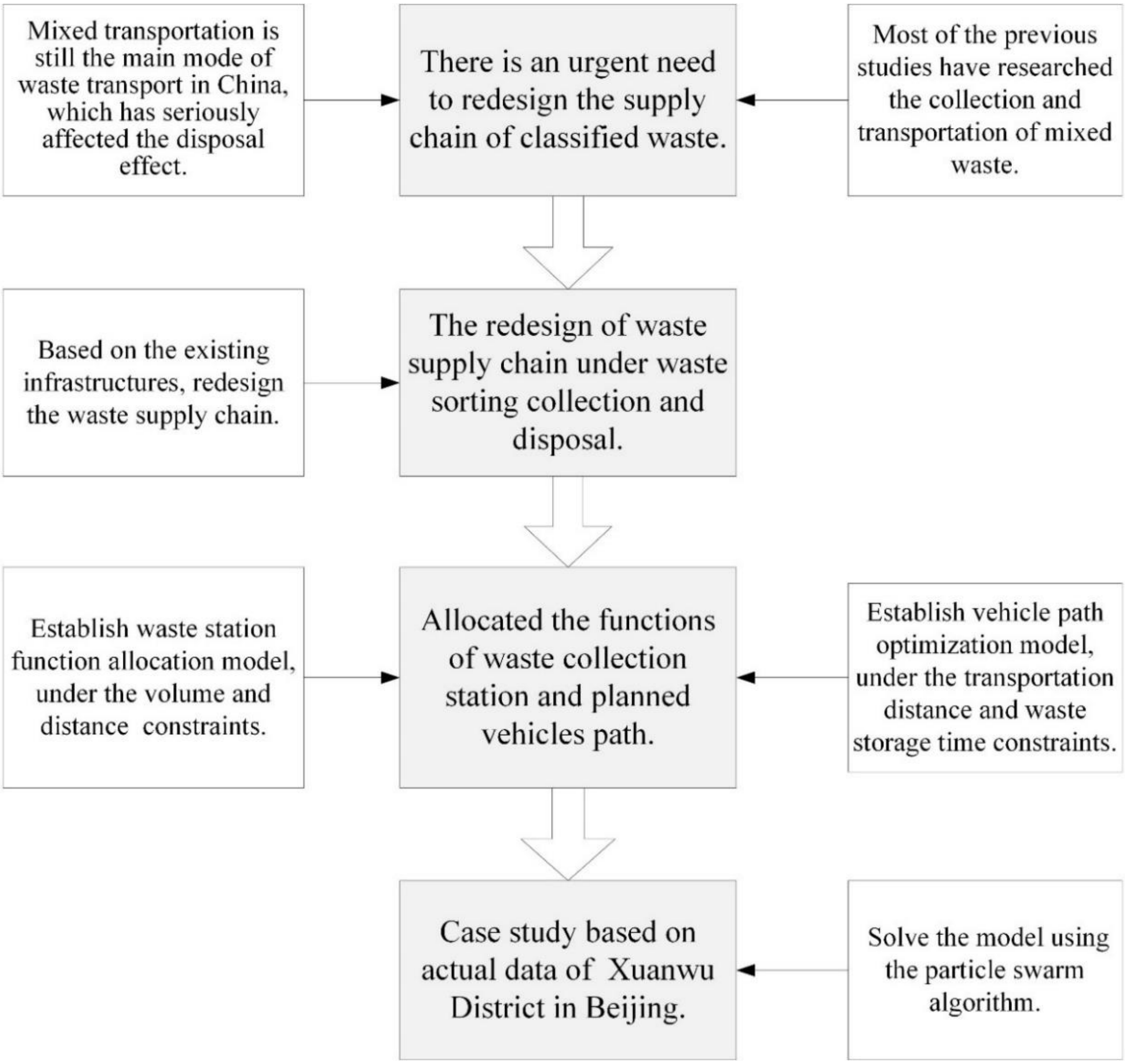

Figure 1. The specific structure of the paper.

2. Literature Review

The redesign of the MSW supply chain should consider the situation of waste collection and transportation [2]. Therefore, we summarize the research about waste supply chain design, the waste collection facilities layout, and the transportation route optimization.

2.1. The Design of MSW Supply Chain

MSW supply chain design and management can effectively resolve energy supply, waste management, and greenhouse gas issues [3]. In order to promote waste recovery, treatment, and recycling, previous research has studied the methods to improve the MSW collection effect [4,5], the waste governance modes [6], and the distribution of profits among all parties in the MSW supply chain [7,8], which provide the basis for MSW supply chain design. In MSW supply chain research, several studies using multi-objective programming methods design or optimize the MSW supply chain with economic, environmental, and social impact [9–11]. Additionally, with the deepening of MSW supply chain research, the effect of the uncertainty of waste collection levels [12] and sustainability issues such as land-use and public health impacts [13] on waste supply chain design have been focused on.

The mixed-integer linear programming (MILP) method has also been applied in the design of the waste supply chain. Previous studies mainly use the MILP method to explore the environmental impact [14] and the conflicts of waste collection and supply [15] on supply chain design. After that, a two-stage stochastic MILP model is formulated to examine the effects of the power price uncertainties on the MSW supply chain design [16] [15]. Additionally, an MILP model for waste supply chain networks containing the logistics, production, and distribution is presented with the aim of maximum profit of the entire supply chain [17].

Generally, the design of the waste supply chain mostly uses multi-objective planning methods, considering the economic and environmental impacts. However, previous studies have mostly neglected the waste classified and the existing infrastructure, which is not suitable for the redesign of the MSW supply chain. Therefore, combined with the current status of waste collection, transportation, and facility layout, this paper redesigns the waste supply chain, which effectively improves the waste supply chain in the case of waste sorting clearance and treatment.

2.2. The Layout of Waste Treatment Facility

The layout of waste treatment facilities is closely related to environmental protection and residents' lives. In different processing stages, treatment facilities are different. They mainly contain various waste treatment plants and waste collection stations that collect waste generated by residents. The location of waste collection stations is mostly close to the residential quarter. When waste is stored and removed, collection stations generate irritating gas, affecting nearby residents' lives [18]. There is a direct relationship between the surrounding environment of the waste collection station, the storage time of waste, and the times of vehicle clearance operations [19]. Additionally, when the waste classification level improves, the energy consumption and emission of waste collection stations is reduced [20].

Multi-objective programming and the geographic information system (GIS) are the most common methods used to research the layout of waste treatment facilities. Yadav et al. combined GIS with multi-objective programming to research the layout of waste transfer centers [21]. Based on the same method, Yadav et al. further studied the layout of waste transfer centers with the optimal economic cost when the waste output is uncertain [22]. Liu et al. analyzed the natural environment and human environment of Beijing by GIS and, using the multi-objective programming method, planned the layout of the waste collection station [23]. Furthermore, the disposal of waste has the most serious impact on the environment, so the location problem of waste disposal plants is mainly discussed, and the layout of landfill is mostly focused on plants' location selection [24–28]. The energy conversion rate also is one of the factors that affect the location of waste disposal plants. Kyriakis et al. selected a site for a waste-to-energy facility, under the constraints of maximum output energy and minimization of the gate fee [29]. Summarizing the previous studies, we found that few studies have studied the layout of facilities in waste classification.

It is found that the waste collection station has a great impact on residents' lives, and the impact of waste collection stations on the surrounding environment is directly proportional to the waste storage time and the clearance times of vehicles. Therefore, the redesign of the MSW supply chain should fully consider the impact on the surrounding residents, reducing the storage time and clearance times of the waste collection station.

2.3. The Optimization of Waste Transportation Routes

Transportation is an important process in the MSW supply chain. The optimization of waste transportation mostly has the goal of minimum economic cost [30] or transportation distance [31–33]. However, the above studies only optimized waste transportation under a single objective. The single-objective method has significant shortcomings in waste transportation optimization [34]. The multi-objective optimization model was established considering both transportation costs and social environmental impact. With the constraints of minimum transportation distances and emissions, Zdena et al., using GIS, optimized the path and schedule of waste transportation vehicles [35]. Dirk et al. studied the feasibility of using multimodal trucks and waterway transportation instead of waste highway transportation in the waste supply chain with the restrains of transportation costs and social impact [36].

GIS also is one of the common methods in transportation route optimization [37]. Kinobe et al. used GIS to select the site of the waste landfill plant in Kampala under the constraint of waste transportation routes and time [38]. Additionally, the simulation method has also been applied in waste transportation optimization. Khanh et al. established a multi-intelligent waste transportation simulation model for Hagiang city in Vietnam [39]. Xue et al. reviewed the problems of waste collection and disposal in Singapore and utilized the space allocation model, studying the resource allocation of waste incineration [40].

