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Research Article

Optimizing the WEEE Recovery Network Associated with Environmental Protection Awareness and Government Subsidy by Nonlinear Mixed Integer Programming

Yanan Bo, Yanqi Wang, and Zhong Wan

School of Mathematics and Statistics, Central South University, Changsha, China

Correspondence should be addressed to Zhong Wan; wanmath@163.com

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Recovery of waste electrical and electronic equipment (WEEE) plays an important role in protecting environment and conserving resources. Design of a more efficient WEEE recovery system is an imperative need for the relevant decision-makers, such as alleviation of overcapacity or insufficient recycling in many developing countries. In this paper, we optimize the WEEE recovery network which is associated with recycling prices and government subsidies by a nonlinear mixed integer programming approach. An integrated model is first proposed to formulate a design problem of WEEE recovery network, being involved with collection centers, two types of transfer stations, processing centers, incineration plants, landfill plants, secondhand product markets, and government subsides. The recycling prices and the transported quantities of WEEE (the number of batches) are endogenous variables of the model, being subject to a number of practical constraints. For solving this model, an algorithm is developed based on the branch and bound method. Scenario analysis and numerical experiments indicate that: (1) appropriate capacities of transfer stations can be provided by the proposed model for designing an environmentally and economically efficient WEEE recycling system, especially for alleviating the existing overcapacity or insufficient recycle. (2) An optimal governmental subsidy can be obtained in virtue of the proposed model and algorithm. (3) Diversity of transportation modes and permission of more than one mode in the same delivery route can greatly reduce the cost of recycling WEEE. (4) Preferred awareness of environmental protection can increase the profit and the recycled quantities, as well as reduction of the total recycling cost.

1. Introduction

Statistically, the electronic wastes generated per year are estimated to be about 44.7 million tons [1]. Recovery of waste electrical and electronic equipment (WEEE) plays an important role in protecting environment and conserving resources [2].

On the one hand, the WEEE contains more than 60 kinds of metals, such as copper, gold, silver, palladium, platinum and the other precious ones. Recovering these metals from the WEEE can partly reduce the total demand to exploit natural metal resources. Additionally, the WEEE industry can create employment opportunities more easily for society. In 2014, only owing to computer reuse, every 10,000 tons of material handling can bring at least 296 jobs according to ETBC statistics [3]. It is estimated that the recycling behavior of the WEEE creates the profit up to \$14.6 billion in 2014 [4].

On the other hand, the WEEE contains some toxic materials that may pollute the air, soil, and water if they are arbitrarily discarded, or improperly disposed [5]. For example, many components of waste mobile phones (WMP), just like batteries and printed circuit boards (PCBs), contain heavy metals, such as Cd, Cu, Ni, Sb, and Pb. If these metals in WMPs are recycled or reused, there is a consequent decline in environmental pollution [5]. Cucchiella suggested that the laptops, tablets and smart phones are the most valuable categories of WEEE [6].

However, in spite of a notable potential benefit from recycling WEEE, only 15% of WEEE in the world was fully recycled and reused in the actual implementation process [7].

Actually, efficiently recycling the WEEE is still a challenge in practice, especially in the developing countries.

In China, to impel the WEEE recovery, a series of laws or regulations have been issued in recent years. Regulations, such as "Measures for the Control of Pollution from Electronic Information Products (Chinese RoHS Directive)" in 2006, "Regulation on the Administration of the Recovery and Disposal of Waste Electrical and Electronic Products (Chinese WEEE Directive)" in 2009, and "Special Planning for the 'Twelfth Five-year' Waste Recycling Technology Project" in 2012, have been proposed to promote complete recovery of WMP components and to normalize the treatment of WMPs. On the 9th February 2015, the latest "Directory of Waste Electrical and Electronic Products Processing" was enacted [5]. But even so, there are still many obstacles to develop Chinese WEEE management system, such as higher operating cost, weaker awareness of environmental protection, and imperfect incentive mechanism [8].

It is because of complexity for recycling WEEE in practice, design of an efficient WEEE recovery network by mathematical modelling has received immense research attentions in recent two decades. These networks fall into two categories: open-loop networks and closed-loop ones.

In the open-loop network design (OLND), the researchers focused on recycling behavior and material recovery flows. The network begins with the collecting behavior and then through the inspection, classification, disassembling, processing and disposal operations, completes the main parts of reverse logistics (RL) [9]. Shokouhyar established an open-loop network with allocation problem of collection centers and the treatment plants [10]. The model considered a two-stage reverse logistics network and designed a genetic algorithm to solve the problem. With the algorithm, an approximate most preferred policy which can balance environmental, economical and social impacts was obtained. This model was numerically verified by case study of recycling WEEE in Iran. Tuzkaya proposed a multiobjective model for a reverse logistics network design, which consists two phases: a centralized recycling center (CRC) evaluation phase to obtain the CRC weights and a reverse logistics network design (RLND) phase to study the best possible location and the minimum cost of the RL network [11]. Maria Isabel Gomes developed an MILP model to represent the reverse logistics network for establishment of an nationwide WEEE logistics network in Portugal, which is suitable for the national WEEE reverse logistics network's design and planning [12]. Location problems of open-loop network nodes were also addressed in [13–16]. Erhan Erkut constructed a multiobjective mixed integer linear programming model and used this model to derive a "fair" uncompensated solution that can balance economic and environmental benefits at the same time [17]. Hao formulated a multisource, multilevel and sustainable reverse logistics network of WEEE management by a random mixed integer programming model under uncertain environment [18], where a multicriteria two-stage scenario solution was used to describe an optimal solution of the stochastic optimization model. Achillas formulated a design problem of reverse logistics network by a mixed integer linear programming mathematical model, where the existing infrastructure of collection points and recycling facilities were considered [19]. Additionally, this article also provided WEEE management policies for the government. However, the collected WEEE quantities in [19] were assumed to be given. In [20], the authors studied how to minimize the number of vehicles in logistics transportation management.