Generally, in transportation route optimization, previous studies mostly use GIS or mathematical algorithms to optimize vehicle routes under the constraints of the economy. Moreover, most studies were conducted under waste mixed collection and transportation. Few scholars have researched the collection and transportation of waste in classification. Additionally, very little research has considered the perishability of waste, combining waste storage and transportation together, exploring waste transportation paths with the minimum impact on the surrounding environment.

Based on the current situation of waste collection, transportation, and disposal, this paper redesigned the supply chain of waste sorting. First of all, on the basis of the existing layout of the waste collection stations, we distributed the function of waste collection stations, changing the mode of one collection station collecting various types of waste to one type of waste. Secondly, in order to reduce the impact of waste collection and transportation on surrounding residents, with the goal of minimum storage time and transportation distance, this paper optimized the path of waste transportation vehicles. Finally, the case study about Xuanwu District in Beijing was given. It is hoped that the research in this paper can help to improve the effect of the waste disposed and provide a reference for the supply chain mode redesign in waste sorting.

3. The Methodology for Supply Chain Redesign

3.1. The Supply Chain Redesign

In the actual treatment of waste, from generation to disposal, the waste mainly passes the three processes: collection, transportation, and disposal. Residents transfer the waste generated by the family to the waste cans in the community collection point; then, the property in the community mixes the separately collected waste and transports it to the nearby waste collection station. Additionally, after a short period of storage, the waste is transported to the waste treatment plant by truck. When the distance between the waste collection station and the treatment plant is far, it is necessary to set up a waste transfer center. To improve the treatment effect, the transfer center compresses and sorts the waste. To vividly express the waste treatment processing, Figure 2, the current waste collection–transportation–disposal process in China, has been given.

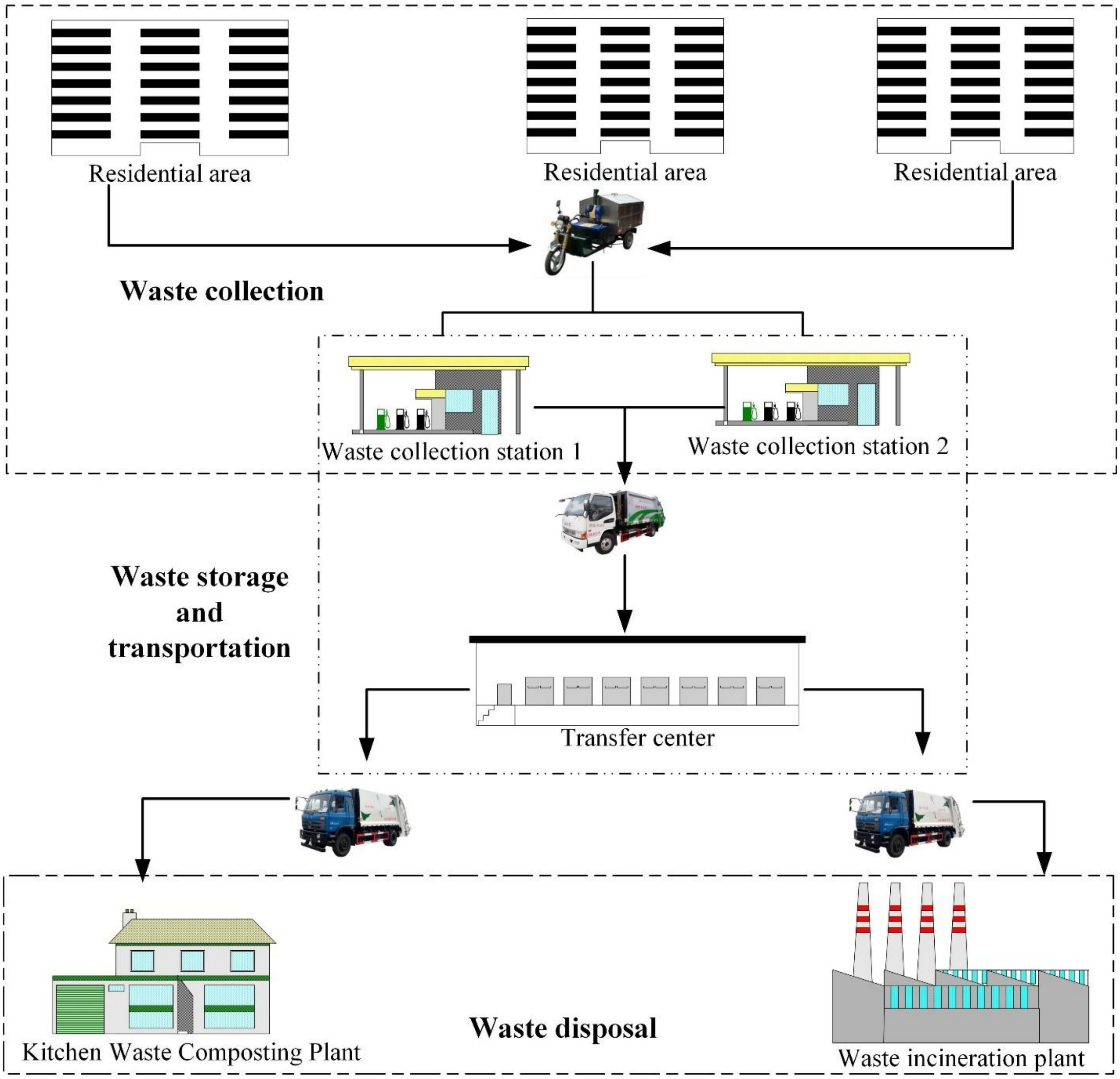

Figure 2. The current waste collection–transportation–disposal process in China.

Through investigation, it was found that when waste was transported from the residential area to the collection station, the sorted waste began to be mixed. It is necessary to prevent the mixed transportation of waste in this process. In order to restrict the mixed transportation, this paper redesigned the MSW supply chain, in which the waste collection station only gathers and transports one type of waste. The supply chain of sorting waste is shown in Figure 3.