The closed-loop supply chain (CLSC) network design refers to the direct and coordinated relationship between forward logistic activities (i.e., material processing, manufacturing and distribution) and tasks related to the reverse supply chain (RSC), transforming the supply chain into closed-loop overall structure [9]. Compared with OLND, research on CLSC network about the WEEE recovery was relatively rare in the literature. Amin and Zhang proposed a three-stage model that includes assessment, network selection, and orders assignment [21]. In the first phase, the proposed QFD model was used to determine the relationship among customer requirements, part requirements and process requirements. In the second stage, a stochastic mixed integer nonlinear programming model of CLSC network was established and the location and order decision problems were solved in the third stage. Kannan established a multilevel, multicycle and multiproduct CLSC network with the goal of reducing cost and making decisions on procurement, distribution, recycling and processing of used batteries [22]. This model was an MILP problem and used a genetic algorithm to obtain an approximate optimal solution. In order to optimize the cost and delivery assignments, Sasikumar designed a multilevel multiproduct closed-loop distribution supply chain (CLDSC) network, and studied how to choose the best third-party reverse logistics provider (3PRLP) [23].

CLSC is also associated with vehicle routing problems (VRP). A greedy random adaptive search process (GRASP) algorithm [24] was designed for determining the collection capabilities and processing times of fixed and heterogeneous vehicle groups, which have general characteristics of the vehicles collecting WEEE from customers. Manzini proposed a model considering both collecting vehicle routing problems and customer demand assignments problems considering different modes of transportation [25]. This model also considered minimization of the cost and environmental impacts by optimizing the transportation plan.

However, as far as we know, few authors take into account the impacts of recycling prices on the collected quantities of WEEE in the existing optimization models of OLND and CLSC, combined with a strategy of hybrid transportation mode. Our previous research has indicated that the recycling prices can seriously affect the recovered quantities of wastes, and plays an important role in improving performance of reverse logistics system as endogenous variables of model [26–28]. It is easy to see that in the case of poor environmental protection awareness, it is necessary to encourage the public to actively participate in recycling WEEE by increasing their recycling price [29]. For example, in [27], Wu et al. built a multiobjective mixed-integer piecewise nonlinear programming model (MOMIPNLP) to formulate the management problem of urban mining system, where the decision variables are associated with buy-back pricing, choices of sites, transportation planning, and adjustment of production capacity. Different from the existing approaches, the social negative effect, generated from structural optimization of the recycling system, was minimized as well as the total recycling profit and utility from environmental improvement were jointly maximized. Then, based on technique of orthogonal design, a hybrid heuristic algorithm was developed to find an approximate Pareto-optimal solution.

Motivated by the mentioned need to design a WEEE recovery system with stronger applicability, we attempt to improve the WEEE recovery system by addressing the following issues:

(i) How to design an integrated system of recovery network? The network elements should include all the relevant essential factors: the collection centers and the recycling prices paid by them, the different types of transfer stations, the processing centers, the incineration plants, the landfill plants, the secondhand product markets, and the subsides from government.

(ii) How to efficiently inspire the public to participate in the WEEE recycling? In practice, it is often that the recycled quantity of WEEE depends on the recycling prices, rather than a given constant as assumed in the existing results.

(iii) What is an appropriate transportation mode based on the quantity of WEEE to be transported. In this paper, container transportation with two different sizes is an optional mode, where both container leasing fee and transportation cost are needed to be considered.

Consequently, the proposed model in this paper is a mixed integer nonlinear programming problem. In order to solve this complicated model, we will develop a computer procedure on Matlab platform based on branch and bound method. With our new model, we attempt to answer the following questions by numerical analysis:

(i) What is the role of transfer stations in the WEEE recovery system? Actually, we will show that transfer stations play an important role in improving the performance of the WEEE recovery system by alleviating overcapacity and insufficient recovery of WEEE, as well as increasing profit. Appropriate capacities of transfer stations will be provided by the proposed model in order to design an environmentally and economically efficient system of recycling WEEE.

(ii) What is the impacts of governmental subsidies on the WEEE recovery system? In practice, effects of governmental subsidies can be calculated by marginal merit analysis. Our model will furnish optimal subsidies when both environmental protection and financial burden of government are considered.

(iii) Whether an appropriate choice among different transportation modes is a key way to reduce the recovery cost of system or not? We will show that improvement of transportation modes, such as permission of more than one transportation mode in the same route, is a preferable way to increase the recycled quantities and the profit of recovery system. Moreover, the selection of multiple modes will make our model more adaptable to different scenarios.

(iv) What are the impacts of the public's awareness of environmental protection on the recovery system? We shall demonstrate that the differences of public's environmental protection awareness may seriously affect the optimal decision for recycling WEEE.

The rest of the paper is organized as follows. Next section is devoted to modelling the WEEE recovery system. In Section 3, an algorithm is developed in the framework of branch and bound method to solve the model. Numerical analysis of model is conducted in Section 4. Sensitivity analysis is made in Section 5, which is employed to reveal some practical managerial implications. Some conclusions and suggestions for future research are presented in the last section.

2. Model for Recycling WEEE

In this section, we will build a mixed integer nonlinear programming model (MINLP) for the WEEE recycling management problem, which is associated with optimal choices of recycling prices, transportation modes and government subsidies.

2.1. Problem Definition and Notations. We first describe what is the practical problem to be solved in this paper.

Collection centers are the starting points of WEEE recovery network. Due to lower public awareness of environmental protection, the proportion of successfully collected WEEE has not reached a proper level in practice. Since paid recovery may be an efficient strategy to increase collected quantity, different from the existing results, the recycling price in each collection center for each type of WEEE is regarded as a decision variable in this paper.

In the collection centers, the collected WEEE are disassembled if necessary, and are sorted by their categories. Then, the collected WEEE are first sent to different transfer stations for temporary storage and package. Note that use of the transfer stations can reduce transportation cost by choice of suitable transportation tools. Therefore, each type of the WEEE during the storage in some transfer stations can be reorganized and packaged to accommodate the subsequent large-volume transportation.

Finally, the packaged WEEE is transported to processing centers by large-volume vehicles for unit and final treatment. When the WEEE are processed in processing centers, a part of reusable components are dismantled or refurbished, then they are sold to secondary markets as secondhand products. Unlike the results available in the literature, the returns from sale of the secondhand products constitutes the main revenue part of the objective function in this paper. The second part of the processed WEEE in the processing centers is hazardous waste, which is necessarily transported to incineration centers for centralized incineration disposal. The last part is ordinary garbages, which is directly transported to landfill plants.

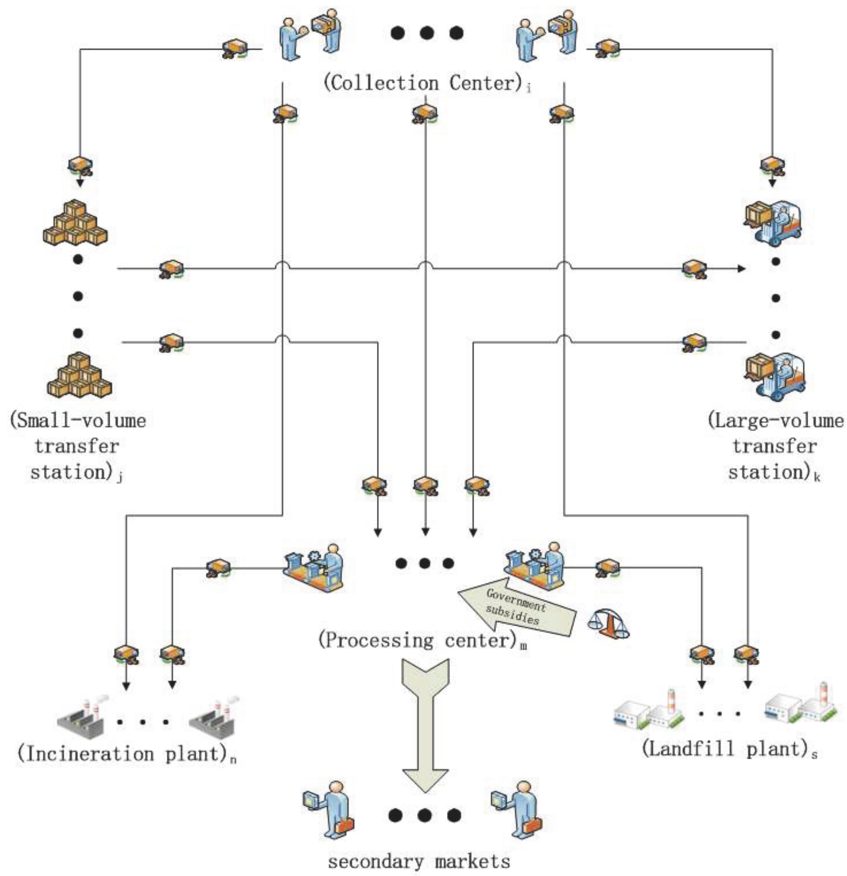


Figure 1: Schematic diagram of the WEEE recovery system.

Clearly, transportation plan is the most critical part of the WEEE recovery system. In this paper, we suppose that the transportation cost of the WEEE recycling system is associated with the distance between two nodes of the recovery network, the transported quantity of the WEEE, the unit transportation price of the chosen type of vehicles and the cost for leasing containers. Specifically, if the distance between a collection center and a processing center is short, the collected WEEE are directly transported by small-size vehicles from the collection center to the processing center. If the collected center is far from the processing center, then the WEEE are first transported to the transfer stations, where they are repacked, and then transported in containers to processing centers by medium or large-volume vehicles. In general, the unit cost of the small-volume vehicles is higher than that of the medium or large-volume ones. Apart from the transportation cost, our recovery system also needs to pay the treatment costs to the incineration centers and landfill plants. In other words, the incineration centers and landfill plants, as well as the secondary markets, are regarded as external environment of the system in this paper, other than its interior components.

Summarily, we use Figure 1 to show the schematic diagram of the WEEE recovery system as described above.

Different from the treated recycle networks in the literature [8, 12, 19], the recycle system shown in Figure 1 does not consist of the incineration plants, the landfill plants and the secondhand markets (outside the dotted line). These nodes of recycle network are only regarded as external factors of system such that the system is in accordance with the existent practical situations. Instead, our system has to pay the processing costs to the incineration plants and the landfill plants, as well as earning the revenue by selling some valuable components in WEEE to the secondhand markets.

The following notations are useful to the subsequent mathematical description of the above management problem of recycling the WEEE.

Indices

i: The labels of collection centers, $i = 1, 2, \ldots, I$.

I: The number of collection centers.

j: The labels of small-volume transfer stations, $j = 1, 2, \ldots, J$.

J: The number of small-volume transfer stations.

k: The labels of large-volume transfer stations, $k = 1, 2, \ldots, K$.

K: The number of large-volume transfer stations.

m: The labels of processing centers, $m = 1, 2, \ldots, M$.

M: The number of processing centers.

n: The labels of incineration plants, $n = 1, 2, \ldots, N$.
N: The number of incineration plants.
s: The labels of landfill plants, $s = 1, 2, \ldots, S$.
S: The number of landfill plants.
w: The labels of the WEEE categories, $w = 1, 2, \ldots, W$.
W: The number of the WEEE categories.
a: The labels of departure node of transportation.
b: The labels of arrival node of transportation.
t: The labels of transportation modes, $t = 1, 2, \ldots, T$.
T: The number of transportation modes.