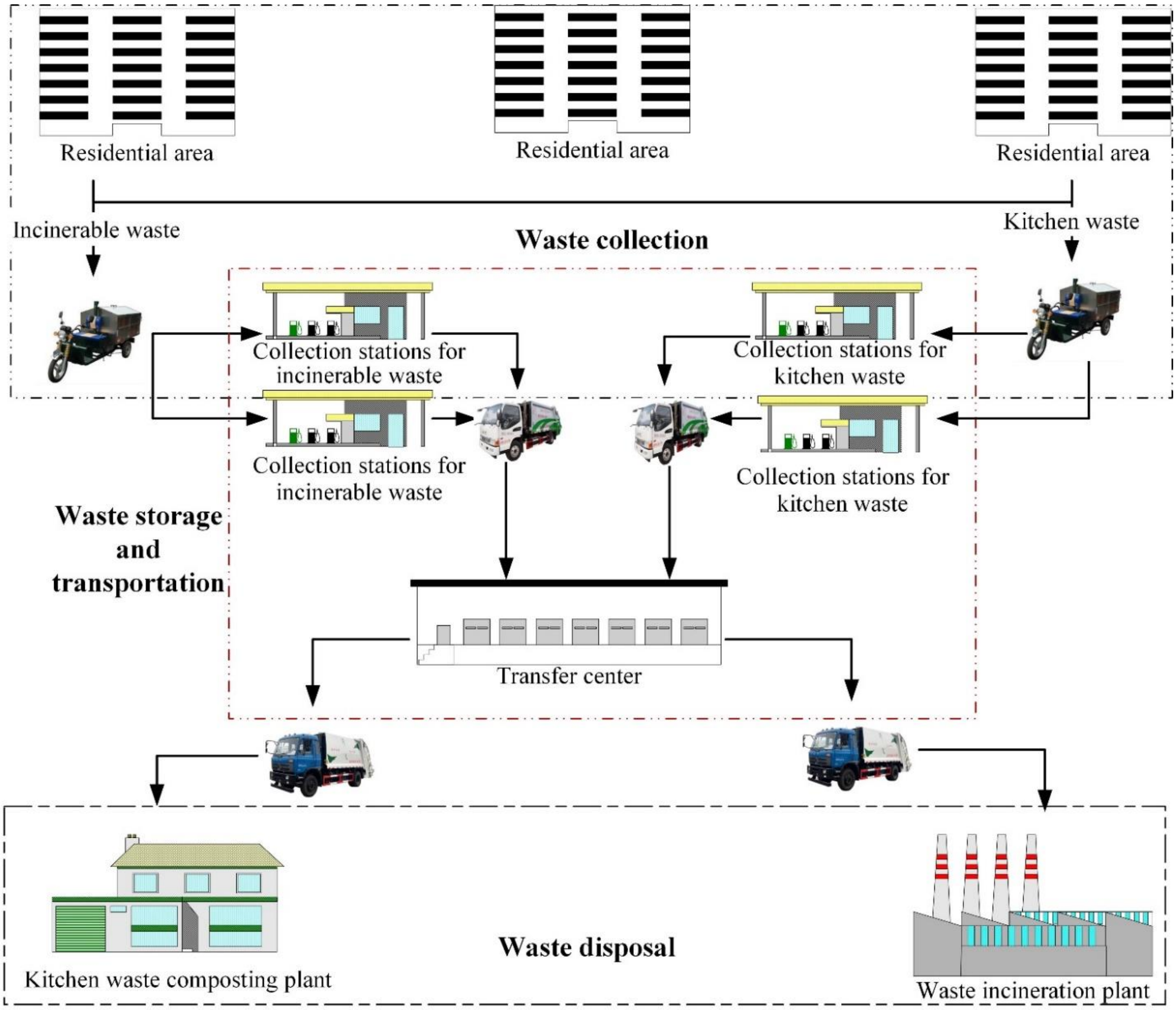

Figure 3. The redesigned collection–transportation–disposal model under waste classification.

3.2. The Function Allocation Model for Waste Collection Station

The essential basis of the redesigned MSW supply chain is that each waste collection station only collects and transports one type of waste. In order to realize the design, the function of collection stations needs to be redistributed. Additionally, the number and capacity of every type of waste collection station should fulfill the waste output and the proportion in total waste output. The proportions of kitchen waste, recyclable waste, disposable packaging, and other waste within the total amount of MSW, respectively, are 52.2%, 17.2%, 9.9%, and 20.7% [41]. Disposable packaging and other waste both can be incinerated, so the proportions of kitchen waste, incinerable waste, and recyclable waste in MSW, respectively, are 52.2%, 30.6%, and 17.2%. Therefore, kitchen waste collection stations account for 52.2% of the total collection stations, incinerable waste collection stations account for 30.6%, and the rest are recyclable waste collection stations. Affected by local characteristics and urban functions, the composition of MSW is various in different cities [42] and locations [43]. In actual applications, the proportion of collection stations needs to be adjusted according to the local conditions. The amount of renewable waste is relatively small, and most of it is collected by waste pickers; this paper focuses on kitchen waste and incinerable waste.

3.2.1. Modeling Assumptions

Since the function allocation model is built on the existing collection stations, the construction cost of the collection station is no longer considered in the total cost. In order to make the model reasonable, this paper makes assumptions about the distribution of waste generation sources, waste transportation costs, and other factors.

(1) The waste production sources are evenly distributed around the collection station.
(2) The capacity of the collection station meets the maximum volume of waste in one day.
(3) The unit cost of waste transportation is the same between all stations.
(4) Collection stations can gather the same kind of waste from multiple residential areas.
(5) The same kind of waste in a waste production source can be transported to multiple collection stations.
(6) Straight-line transportation can be realized from the waste production source to the collection station, and the transportation distance can be calculated by the Euclidean Distance.
(7) The construction and operation of collection stations are the same, and the impact of collection stations on the surrounding environment is equal.
(8) There is no demolished risk for the existing collection stations.

3.2.2. Symbol Description

There are many variables. Additionally, we use the following symbols to represent them.

(1) Common variables:

N	The aggregate of waste collection stations, $i \in N, i = \{1, 2, \ldots n\}$.
N_0	The aggregate of waste production source, $j \in N_0$
C_i	The capacity of waste collection station, $i \in N$
g_j	The volume of kitchen waste in waste production source $j, j \in N_0$
p_j	The volume of incinerable waste in waste production source $j, j \in N_0$
f_{ij}	The volume of kitchen waste transferred from production source j to collection station i
f_{1ij}	The volume of incinerable waste transferred from production source j to collection station i
d_{ij}	The distance between i and j

(2) Decision variables:

$$\mathrm{Z_i} = \begin{cases} 1, \text{ if collection station } i \text{ gather kitchen waste} \\ \\ 0, \text{ if not} \end{cases}$$

$$Z_{ij} = \begin{cases} 1, \text{ if the kitchen waste in production source } j \text{ transported to collection station } i \\ \\ 0, \text{ if not} \end{cases}$$

$$M_i = \begin{cases} 1, \text{ if collection station } i \text{ gather incinerated garbage} \\ \\ 0, \text{if not} \end{cases}$$

$$M_{ij} = \begin{cases} 1, \text{ if the incinerated gargage in production source } j \text{ transported to collection station } i \\ \\ 0, \text{if not} \end{cases}$$

3.2.3. The Function Allocation Model

With the above assumptions and symbol definitions, in waste classification, the function allocation for waste collection stations can be described as the following mathematical model.

$$\min F = \sum_{i\in N}\sum_{j\in N_0} Z_i * Z_{ij} * g_j * d_{ij} + \sum_{i\in N}\sum_{j\in N_0} M_i * M_{ij} * p_j * d_{ij} \tag{1}$$

Formula (1) is the objective function, which has the goal of minimizing transportation volume and distance of kitchen waste and incinerable waste from production sources to collection stations.

Formulas (2)–(9) are constraints.

$$M_i + Z_i \leq 1,\ \forall i \in N \tag{2}$$

Formula (2) indicates that a collection station only gathers and transports one type of waste.

$$\sum_{j\in N_0} g_j - \sum_{i\in N} Z_i * C_i \leq 0 \tag{3}$$

$$\sum_{j\in N_0} P_j - \sum_{i\in N} M_i * C_i \leq 0 \tag{4}$$

Formulas (3) and (4) indicate that the total capacity of the selected collection stations for kitchen waste or incinerable waste should meet the output of kitchen waste or incinerable waste.

$$g_j - \sum_{i\in N} Z_i * Z_{ij} * f_{ij} = 0,\ \forall j \in N_0 \tag{5}$$

$$p_j - \sum_{i\in N} M_i * M_{ij} * f_{1ij} = 0,\ \forall j \in N_0 \tag{6}$$

Formulas (5) and (6) indicate that all kitchen waste and incinerable waste in waste production sources are collected by collection situations.

$$\sum_{i\in N} Z_i = 52.2\% * n \tag{7}$$

$$\sum_{i\in N} M_i = 30.6\% * n \tag{8}$$

Formulas (7) and (8) are the quantity constraints of collection stations. The number of collection stations should satisfy the proportion of kitchen waste and incinerable waste. Because one collection station only collects one kind of garbage, it is necessary to take the integer of the number of collection stations. This paper rounds up the number of collection stations to ensure the collection station is enough to accommodate all the waste.

$$Z_i, M_i, Z_{ij}, M_{ij} \in \{0, 1\} \tag{9}$$

Formula (9) is the range of decision variables, which is 1 or 0.

3.3. The Transportation Path Planning Model for Waste Truck

Through the allocation of the waste collection station function, the design that one collection station receives and transports one type of waste has been realized. In order to prevent the mixed transportation of waste from the collection station to the transfer center, this paper plans the path of the waste truck that transfers the same kind of waste in collection stations on the basis of the function allocation. Combined with the impact of the waste collection station on the surrounding environment, under the goals of the shortest transportation path of the truck, the shortest storage time of waste in the collection station, and the minimum transported times of waste for the collection station, a waste truck path optimization model for one kind of waste was established.

3.3.1. Modeling Assumptions

In order to make the model reasonable, this paper makes the following assumptions.

(1) The amount of waste in the collection station is known and will not significantly change.
(2) When the load and time permit, the truck can go to multiple collection stations to transport waste.
(3) The truck does not affect each other in driving and operation;
(4) The opening hours of the collection station are consistent with the waste truck.
(5) The truck travels at the same speed.
(6) Straight-line transportation can be realized between collection stations, and the distance is equal to the Euclidean Distance.
(7) All trucks start from the transfer center, and after finished waste transportation, they will return to the transfer center.
(8) The unit transportation cost of trucks is the same.

3.3.2. Symbol Description

There are many variables. Additionally, we use the following symbols to represent them.

(1) Common variables:

N_1	The aggregate of waste collection stations i that gather the same kind of waste, $i \in N_1, i = \{1, 2, \ldots n\}$
N_2	The aggregate of the transfer center and the aggregate of the waste collection station N_1
q_i	The volume of waste in the collection station i, $i \in N_1$.
K	The aggregate of a waste truck k, $k \in K, k = \{1, 2, \ldots k\}$
C	The number aggregate of a truck, $c = \{1, 2, 3 \ldots c\}$, $c \in C$.
W	The maximum load of a truck
e	The collection station starting work time
l	The collection station ending work time
v	The speed of a truck
S	Time for waste truck loading
T_{ic}^k	The time point that the collection station i was cleared by the truck k when it starts from transfer center in Cth time.
q_{ic}^k	The transported volume of waste in collection stations i, if the truck k collected waste from collection station i when it starts from transfer center in Cth time.

(2) Decision variables:

$$X_{ic}^k = \begin{cases} 1, \text{ if the truck } k \text{ collected the garbage in the collection} \\ \text{station } i \text{ when it departs from transfer center in Cth time} \\ \\ 0, \text{ if not} \end{cases}$$

$$X_{ijc}^k = \begin{cases} 1, \text{ if the trunk pass through path between } i \text{ and } j \\ \text{when it departs from transfer center in Cth time } (i, j \in N_2) \\ \\ 0, \text{ if not} \end{cases}$$

3.3.3. The Transportation Path Planning Model

In transportation path planning, with the same unit transportation cost of trucks, the smaller the mileage of vehicles, the lower the total cost of transportation [31–33]. Therefore, the mileage of vehicles is used to represent the economic benefits of waste transportation.

The irritating gas generated by the waste in collection stations significantly affects the nearby residents' lives [18]; transportation path planning should consider the impact of irritating gas on residents. There is a direct relationship between the surrounding environment of the waste collection station, the storage time of waste, and the times of vehicle clearance operations [19], so the storage time of waste and the transported times of collection stations are used to represent the impacts of the waste collection station on the surrounding environment. The path optimization model for the waste truck aims at achieving the shortest travel path for the truck, the shortest waste storage time for the collection station, and the minimum times for waste transportation in the collection station. The constraints of the model include vehicle load, waste transportation volume, and the working time of the collection station.

$$\min F = w_1 F_1 + w_2 F_2 + w_3 F_3 \tag{10}$$

$$F_1 = \sum_{k\in K} \sum_{c\in C} \sum_{i\in N_2} d_{ij} * X_{ijc}^k \tag{11}$$

$$F_2 = \sum_{i\in N_1} \max\left\{T_{ic}^K, i = 1, 2, \ldots n\right\} \tag{12}$$

$$F_3 = \sum_{k\in K} \sum_{c\in C} \sum_{i\in N_2} X_{ic}^k \tag{13}$$

Equation (10) is the overall objective function; F_1, F_2, and F_3 are the sub-objectives, whose specific explanations are Formulas (11)–(13); w_1, w_2, and w_3 are the weight of the sub-objective.

F_1 is the total travel distances of trucks, which are the sum distances of every truck. Additionally, every trucks' travel distances are affected by d_{ij}, the distance between i and j, and X_{ijc}^k, whether the truck passes through the way between i and j when the truck starts from the transfer center in Cth time.

F_2 is the total waste storage time of collection stations, which is the sum of the maximum of T_{ic}^k, $\forall i \in N_1$, the time that every collection station i was transferred by the truck k, when it starts from the transfer center in Cth time.

F_3 is the total time for collection stations transported by trucks, which is the sum of times that all collection stations are transported by all waste trucks. The specific calculation is shown in Equation (13).

The waste collection stations are close to the residential quarter. Waste with long-time storage produces a significant amount of irritating gas, which has a serious impact on the lives of surrounding residents, especially in summer. In order to achieve the optimal economic and environmental benefits, this paper assumes that economic impacts and environmental impacts are equally important when transporting waste. Therefore, w_1, the weight of vehicles mileage, is equal to the sum of w_2, the weight of waste storage time, and w_3, the weight of the waste in collection stations be transported times. Since the effect of waste storage time on the environment is more than the impact of transported times, the weight of storage time should be greater than the transported times. We assume that w_1, w_2, and w_3, respectively, are 0.5, 0.3, and 0.2.

$$\sum_{k\in K} \sum_{c\in C} X_{ic}^k \geq 1,\ \forall i \in N_1 \tag{14}$$

$$\sum_{i\in N_1} \sum_{k\in K} \sum_{c\in C} X_{ic}^k \geq n \tag{15}$$

Equations (14) and (15) are the constraints of waste transported times in the collection station. Formula (14) indicates that the waste in the collection station must be transported, and Formula (15) indicates that a collection station can be transported multiple times.

$$\sum_{i\in N_1}\sum_{k\in K}\sum_{c\in C} q_{ic}^{k} * X_{ic}^{k} \geq \sum_{i\in N_1} q_i \tag{16}$$

$$\sum_{k\in K}\sum_{c\in C} q_{ic}^{k} * X_{ic}^{k} \geq q_i,\ \forall i \in N_1 \tag{17}$$

Formulas (16) and (17) are the transportation volume constraints. Formula (16) indicates that the total transportation volume of waste trucks is equal to the storage volume of collection stations. Formula (17) indicates that the amount of waste being transported at each collection station is equal to the amount stored. Additionally, q_{ic}^{k} is the shipment volume of the truck when it passes through collection station i, which is greater than 0.

$$\sum_{c\in C}\sum_{i\in N_1} q_{ic}^{k} \leq w, \forall k \in K \tag{18}$$

Formula (18) is the truck's load constraints, which mean that for any vehicle, the load cannot exceed the vehicle maximum load.

$$T_{ic}^{k} = e + \sum_{c=1}^{c} X_{ijc}^{K} * d_{ij} \div v + \left[\sum_{i=1}^{n}\sum_{c=1}^{c} X_{ic}^{k}\right] * S \tag{19}$$

Formula (19) is the working time constraints, which mean that when the waste in the collection station i is transported, the time must be the working time of collection station, $e \lhd T_{ic}^{k} \lhd l$. Additionally, T_{ic}^{k} is the sum of the time collection station starting work, the time truck driving on the road, and the loading time. The driving time is calculated by the travel distance and truck speed. The loading time is equal to the product of the number of loading times and the time required to load once.

4. Data Collection and Processing

Waste disposal should follow the principles of reduction, recycling, and harmlessness. Due to the large demand for land, the landfill has no longer been used in an increasing number of countries and districts. In China, renewable waste is mostly collected by waste pickers. Therefore, we mainly discuss the supply chain of waste for incinerated, based on the actual data of Xuanwu District (It has been merged with other districts, becoming Xicheng District) in Beijing.

Xuanwu District is located in the southwest of Beijing. The shape of Xuanwu District is similar to a rectangle, and the total area is 19.04 square km. There are about 107 communities in Xuanwu District, with an approximate population of 544,000. In general, Xuanwu District has a large population, frequent personnel activities, and a large amount of waste production. There are 30 waste collection stations in Xuanwu District, and their distribution is shown in Figure 4. After collecting and temporarily storing, the waste in Xuanwu District is transported to the Majialou Sorting Transfer Station (Majialou transfer center). In the transfer station, the waste is transported to the corresponding disposal plant for processing after weighing, sorting, compressing, and removing impurities.