Parameters

XC_{iw}: The WEEE quantity in the i-th collection center for the w-th type of WEEE (ton).

γ_{iw}: The recycling variable costs of i-th collection center for the w-th type of WEEE, such as collection, disassembly staff wage (RMB Yuan).

β_{iw}: The recycling price coefficient of the i-th collection center for the w-th type of WEEE, called a sensitivity coefficient of recycling price (RMB Yuan/ton).

μ_{iw}: The collected quantity of the i-th collection center for the w-th type of WEEE when the recycling price is zero, called an inherent collected quantity (ton).

T_{ab}: The number of transportation modes in the same route from Node a to Node b.

C_{abtw}: The unit transfer cost from Node a to Node b for the w-th type of WEEE by the t-th transportation mode (RMB Yuan/km/ton).

D_{ab}: The distance from Node a to Node b (km).

Y_t: The container leasing costs by the t-th transportation mode (RMB Yuan/time).

NP_{jw}: The unit management fees for the w-th type of WEEE in the j-th small-volume transfer stations (RMB Yuan/ton).

NR_{kw}: The unit management fees for the w-th type of WEEE in the k-th large-volume transfer stations (RMB Yuan/ton).

NU_{mw}: The unit processing fees for the w-th type of WEEE in the m-th processing center (RMB Yuan/ton).

XU_{mw}: The total quantity of processing for the w-th type of WEEE in the m-th processing center (ton).

SU_w: The government subsidies for the w-th type of WEEE received in the processing center (RMB Yuan).

PS_{mw}: The sell price of m-th processing center for the w-th type of WEEE (RMB Yuan/ton).

NI_{nw}: The fee paid to the n-th incineration plant for the hazardous part of the w-th type of WEEE (RMB Yuan/ton).

XI_{nw}: The total incinerated quantity for the w-th type of WEEE in the n-th incineration plant (ton).

NL_{sw}: The fee charged by the s-th landfill plant for the unavailable part in the w-th type of WEEE (RMB Yuan/ton).

XL_{sw}: The total landfill quantity for the w-th type of WEEE in the s-th landfill plant (ton).

$XU_{min_{mw}}$: The minimum processing quantity for the w-th type of WEEE in the m-th processing center (ton).

$XU_{max_{mw}}$: The maximum processing capacity for the w-th type of WEEE in the m-th processing center (ton).

XC_{max_i}: The recycling capacity in the i-th collection center (ton).

XP_{max_j}: The storage capacity in the j-th small-volume transfer stations (ton).

XR_{max_k}: The storage capacity in the k-th large-volume transfer stations (ton).

Q_{tw}: The storage capacity of a single shipment of the w-th type of WEEE by the t-th transportation mode (ton/time).

α_w: The proportion of the w-th type of WEEE sent to incineration plants among the recycled WEEE.

λ_w: The proportion of the w-th type of WEEE sent to landfill plants among the recycled WEEE.

η_w: The proportion of the w-th type of WEEE sent to incineration plants among the processed WEEE.

χ_w: The proportion of the w-th type of WEEE sent to the landfill plants among the processed WEEE.

X_{max_w}: The predicted social stock of the w-th type of WEEE (ton).

Decision Variables

PC_{iw}: The recycling price of the i-th collection center for the w-th type of WEEE (RMB Yuan).

X_{abtw}: The transported quantity from Node a to Node b for the w-th type of WEEE by the t-th transportation mode (ton).

Z_{abtw}: The delivery times of the w-th type of WEEE from Node a to Node b by the t-th transportation mode (time).

2.2. Objective Function. Since recycling prices are regarded as critical decision variables in our model, the objective function is to maximize the total profit of the WEEE recovery system, rather than minimization of costs as the results available in the literature. In addition, the revenue of the recovery system also includes government subsidy and income from sale of the secondhand products.

Similar to the existing WEEE recovery system, the expenditures for recycling the WEEE include the costs of paid collection, transportation, storage, processing, and paid incineration and landfill in all the relevant treatment centers.

Since the recycling price in a collection center for each type of WEEE is regarded as a decision variable in this paper, together with treatment costs, the total expense in all the collection centers can be written as

$$f_1 = \sum_w \sum_i PC_{iw} XC_{iw} + \sum_w \sum_i \gamma_{iw} XC_{iw}, \quad (1)$$

where the first term is the expense of paid-collection, and the second term represents the variable treatment cost associated with the treated WEEE quantity, which is positively correlated with the recycling price. For simplification, we suppose that

$$XC_{iw} = \beta_{iw} PC_{iw} + \mu_{iw}, \quad (2)$$

where $\beta_{iw} > 0$ and $\mu_{iw} \geq 0$ called a sensitivity coefficient of recycling price and an inherent collected quantity, respectively. In practice, the sensitivity coefficient of recycling price (SCRP) describes the change of the collected WEEE quantity in i-th collection center corresponding to fluctuation of the unit recycling price of that center for the w-th type of WEEE. The so-called inherent collected quantity (ICQ) represents the collected WEEE quantity of the i-th collection center as the recycling price is zero for the w-th type of WEEE. Clearly, both of them depend on the public environmental protection awareness for the w-th type of WEEE in the i-th collection center. In general, larger β_{iw} and μ_{iw} mean a strong public's awareness of environmental protection. In other words, if β_{iw} and μ_{iw} are large, the collected quantity is great even if no pay for the collection or a lower recycling price is paid.