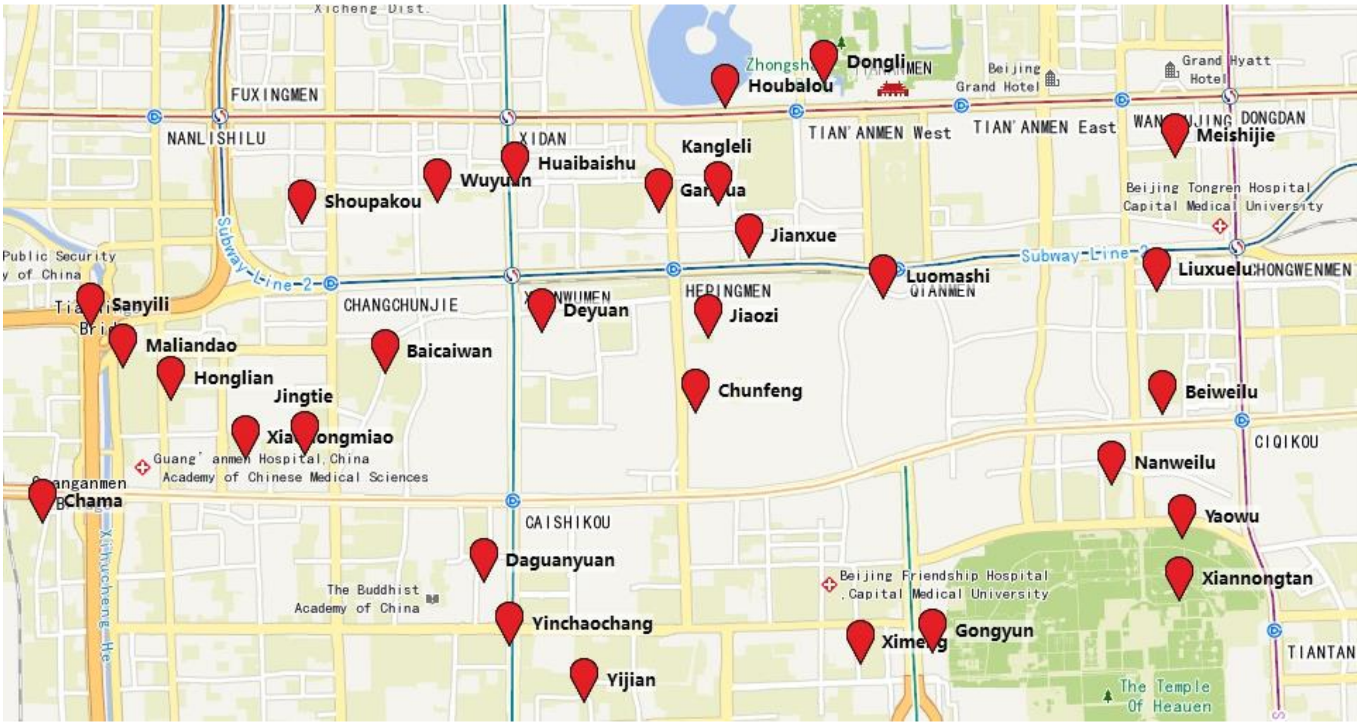

Figure 4. The distribution of waste collection stations.

(1) The basic data of waste output and collection stations

This paper quotes the basic data of collection stations and waste output in Xuanwu District from the "Research on Vehicle Dispatching and Optimization of Beijing Refuse Collection based on Municipal Solid Waste Classification" [44]. There are two working hours for waste collection and transportation. Since the waste output and the trucks are the same, we design the waste collection and transportation model using the data in the working hours from 5:30 to 13:30. We calculated the quantity of kitchen waste, incinerable waste, and recyclable waste in each collection station according to the proportion of them in total waste output [41] and established the coordinate system using the point (116.3334, 39.840239) as the origin. The coordinate value of each point is calculated by gpsCalc (2.0). The waste output and coordinate value are shown in Table 1.

The layout of the waste collection stations shows that the distribution of waste collection stations is uneven, and the waste collection stations are dense in some areas. For example, for Nanweilu, Xiannongtan, and Yaowu, the longest distance between them is only 696 m, and the waste collection volume of Yaowu and Xiannongtan is only 3 tons. This violates the construction requirements of the collection stations. Therefore, the waste collection stations in Xuanwu District have been filtrated. Additionally, 8 waste collection stations with 3 tons maximum capacity were eliminated; they are Yaowu, Xiannongtan, Gongyun, Kangleli, Jianxue, Wuyuan, Yinchaochang, and Sanyili.

(2) The basic data of vehicles

At present, there are 22 vehicles in the Majialou transfer center, including 18 vehicles with a load of 3 tons and 4 waste compression vehicles with a load of 6.1 tons. Considering the amount of waste, and the professional development of waste transportation, we assume that the 4 waste compression vehicles with the load of 6.1 tons are responsible for the transportation of incinerable waste.

(3) The basic data of working time

The waste collection stations and the vehicles both start working at 5:30 in the morning. Additionally, the vehicles need to complete the transportation of all waste in the collection stations before 13:30 in the afternoon. It is assumed that the loading time of waste compression vehicles is 20 min, 0.33 h. Additionally, the speed of the vehicles is 30 km per hour.

Table 1. The basic data of collection stations and waste output.

Number	Name	X Position (m)	Y Position (m)	The Amount of Kitchen Waste (Kg)	The Amount of Incinerable Waste (Kg)	The Amount of Recyclable Waste (Kg)	The Maximum Capacity of Collection Station (Kg)
1	Meishijie	7659	6925	12,685	7436	4180	27,000
2	Liuxuelu	7536	6233	5638	3305	1858	12,000
3	Dongli	5288	7309	2819	1652	929	6000
4	Luomashi	5688	6193	5638	3305	1858	12,000
5	Beiweilu	7581	5590	4228	2479	1393	9000
6	Nanweilu	7236	5227	7047	4131	2322	15,000
7	Yaowu	7714	4951	1409	826	464	3000
8	Xiannongtan	7692	4624	1409	826	464	3000
9	Gongyun	6022	4356	1409	826	464	3000
10	Ximeng	5533	4298	5638	3305	1858	12,000
11	Houbalou	4620	7183	7047	4131	2322	15,000
12	Kangleli	4564	6677	1409	826	464	3000
13	Jianxue	4776	6408	1409	826	464	3000
14	Jiaozi	4497	5993	4228	2479	1393	9000
15	Chunfeng	4419	5606	4228	2479	1393	9000
16	Ganhua	4163	6644	4228	2479	1393	9000
17	Deyuan	3373	6020	4228	2479	1393	9000
18	Huaibaishu	3195	6782	4228	2479	1393	9000
19	Wuyuan	2672	6700	1409	826	464	3000
20	Daguanyuan	2983	4723	8456	4957	2786	18,000
21	Yinchaochang	3162	4392	1409	826	464	3000
22	Yijian	3662	4103	4228	2479	1393	9000
23	Shoupakou	1759	6588	9866	5783	3251	21,000
24	Baicaiwan	2315	5813	7047	4131	2322	15,000
25	Jingtie	1770	5387	4228	2479	1393	9000
26	Xiaohongmiao	1369	5364	7047	4131	2322	15,000
27	Honglian	868	5677	7047	4131	2322	15,000
28	Maliandao	546	5845	7047	4131	2322	15,000
29	Sanyili	323	6058	1409	826	464	3000
30	Chama	0	5036	4228	2479	1393	9000
31	Majialou transfer center	2661	0	–	–	–	–

5. Results and Discussion

The supply chain of incinerable waste under the classification is redesigned. Based on the data of Xuanwu District, a supply chain redesign case is given, which provides a reference for supply chain redesign in other places.

5.1. The Function Allocated Result of Collection Stations

In order to sort collection and transportation waste, 22 eligible collection stations in Xuanwu District were analyzed. Due to limited data, the 30 waste collection stations are used to simulate the distribution of waste generation sources in Xuanwu District. The function allocation model with the goal of minimum waste transportation volume and transportation distance is established. Incinerable waste accounts for 30.6% of the total output of waste, so the number of incinerable waste collection stations should be 6.44. Rounding up the number of collection stations, the number of incinerable waste collection stations is set at 7. This paper uses Lingo 11 software to solve the function allocation model.

After the function allocation, the waste that can be used for incinerating power generation in Xuanwu District only needs 7 waste collection stations to gather. They are Chunfeng, Huaibaishu, Yijian, Baicaiwan, Xiaohongmiao, Nanweilu, and Maliandao collection station. The specific results are shown in Table 2. The distribution of incinerable waste collection stations is shown in Figure 5, and the collection stations with purple are incinerable waste collection stations.

Table 2. The location and inventory of incinerable waste collection stations.

Number	Name	X Position (m)	Y Position (m)	The Maximum Capacity of Collection Station (Kg)	The Volume of Incinerable Waste (Kg)
1	Chunfeng	4419	5606	9000	8689
2	Huaibaishu	3195	6782	9000	8689
3	Yijian	3662	4103	9000	8689
4	Baicaiwan	2315	5813	15,000	14,482
5	Xiaohongmiao	1369	5364	15,000	14,482
6	Nanweilu	7236	5227	15,000	14,482
7	Maliandao	546	5845	15,000	14,482
0	Majialou Transfer Center	2661	0	–	–

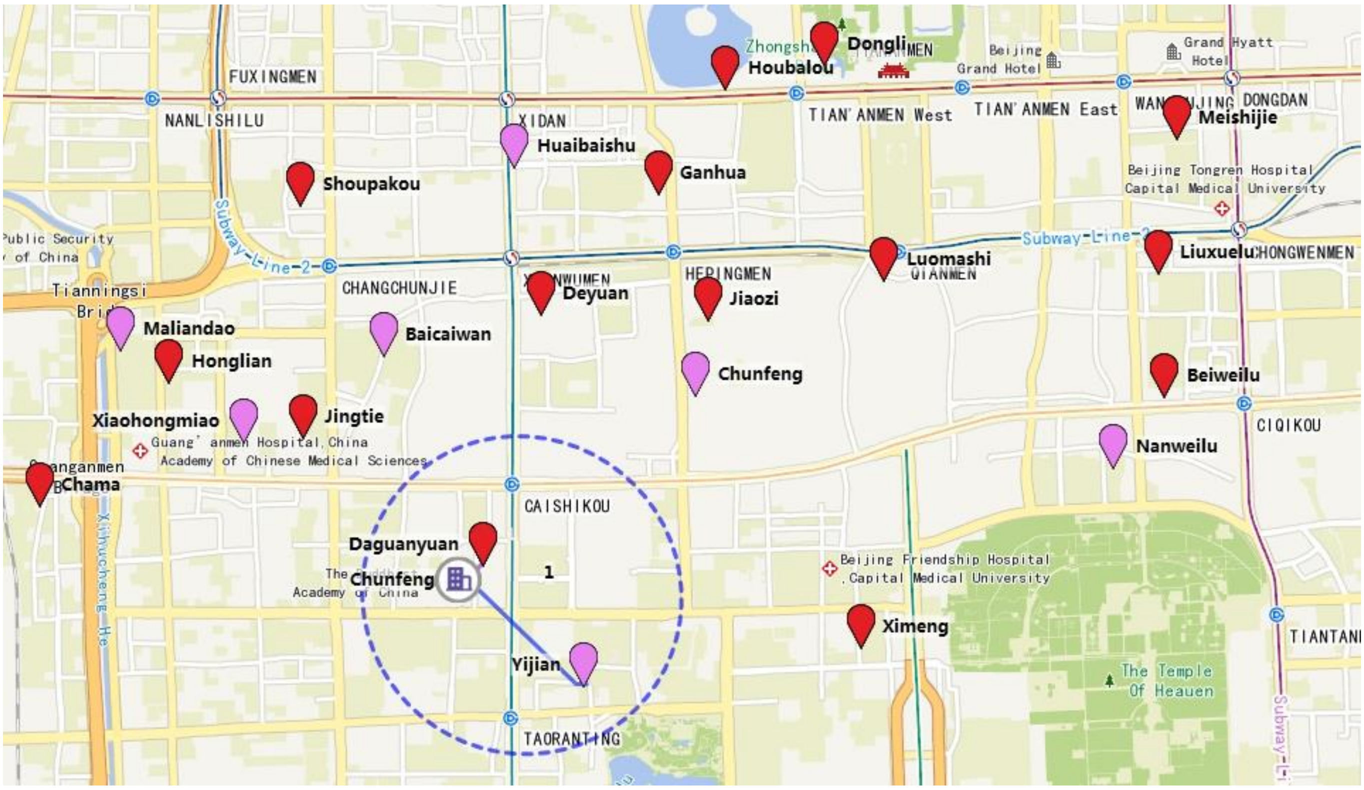

Figure 5. The distribution of incinerable waste collection stations.

It should be noted that due to the function allocation of collection stations, the transportation of waste in residential areas to collection stations has changed. As shown in the dotted box in Figure 5, in the original MSW supply chain mode, the community of Chunfeng only needs to transport all the waste to the nearest collection station Daguanyuan, but in the new mode, it should transport the kitchen waste to the Daguanyuan collection station and transport the incinerable garbage to Yijian collection station, which significantly increased the waste transportation distance and workload from residential areas to the collection station. Owing to shortages of waste production and transportation data in residential areas, this paper cannot measure the change of waste transportation workload from residential areas to collection stations.

The optimization model of the waste transportation path is carried out on the basis of the distribution of incinerable waste collection stations. The Majialou transportation center needs to complete the waste transportation in the seven collection stations.

5.2. The Results of Transportation Path Planning

To prevent mixed transportation and reduce the impact of collection stations on residents' lives, the transportation path of incinerable waste has been studied. The destination of waste transportation is the Majialou transfer center, and the transportation vehicle is the waste compression truck with a load of 6.1 tons. The start and end of the waste truck are both the Majialou transfer center. With the help of Matlab R2014b software, this paper uses a particle swarm algorithm to solve the path planning model. The specific solution processes are as follows.

(1) The dimensionless treatment of objective functions

Due to the different measurement units, the objective functions need to be processed. In this paper, the extremum method was utilized to perform dimensionless processing. First, under a single objective, the optimal value was calculated and used as a magnitude standard. Then, using the objective function values under multiple objectives, the corresponding magnitude standard as the dimensionless values was divided.

(2) Model solution using particle swarm optimization

The particle swarm algorithm is a commonly used intelligent solution algorithm, which has the advantages of fewer parameters and easier implementation. Combined with previous research [45], the initialization parameters are set. This paper sets the range of particle position as [0, 1] and the speed range as $[-0.1, 0.1]$; the population size is 200, the number of iterations is 200, and the acceleration coefficient C_1 and C_2 both are 2; the parameter inertia weight is 0.8 and 0.4. In order to improve the ability to seek optimization, during the calculation process, the parameter inertia weight is adjusted from large to small.

The particle swarm algorithm relies on iterative learning to find the optimal solution of the model. In iteration, the optimal solution of the model was determined by the optimal value of the particle and the average value of the population. After solving the waste truck transportation path model by particle swarm optimization, we obtained the value of the average target and optimal target (Figure 6). The results show that after 20 times iteration, the optimal transportation path scheme was found, and the vehicle's transportation path is shown in Table 3.

Since the amount of waste in one collection station is greater than the load of the waste truck, the waste truck needs to go to the collection station several times. At the beginning of waste transportation, waste trucks will be fully loaded by transporting waste in one collection station. Additionally, then, waste trucks should collect waste in several stations to achieve a full load. The waste trucks 1 and 4 both completed transportation four times, and the waste trucks 2 and 3 completed transportation three times. The waste in collection station 7 (Maliandao, the number of collection station is shown in Table 2) was finished being first transported, and the waste storage time in collection station 7 is the shortest; the waste in collection station 2 (Huaibaishu) was finished being transported last, and the waste storage time in collection station 2 is the longest.

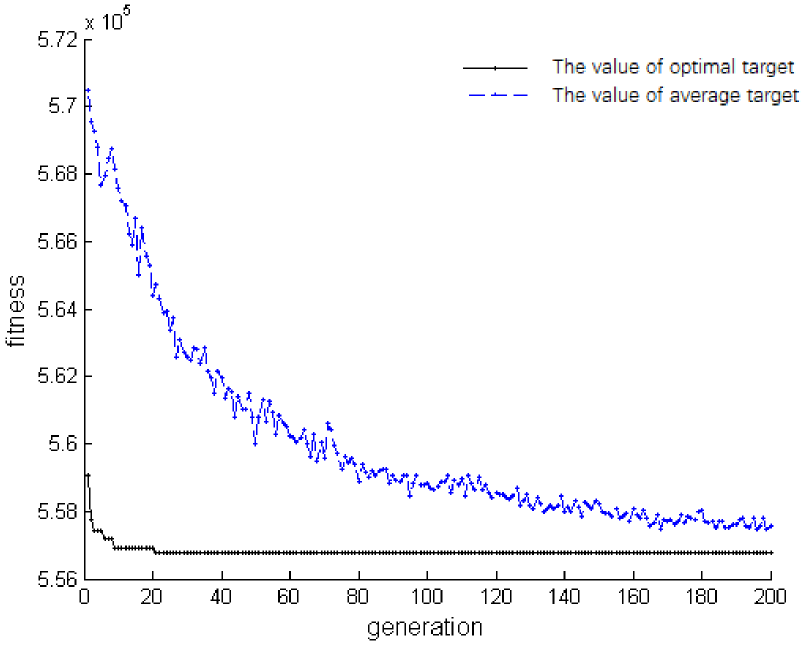

Figure 6. The change of average target and optimal target.

Table 3. The path and time of vehicles.