Since delivery by containers is the most common mode from a transfer station to a processing center, the fee of renting the containers is written as

$$\begin{aligned} f_2 &= \sum_j\sum_k\sum_t\sum_w Y_t Z_{jktw} + \sum_j\sum_m\sum_t\sum_w Y_t Z_{jmtw} \\ &\quad + \sum_m\sum_n\sum_t\sum_w Y_t Z_{mntw} + \sum_m\sum_s\sum_t\sum_w Y_t Z_{mstw} \\ &\quad + \sum_k\sum_m\sum_t\sum_w Y_t Z_{kmtw} \triangleq \sum_a\sum_b\sum_t\sum_w Y_t Z_{abtw} \end{aligned} \tag{3}$$

As shown in Figure 1, if T_{ab} stands for the number of transportation modes permitted in the same routine between Nodes a and b, then the transportation cost of the recovery system is

$$\begin{aligned} f_3 &= \sum_i\sum_j\sum_t\sum_w C_{ijtw} X_{ijtw} D_{ij} \\ &\quad + \sum_i\sum_m\sum_t\sum_w C_{imtw} X_{imtw} D_{im} \\ &\quad + \sum_i\sum_k\sum_t\sum_w C_{iktw} X_{iktw} D_{ik} \\ &\quad + \sum_i\sum_s\sum_t\sum_w C_{istw} X_{istw} D_{is} \\ &\quad + \sum_i\sum_n\sum_t\sum_w C_{intw} X_{intw} D_{in} \\ &\quad + \sum_j\sum_k\sum_t\sum_w C_{jktw} X_{jktw} D_{jk} \\ &\quad + \sum_j\sum_m\sum_t\sum_w C_{jmtw} X_{jmtw} D_{jm} \\ &\quad + \sum_m\sum_n\sum_t\sum_w C_{mntw} X_{mntw} D_{mn} \\ &\quad + \sum_m\sum_s\sum_t\sum_w C_{mstw} X_{mstw} D_{ms} \\ &\quad + \sum_k\sum_m\sum_t\sum_w C_{kmtw} X_{kmtw} D_{km} \\ &\triangleq \sum_a\sum_b\sum_t\sum_w C_{abtw} X_{abtw} D_{ab} \end{aligned} \tag{4}$$

For the transfer stations, since the input WEEE need further packaging and storage, the total maintenance fee in these stations is

$$\begin{aligned} f_4 &= \sum_i\sum_j\sum_t\sum_w NP_{jw} X_{ijtw} \\ &\quad + \sum_i\sum_j\sum_k\sum_t\sum_w NR_{kw} \left(X_{iktw} + X_{jktw} \right). \end{aligned} \tag{5}$$

Since the processing centers are responsible for refurbishing, processing, and replacing parts of the WEEE that have been sorted, and the secondhand products are sold to the secondary market, the total return in the processing centers reads

$$f_5 = \sum_m\sum_w NU_{mw} XU_{mw}. \tag{6}$$

From (6), we know that different types of WEEE have distinct processing costs, such as the staff salary, the cost of renewing, etc.

Because the recycle of WEEE not only protects the environment from the pollution, but also promotes reuse of valuable resources, government subsidy is an efficient way to directly compensate higher recycling cost such that the recycling company's profit is improved. In this paper, to improve the practicability of model, we suggest that for different types of the processed WEEE, the processing centers can get different unit government subsidy. Suppose that SU_w represents the unit government subsidy for the w-th type of WEEE, for then all the processing centers can get the following total government subsidy:

$$f_6 = \sum_w SU_w \sum_m XU_{mw} \tag{7}$$

Since the revenue of selling to the secondhand markets is nonnegligible in practice, we express the sale income by

$$\begin{aligned} f_7 &\\ &= \sum_m\sum_w PS_{mw} \left(XU_{mw} - \sum_s\sum_t X_{mstw} - \sum_n\sum_t X_{mntw} \right), \end{aligned} \tag{8}$$

where PS_{mw} is the sale price of the w-th type of WEEE in the processing center m.

Finally, apart from the transportation costs, the recovery system needs to pay the treatment costs to incineration centers and landfill plants. It is written as:

$$f_8 = \sum_w\sum_n NI_{nw} XI_{nw} + \sum_w\sum_s NL_{sw} XL_{sw}. \tag{9}$$

Clearly, the total treatment fee depends on the total quantity of each type of WEEE transported to each plant.

On the basis of the above analysis, we obtain the profit function of the recovery system as follows.

$$f = f_6 + f_7 - f_1 - f_2 - f_3 - f_4 - f_5 - f_8. \tag{10}$$

2.3. Constraints. We now come to consider the constraints of model.

The first set of constraints is on the balance of network flows.

$$XC_{iw} = \sum_j \sum_k \sum_m \sum_n \sum_s \sum_t \left(X_{ijtw} + X_{imtw} + X_{iktw} + X_{istw} + X_{intw}\right), \quad \forall i, w, \tag{11}$$

$$XU_{mw} = \sum_i \sum_j \sum_k \sum_t \left(X_{imtw} + X_{jmtw} + X_{kmtw}\right), \quad \forall m, w, \tag{12}$$

$$XI_{nw} = \sum_i \sum_m \sum_t \left(X_{intw} + X_{mntw}\right), \quad \forall n, w, \tag{13}$$

$$XL_{sw} = \sum_i \sum_m \sum_t \left(X_{istw} + X_{mstw}\right), \quad \forall s, w. \tag{14}$$

Clearly, (11) indicates that all the collected WEEE for each type in each collection center are transported to the transfer stations, or shipped directly to the processing centers, the incineration plants, or the landfill plants by a suitable transportation mode. (12) shows that the input WEEE in the processing centers are all come from the collection centers, or the transfer stations. Equations (13) and (14) demonstrate that the WEEE in the incineration centers and the landfill plants come from the following: (1) The collection center transports unavailable part of WEEE directly to the incineration plants or landfill plants after being disassembled and (2) a part of the WEEE that can not be processed by processing centers.