Vehicles	**Name**	**Path and Time**										
Truck 1	The number of collection station	0	5	0	5	0	3	0	3	1	2	0
	Arrival time	5.5	6.02	6.83	7.35	8.17	8.49	9.11	9.43	9.8	10.12	10.79
	Departure time	5.5	6.32	6.83	7.65	8.17	8.79	9.11	9.73	10.1	10.42	11.09
Truck 2	The number of collection station	0	4	0	6	0	7	0	–	–	–	–
	Arrival time	5.5	6.02	6.84	7.36	8.18	8.71	9.54	–	–	–	–
	Departure time	5.5	6.32	6.84	7.66	8.18	9.01	9.54	–	–	–	–
Truck 3	The number of collection station	0	7	0	6	0	7	6	5	0	–	–
	Arrival time	5.5	6.03	6.85	7.37	8.19	8.72	9.03	9.34	10.16	–	–
	Departure time	5.5	6.33	6.85	7.67	8.19	9.02	9.33	9.64	10.46	–	–
Truck 4	The number of collection station	0	4	0	2	0	1	0	5	4	3	0
	Arrival time	5.5	6.02	6.84	7.21	7.88	8.23	8.88	9.4	9.73	10.07	10.69
	Departure time	5.5	6.32	6.84	7.51	7.88	8.53	8.88	9.7	10.03	10.37	10.99

5.3. Discussion of the Supply Chain Redesign Results

There is an inevitable requirement for sustainable development of cities that decrement harmless and resources for waste treatment. In China, waste treatment has become a major issue in the sustainable development of cities, either large cities or small towns. Based on the present situation that mixed transportation seriously affects the waste classified disposal and sorted collection effect, this paper redesigns the waste supply chain to improve the waste treatment effect. In collection processing, the redesigned waste supply chain can supervise the waste classification effect, which is conducive to evaluating the waste classification effect of each enterprise, public institution, and community. In transportation processing, it can effectively avoid waste mixed transportation, reduce mutual pollution between waste, and solve the problem of false waste classification. Additionally, in disposal processing, it is helpful to improve the final disposal effect of waste and solve the problem caused by excessive impurities [46].

To achieve sustainable development, Beijing, Shanghai, and many other cities have issued strict waste classification policies, hoping to improve the level of classification of waste collected. However, mixed transportation mixes the classified collected waste together, which makes the front-end of the waste supply chain classified collection invalid and seriously affects the waste disposal effect of the supply chain back-end. Based on the existing infrastructure, this paper redesigns the sorting waste collection–transportation–disposal supply chain and allocates the function of the waste collection station, making the waste collection station only collect and transport one type of waste. Compared with the original waste supply chain mode, the new waste supply chain mode proposed in this paper can provide corresponding supporting facilities for the waste classification policy. The improvement of the waste supply chain can ensure the effect of the waste classification policy and promote the implementation of the waste classification policy.

In addition, the waste supply chain proposed in this paper is contributed to promote the waste transportation infrastructure upgrades. The waste classified collection and transportation is conducive to maximizing the advantages of professional waste removal facilities, improving the waste removal efficiency. In waste transportation, with the goal of optimal transportation distance and impact of the collection station on surrounding residents, this paper studies the path planning under the waste classification. Affected by the waste transportation facilities situation, the trucks actually used in transportation fail to fully meet the professional standards of trucks used in this paper. Therefore, it is impossible to quantitatively calculate the improved benefits of waste transportation. Combined with the specialization requirements of waste removal and treatment, the waste trucks will be more specialized in the future.

It should be noted that the waste supply chain mode proposed in this paper may increase the workload of transporting waste from residential areas to collection stations and augment the specialized equipment for waste transportation. In the original model, the waste in one community only needs to be transported to one collection station. However, in the redesigned waste supply chain, the waste in one community needs to be transported to the corresponding sorting collection stations, which will increase the transport distance. Due to the lack of residential areas' waste production data, it is impossible to specifically measure the increased workload of waste transportation from residential areas to collection stations. Additionally, because the redesigned supply chain has not yet been applied, it is impossible to concretely measure the improved ecological footprint or carbon emission in waste disposal. However, considering the situation that the social health cost of waste incineration is 764 yuan/ton, accounting for 70% of the waste incineration cost, which is close to the total cost of waste collection cost in residential areas and waste transportation costs from residential areas to the collection station [1], it is feasible to improve the effectiveness of waste incineration by optimizing the collection and transportation mode since, in long-term operational effects, the redesigned supply chain will play a positive role in the sustainable development of cities.

6. Conclusions

In China, mixed transportation is still the main mode of waste transportation, which mixes the sorted waste, seriously affecting the waste disposal effect. It is the general trend for the waste treatment industry to replace waste mixed transportation with classified transportation. Combined with the impact of waste collection stations on the surrounding environment, this paper, with the goal of optimal economic benefits and minimum environmental impact, has redesigned the supply chain of sorted waste. Based on the data of Xuanwu District in Beijing, an application case of the design model is given.

In general, the method proposed in this paper fully considered the existing waste treatment facilities, which are applicable to most cities in China. However, the model in this paper still has deficiencies, and the following questions are proposed for subsequent related research.

(1) When allocating the functions of waste collection stations, this paper only considers the transportation volume and collection station capacity and does not consider the environment around the collection station and the residents' attitude. Because of the limited data, in the function allocation model, we only use 30 waste collection stations

simulating the waste generation sources. The actual waste generation sources are more complicated.

(2) The production and composition of waste will vary with seasons and positions. The composition of waste in residential areas and commercial areas is different. In this paper, neither the function allocation model for waste collection stations nor the transportation path planning model for waste trucks takes the changes of waste production and composition into account. In the model actual application, the changes in waste production and composition should be considered.

Author Contributions: X.Y.: investigation, methodology, model analysis, writing—original draft, and writing and editing. X.G.: methodology, investigation, writing—review and editing, and funding acquisition. K.Y.: supervision and writing review—editing. All authors have read and agreed to the published version of the manuscript.

Funding: Project supported by the National Key R&D Program of China (2020YFB1707802) and the Fundamental Research Funds for the Central Universities (2019FR002).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they agree with the publication of this paper in this journal. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Guojun, S.; Yueyang, S.; Chang, Z.; Shuai, L.; Ying, W. Social cost accounting for municipal solid waste incineration in Beijing. *China Popul. Resour. Environ.* **2017**, *27*, 17–27.
2. Mota, B.; Gomes, M.I.; Carvalho, A.; Barbosa-Povoa, A.P. Sustainable supply chains: An integrated modeling approach under uncertainty. *Omega* **2018**, *77*, 32–57. [CrossRef]
3. Pan, S.Y.; Du, M.A.; Huang, I.T.; Liu, I.H.; Chang, E.E.; Chiang, P.-C. Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: A review. *J. Clean. Prod.* **2015**, *108*, 409–421. [CrossRef]
4. Rai, R.K.; Nepal, M.; Khadayat, M.S.; Bhardwaj, B. Improving Municipal Solid Waste Collection Services in Developing Countries: A Case of Bharatpur Metropolitan City, Nepal. *Sustainability* **2019**, *11*, 3010. [CrossRef]
5. Hannan, M.A.; Hossain Lipu, M.S.; Akhtar, M.; Begum, R.A.; Al Mamun, M.A.; Hussain, A.; Mia, M.S.; Basri, H. Solid waste collection optimization objectives, constraints, modeling approaches, and their challenges toward achieving sustainable development goals. *J. Clean. Prod.* **2020**, *277*. [CrossRef]
6. Peng, L.; Gu, M.; Peng, Z. Study on the Optimized Mode of Waste Governance with Sustainable Urban Development Case from China's Urban Waste Classified Collection. *Sustainability* **2020**, *12*, 3706. [CrossRef]
7. Jafari, H.; Hejazi, S.R.; Rasti-Barzoki, M. Sustainable development by waste recycling under a three-echelon supply chain: A game-theoretic approach. *J. Clean. Prod.* **2017**, *142*, 2252–2261. [CrossRef]
8. Ghalehkhondabi, I.; Maihami, R. Sustainable municipal solid waste disposal supply chain analysis under price-sensitive demand: A game theory approach. *Waste Manag. Res.* **2020**, *38*, 300–311. [CrossRef]
9. Van Engeland, J.; Beliën, J.; De Boeck, L.; De Jaeger, S. Literature review: Strategic network optimization models in waste reverse supply chains. *Omega* **2020**, *91*, 102012. [CrossRef]
10. Mamashli, Z.; Javadian, N. Sustainable design modifications municipal solid waste management network and better optimization for risk reduction analyses. *J. Clean. Prod.* **2021**, *279*, 123824. [CrossRef]
11. Yılmaz Balaman, Ş.; Wright, D.G.; Scott, J.; Matopoulos, A. Network design and technology management for waste to energy production: An integrated optimization framework under the principles of circular economy. *Energy* **2018**, *143*, 911–933. [CrossRef]
12. Xu, Z.; Elomri, A.; Pokharel, S.; Zhang, Q.; Ming, X.G.; Liu, W. Global reverse supply chain design for solid waste recycling under uncertainties and carbon emission constraint. *Waste Manag.* **2017**, *64*, 358–370. [CrossRef] [PubMed]
13. Olapiriyakul, S.; Pannakkong, W.; Kachapanya, W.; Starita, S. Multiobjective Optimization Model for Sustainable Waste Management Network Design. *J. Adv. Transp.* **2019**, *2019*, 3612809. [CrossRef]
14. Mohammadi, M.; Jämsä-Jounela, S.-L.; Harjunkoski, I. Optimal planning of municipal solid waste management systems in an integrated supply chain network. *Comput. Chem. Eng.* **2019**, *123*, 155–169. [CrossRef]

15. Mohammadi, M.; Harjunkoski, I. Performance analysis of waste-to-energy technologies for sustainable energy generation in integrated supply chains. *Comput. Chem. Eng.* **2020**, *140*, 106905. [CrossRef]
16. Saif, Y.; Rizwan, M.; Almansoori, A.; Elkamel, A. Municipality solid waste supply chain optimization to power production under uncertainty. *Comput. Chem. Eng.* **2019**, *121*, 338–353. [CrossRef]
17. Mohammadi, M.; Jämsä-Jounela, S.L.; Harjunkoski, I. Sustainable supply chain network design for the optimal utilization of municipal solid waste. *AIChE J.* **2018**, *65*, e16464. [CrossRef]
18. Zimin, Z. Status and Countermeasures of Waste Collection and Transportation in Xicheng District of Beijing. *Environ. Sanit. Eng.* **2017**, *6*, 7–9.
19. Ying, L.; Shaohua, X.; Jing, Z. Study of Collection and Transportion System of Beijing Municipal Solid Wastes. *China Popul. Resour. Environ.* **2011**, *21*, 136–139.
20. Zhao, W.; Zhenshan, L.; Yabin, F.; Anying, J.; An, X. Characteristics and Influence Factors of the Energy Consumption and Pollutant Discharge of Municipal Solid Waste Transfer Stations in Beijing. *Environ. Sci.* **2013**, *4*, 2456–2463.
21. Yadav, V.; Karmakar, S.; Dikshit, A.K.; Vanjari, S. A feasibility study for the locations of waste transfer stations in urban centers: A case study on the city of Nashik, India. *J. Clean. Prod.* **2016**, *126*, 191–205. [CrossRef]
22. Yadav, V.; Bhurjee, A.K.; Karmakar, S.; Dikshit, A.K. A facility location model for municipal solid waste management system under uncertain environment. *Sci. Total. Env.* **2017**, *603–604*, 760–771. [CrossRef]
23. Sijun, L.; Changfeng, J.; Ming, D.; Yanli, F. Spatial layout optimization and location of urban waste buildings based on GIS-multicria. *Sci. Surv. Mapp.* **2018**, *43*, 45–49.
24. Wang, Y.; Li, J.; An, D.; Xi, B.; Tang, J.; Wang, Y.; Yang, Y. Site selection for municipal solid waste landfill considering environmental health risks. *Resour. Conserv. Recycl.* **2018**, *138*, 40–46. [CrossRef]
25. Demesouka, O.E.; Anagnostopoulos, K.P.; Siskos, E. Spatial multicriteria decision support for robust land-use suitability: The case of landfill site selection in Northeastern Greece. *Eur. J. Oper. Res.* **2019**, *272*, 574–586. [CrossRef]
26. Soroudi, M.; Omrani, G.; Moataar, F.; Jozi, S.A. A comprehensive multi-criteria decision making-based land capability assessment for municipal solid waste landfill sitting. *Env. Sci. Pollut. Res. Int.* **2018**, *25*, 27877–27889. [CrossRef]
27. Spigolon, L.M.; Giannotti, M.; Larocca, A.P.; Russo, M.A.; Souza, N.D.C. Landfill siting based on optimisation, multiple decision analysis, and geographic information system analyses. *Waste Manag. Res.* **2018**, *36*, 606–615. [CrossRef]
28. Liu, K.M.; Lin, S.H.; Hsieh, J.C.; Tzeng, G.H. Improving the food waste composting facilities site selection for sustainable development using a hybrid modified MADM model. *Waste Manag.* **2018**, *75*, 44–59. [CrossRef] [PubMed]
29. Kyriakis, E.; Psomopoulos, C.; Kokkotis, P.; Bourtsalas, A.; Themelis, N. A step by step selection method for the location and the size of a waste-to-energy facility targeting the maximum output energy and minimization of gate fee. *Env. Sci. Pollut. Res. Int.* **2018**, *25*, 26715–26724. [CrossRef]
30. Vecchi, T.P.B.; Surco, D.F.; Constantino, A.A.; Steiner, M.T.A.; Jorge, L.M.M.; Ravagnani, M.A.S.S.; Paraíso, P.R. A sequential approach for the optimization of truck routes for solid waste collection. *Process. Saf. Environ. Prot.* **2016**, *102*, 238–250. [CrossRef]
31. Carlos, M.; Gallardo, A.; Edo-Alcon, N.; Abaso, J.R. Influence of the Municipal Solid Waste Collection System on the Time Spent at a Collection Point: A Case Study. *Sustainability* **2019**, *11*, 6481. [CrossRef]
32. Yonggang, W.; Xiangxin, X.; Mei, L.; Long, Z. Research on City Waste Removal Routes Based on Genetic Algorithm. *Comput. Simul.* **2012**, *4*, 259–262.
33. Son, L.H.; Louati, A. Modeling municipal solid waste collection: A generalized vehicle routing model with multiple transfer stations, gather sites and inhomogeneous vehicles in time windows. *Waste Manag.* **2016**, *52*, 34–49. [CrossRef]
34. Chunping, L. Atmosphere Monitoring and Safe Protective Distance inside and outside Municipal Solid Waste Collecting Station in Beijing. *Urban Environ. Urban Ecol.* **2017**, *24*, 39–42.
35. Zsigraiova, Z.; Semiao, V.; Beijoco, F. Operation costs and pollutant emissions reduction by definition of new collection scheduling and optimization of MSW collection routes using GIS. The case study of Barreiro, Portugal. *Waste Manag.* **2013**, *33*, 793–806. [CrossRef]
36. Inghels, D.; Dullaert, W.; Vigo, D. A service network design model for multimodal municipal solid waste transport. *Eur. J. Oper. Res.* **2016**, *254*, 68–79. [CrossRef]
37. Chatzouridis, C.; Komilis, D. A methodology to optimally site and design municipal solid waste transfer stations using binary programming. *Resour. Conserv. Recycl.* **2012**, *60*, 89–98. [CrossRef]
38. Kinobe, J.R.; Bosona, T.; Gebresenbet, G.; Niwagaba, C.B.; Vinnerås, B. Optimization of waste collection and disposal in Kampala city. *Habitat Int.* **2015**, *49*, 126–137. [CrossRef]
39. Nguyen-Trong, K.; Nguyen-Thi-Ngoc, A.; Nguyen-Ngoc, D.; Dinh-Thi-Hai, V. Optimization of municipal solid waste transportation by integrating GIS analysis, equation-based, and agent-based model. *Waste Manag.* **2017**, *59*, 14–22. [CrossRef]
40. Xue, W.; Cao, K.; Li, W. Municipal solid waste collection optimization in Singapore. *Appl. Geogr.* **2015**, *62*, 182–190. [CrossRef]
41. Li, Z.; Guiqin, W.; Dian, W. Investigation and Analysis of Domestic Waste Output of Residential Area in Central Six Districts of Beijing. *Environ. Sanit. Eng.* **2018**, *26*, 59–62.
42. Benis, K.; Safaiyan, A.; Farajzadeh, D.; Nadji, F.; Shakerkhatibi, M.; Harati, H.; Safari, G.; Sarbazan, M. Municipal solid waste characterization and household wast behaviors in a megacity in the northwest of Iran. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 4863–4872. [CrossRef]

43. Zakarya, I.A.; Fazhil, N.S.A.; Izhar, T.N.T.; Zaaba, S.K.; Jamaluddin, M.N.F. Municipal Solid Waste Characterization and Quantification as A Measure Towards Effective Solid Waste Management in UniMAP. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *616*, 12047. [CrossRef]
44. Chendi, W. *Research on Vehicle Dispatching and Optimization of Beijing Refuse Collection Based On Municipal Solid Waste Classification*; Beijing Jiaotong University: Beijing, China, 2018.
45. Feng, P.; Weixng, L.; Qi, G.; Al, E. *Particle Swarm Optimizer and Multi-Object Optimization*; Beijing Institute of Technology Press: Beijing, China, 2013; pp. 89–92.
46. Guo, X.; Yang, X. The economic and environmental benefits analysis for food waste anaerobic treatment: A case study in Beijing. *Env. Sci. Pollut. Res. Int.* **2019**, *26*, 10374–10386. [CrossRef] [PubMed]