The second set of constraints is on the material balance of the two types of transfer stations, respectively.

$$\sum_i \sum_t X_{ijtw} = \sum_k \sum_m \sum_t \left(X_{jktw} + X_{jmtw}\right), \quad \forall j, \tag{15}$$

$$\sum_i \sum_j \sum_t \left(X_{iktw} + X_{jktw}\right) = \sum_m \sum_t X_{kmtw}, \quad \forall k. \tag{16}$$

Constraints (15) ensure that the quantity of the WEEE entering a small-volume transfer station is equal to the quantity of the WEEE departures from that node, and this quantity of the WEEE is shipped to large-volume transfer stations or the processing centers. Similarly, the constraints (16) ensure that the quantity of the WEEE entering each large-volume transfer station, whether from the collection centers or the small-volume transfer stations, is equal to the quantity of the WEEE shipped to the processing centers from that large-volume transfer station.

The third set of constraints is the capacity constraints of the model [30].

$$XU_{min_{mw}} \le \sum_i \sum_j \sum_k \sum_t \left(X_{imtw} + X_{jmtw} + X_{kmtw}\right) \le XU_{max_{mw}}, \quad \forall m, w, \tag{17}$$

$$0 \le \sum_w XC_{iw} \le XC_{max_i}, \quad \forall i, \tag{18}$$

$$0 \le \sum_i \sum_t \sum_w X_{ijtw} \le XP_{max_j}, \quad \forall j, \tag{19}$$

$$0 \le \sum_m \sum_t \sum_w X_{kmtw} \le XR_{max_k}, \quad \forall k. \tag{20}$$

The first inequalities (17) mean that the total quantity of WEEE in every processing center, whether are from collection centers, small-volume transfer stations or large-volume transfer stations, should not exceed the maximum processing capacity of the facility for any WEEE component, so that the capacity of the equipment capacity in the processing center is considered to be the capacity of the processing center. The last three inequalities represent the capacity constraints of collection centers and two kinds of transfer stations. Actually, each specific node in the network corresponds to its minimum and maximum storage capabilities.

The forth set of constraints is used to calculate the minimum delivery times of the w-th type of WEEE by the t-th transportation mode in each O-D route.

$$Z_{ijtw} = \begin{cases} \dfrac{X_{ijtw}}{Q_{tw}}, & \text{if } \dfrac{X_{ijtw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{ijtw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{iktw} = \begin{cases} \dfrac{X_{iktw}}{Q_{tw}}, & \text{if } \dfrac{X_{iktw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{iktw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{imtw} = \begin{cases} \dfrac{X_{imtw}}{Q_{tw}}, & \text{if } \dfrac{X_{imtw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{im}^{tw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{intw} = \begin{cases} \dfrac{X_{intw}}{Q_{tw}}, & \text{if } \dfrac{X_{intw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{intw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{istw} = \begin{cases} \dfrac{X_{istw}}{Q_{tw}}, & \text{if } \dfrac{X_{istw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{istw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{jktw} = \begin{cases} \dfrac{X_{jktw}}{Q_{tw}}, & \text{if } \dfrac{X_{jktw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{jktw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{jmtw} = \begin{cases} \dfrac{X_{jmtw}}{Q_{tw}}, & \text{if } \dfrac{X_{jmtw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{jmtw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{kmtw} = \begin{cases} \dfrac{X_{kmtw}}{Q_{tw}}, & \text{if } \dfrac{X_{kmtw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{kmtw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{mstw} = \begin{cases} \dfrac{X_{mstw}}{Q_{tw}}, & \text{if } \dfrac{X_{mstw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{mstw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases}$$

$$Z_{mntw} = \begin{cases} \dfrac{X_{mntw}}{Q_{tw}}, & \text{if } \dfrac{X_{mntw}}{Q_{tw}} \in Z; \\ \left[\dfrac{X_{mntw}}{Q_{tw}}\right] + 1, & \text{otherwise,} \end{cases} \quad (21)$$

The fifth set of constraints is used to calculate the unrecoverable part delivered to the incineration plants and landfill plants.

$$\sum_n \sum_t X_{intw} = \alpha_w XC_{iw}, \quad \forall i, w, \quad (22)$$

$$\sum_s \sum_t X_{istw} = \lambda_w XC_{iw}, \quad \forall i, w, \quad (23)$$

$$\sum_n \sum_t X_{mntw} = \eta_w XU_{mw}, \quad \forall m, w, \quad (24)$$

$$\sum_s \sum_t X_{mstw} = o_w XU_{mw}, \quad \forall m, w, \quad (25)$$

where α_w, λ_w, η_w, and o_w represent the rejection rates in the disassembling and the processing process of the WEEE, respectively, which are related to the type of equipment. It is worthy to be noted that the proportions appeared above are the detailed numbers coming from the producing process of the electronic equipment.

By (22), (23), (24), and (25), we can get the exact quantity of the WEEE which needs to be sent to the incineration plants and landfill plants from the collected centers or the processing centers.

The sixth set of constraints (26) is the available WEEE social stock constraints.

$$0 \le \sum_i XC_{iw} \le X_{max_w}, \quad \forall w. \quad (26)$$

From the sales of electrical and electronic equipment and their average working lives, the WEEE social stock can be predicted in a given region. Therefore, all the collected WEEE in each collection center can not excess this maximum quantity.

The last set of constraints is on non-negativeness. Clearly, for all i, j, k, m, n, s, t, w, it is necessary that

$$\begin{aligned} &PC_{iw}, X_{imtw}, X_{ijtw}, X_{iktw}, X_{istw}, X_{intw}, X_{jktw}, X_{jmtw}, \\ &X_{mntw}, X_{mstw}, X_{kmtw} \ge 0. \end{aligned} \quad (27)$$

With the above preparation, we can build the following nonlinear mixed integer programming model to formulate the management problem of recycling and processing the WEEE:

$$\begin{aligned} \max_{PC,X,Z} \quad & f = f_6 + f_7 - f_1 - f_2 - f_3 - f_4 - f_5 - f_8 \\ \text{s.t.} \quad & (2), (11), (12), (13), (14), (15), (16), \\ & (17), (18), (19), (20), (21), (22), (23), \\ & (24), (25), (26) \text{ and } (27). \end{aligned} \quad (28)$$

Note that the variables XC_{iw}, XU_{mw}, XI_{nw}, and XL_{sw} in the objective function can be substituted by the continuous decision variables PC_{iw} and $X_{..tw}$. For example, since XC_{iw} represents the recycled quantity of the w-th type of WEEE in the i-th collection center, which depends on the recycling price PC_{iw}, f_1 in the objective function can be reformulated as

$$\begin{aligned} f_1 = \sum_w \sum_i \Big(& \beta_{iw} (PC_{iw})^2 + (\mu_{iw} + \gamma_{iw}\beta_{iw}) PC_{iw} \\ & + \mu_{iw}\gamma_{iw} \Big). \end{aligned} \quad (29)$$

Similarly,

$$f_5 = \sum_m \sum_w NU_{mw} \left(X_{imtw} + X_{jmtw} + X_{kmtw} \right),$$

$$f_6 = \sum_w SU_w \sum_m \left(X_{imtw} + X_{jmtw} + X_{kmtw} \right),$$

$$f_7 = \sum_m \sum_w PS_{mw} \left(\sum_i \sum_j \sum_k \sum_t \left(X_{imtw} + X_{jmtw} + X_{kmtw} \right) - \sum_s \sum_t X_{mstw} - \sum_n \sum_t X_{mntw} \right),$$

$$f_8 = \sum_w \sum_n NI_{nw} \left(\sum_i \sum_m \sum_t (X_{intw} + X_{mntw}) \right),$$
$$+ \sum_w \sum_s NL_{sw} \left(\sum_i \sum_m \sum_t (X_{istw} + X_{mstw}) \right). \tag{30}$$

Consequently, the objective function reads

$$\begin{aligned} f(PC, X, Z) = &-\sum_a \sum_b \sum_t \sum_w Y_t Z_{abtw} \\ &+ \sum_a \sum_b \sum_t \sum_w \pi_{abtw} X_{abtw} \\ &- \sum_w \sum_i \beta_{iw} (PC_{iw})^2 \\ &- \sum_w \sum_i (\mu_{iw} + \gamma_{iw}\beta_{iw}) PC_{iw} - \zeta, \end{aligned} \tag{31}$$

where ζ and π are constants.

From (2) and (11), it follows that, for all i and w, PC_{iw} and $X_{\cdot\cdot tw}$ satisfy

$$\beta_{iw} PC_{iw} + \mu_{iw} = \sum_t \left(\sum_j X_{ijtw} + \sum_m X_{imtw} + \sum_k X_{iktw} + \sum_s X_{istw} + \sum_n X_{intw} \right). \tag{32}$$

Consequently, the constraints (21) can be rewritten into the following forms:

$$Q_{tw} (Z_{\cdot\cdot tw} - 1) \le X_{\cdot\cdot tw} \le Q_{tw} Z_{\cdot\cdot tw}, \tag{33}$$

where $Z_{\cdot\cdot tw} \in N$.

Remark 1. Compared with the existing models [8, 12, 15, 19, 24], our model (28) improves applicability of the WEEE recovery system by considering the following practical situations:

(i) An integrated system of recovery network is designed, where the recycle network consists of two types of nodes: internal and external ones. The collection centers, two types of transfer stations, and processing centers are the internal nodes inside the system, while the incineration plants, the landfill plants, the secondhand product markets, and government are regarded as the external environment of the system.

(ii) The recycled quantity of WEEE depends on recycling prices, rather than a given constant as assumed in the existing results. Actually, in many developing and developed countries, it can be seen that the recycling price seriously affects the quantity of recycled wastes.

(iii) Container transportation is an optional delivery mode, where both of the container leasing fee and the transportation cost are taken into consideration.

3. Development of an Efficient Algorithm

In this section, for the complicated mixed-integer nonlinear programming model (28), we attempt to design a branch and bound method to solve Model (28).

We first note that Model (28) is an optimization problem with a quadratic objective function and only linear constraints if the integer constraints are removed. Actually, if the integer constraints on $Z_{\cdot\cdot tw}$ are removed, then the relaxed model reads:

$$\begin{aligned} \min \quad & -f(PC_{iw}, X_{\cdot\cdot tw}, Z_{\cdot\cdot tw}) = \sum_\cdot \sum_\cdot \sum_t \sum_w Y_t Z_{\cdot\cdot tw} \\ & - \sum_\cdot \sum_\cdot \sum_t \sum_w \pi_{\cdot\cdot tw} X_{\cdot\cdot tw} + \sum_w \sum_i \beta_{iw} (PC_{iw})^2 \\ & + \sum_w \sum_i (\mu_{iw} + \gamma_{iw}\beta_{iw}) PC_{iw} + \zeta. \\ \text{s.t.} \quad & (11), (12), (13), (14), (15), (16), (17), \\ & (18), (19), (20), (22), (23), (24), (25), \\ & (26), (27), (32), (33), \\ & PC_{iw}, X_{\cdot\cdot tw}, Z_{\cdot\cdot tw} \in \mathbb{R}. \end{aligned} \tag{34}$$

The following results show the properties of Model (34).

Theorem 2. *The feasible region of Model (34) is a bounded set.*

Proof. To clarify the structure of the feasible region of Model (34), we show the relationship of all the variables by the constraints in Table 1. From Table 1, we can easily see the bounds of the variables X_{ijtw}, X_{imtw}, X_{iktw}, X_{istw}, X_{intw}, X_{jmtw}, and X_{kmtw}. Based on these known boundaries, we know the bounds of the variables X_{jktw} by the equalities (15). Similarly, by the constraints (24), (25), (32) and (33), we get the bounds of the variables X_{mstw}, X_{mntw}, PC_{iw}, and $Z_{\cdot\cdot tw}$, respectively. Consequently, the values of all the decision variables fall into a bounded set. The desired result has been proved. □

Theorem 3. *Model (34) is a convex quadratic programming problem.*

Table 1: Relationship of variables given by constraints.

	(15)	(16)	(17)	(18)	(19)	(20)	(21)/(33)	(22)	(23)	(24)	(25)	(32)
PC_{iw}												*
X_{ijtw}	*			√	√		*	*	*			*
X_{imtw}			√	√			*	*	*	*	*	*
X_{iktw}		*		√			*	*	*			*
X_{istw}				√			*	*	*			*
X_{intw}				√			*	*	*			*
X_{jktw}	*	*					*					
X_{jmtw}	*		√				*			*	*	
X_{kmtw}		*	√			√	*			*	*	
X_{mntw}							*			*		
X_{mstw}							*				*	
$Z_{\cdot\cdot tw}$							*					

∗ represents that the constraints give the relationship among these variables;
√ represents that the constraints give the bounds of these variables.

Proof. First, it is easy to see that the objective function in Model (34) is quadratic. Then, by direct calculation, we can get the (fixed) Hessian matrix of the objective function:

$$H=\begin{pmatrix}\begin{bmatrix}\beta_{11} & & \\ & \ddots & \\ & & \beta_{iw}\end{bmatrix} & & \\ & \ddots & \\ & & \begin{bmatrix}0 & & \\ & \ddots & \\ & & 0\end{bmatrix}\end{pmatrix} \tag{35}$$

Since any β_{iw} is nonnegative, the above Hessian matrix is semi-definite. Thus, Model (34) is a convex quadratic programming problem. □

According to Theorems 2 and 3, there exists a unique optimal solution in the feasible region of Model (34). This existence and uniqueness of solution can ensure construction of a binary search tree in the following branch and bound algorithm at each node of the tree.

Algorithm 4 (Branch and bound algorithm).

Step 0 (Initialization). Take an upper bound of solution: $UB=\infty$.

Step 1 (Node Selection). Construct a subproblem at the current node of the tree (at the root node, this subproblem is defined by Model (34)). If there exists no any solution for this subproblem, delete this node and return to its parent node in the generated tree. Otherwise, its optimal solution is referred to as $(\hat{x};\hat{y})$, where $\hat{x}=[\widehat{PC}_{iw};\widehat{X}_{\cdot\cdot tw};\widehat{Z}_{\cdot\cdot tw}]$ and $\hat{y}=-\hat{f}$.

Step 2 (Pruning). In the case that $\hat{y}>UB$, prune this branch generated by the current node since it can not contain better solution at any node along this branch. Otherwise, go to Step 3.

Step 3 (Branching). Check whether the elements of $\widehat{Z}_{\cdot\cdot tw}$ are integers or not. If $\widehat{Z}_{\cdot\cdot tw}$ has non-integer elements, denote $\widehat{Z}_{abtw}$ the first fraction, and generate its two children nodes by the following way: add the constraints $Z_{abtw}\le\lfloor\widehat{Z}_{abtw}\rfloor$ and $Z_{abtw}\ge\lfloor\widehat{Z}_{abtw}\rfloor+1$ to each child node, respectively. Otherwise, if $\widehat{Z}_{\cdot\cdot tw}$ satisfies the integer constraints and $\hat{y}\le UB$ holds, then update the upper bound $UB=\hat{y}$, record the current optimal solution $\hat{x}$. With the updated UB, prune the branch defined by the node whose value of the objective function is greater than UB. Go to Step 4.

Step 4 (Termination). Except for the pruned nodes, check whether all the other nodes of the binary tree are visited or not. If not, return to Step 1. Otherwise, the algorithm terminates. Output the current optimal solution.

Remark 5. Algorithm 4 applies the depth-first search strategy for the search tree. It terminates until traversing the branch and bound tree. Since the branching process in Step 3 is actually a procedure of partitioning feasible region by cutting a subset without any feasible integer solution, the optimal value of children nodes are obviously worse than or equal to the parent node. Consequently, the pruning scheme in Step 2, which is based on the updated upper bound UB, can greatly improve efficiency of the developed algorithm.

4. Case Study

In this section, we apply Model (28) and Algorithm 4 into the management problem of recycling WEEE in the central Hunan, China, in order to conduct case study and numerical analysis (see Figure 2). Our aim is to provide optimal recycling prices and an optimal delivery plan for this recovery network of WEEE such that the profit of recovery system is maximized. Model (28) is also applied into other WEEE recovery networks in the end of this section.

In this case study, "mixed WEEE" transportation is adopted (w=1), and in the recycling network of WEEE, there

Figure 2: Geographical positions.

Table 2: Transportation distance (kilometer).

Departure	Arrival							
	STS1	STS2	STS3	LTS1	PC1	IP1	IP2	LP1
CC1	31.2	120	217.2	126	145.2	31.5	41.7	54.3
CC2	16.9	100	196.8	92	129.6	23.4	37.2	49.2
CC3	103.2	20.4	202.8	100.8	134.4	25.2	38.4	50.7
CC4	146.4	72	214.8	123.6	133.2	30.9	34.2	53.7
CC5	62.4	31.2	159.6	56.4	75.6	14.1	27.9	39.9
CC6	134.4	135.6	112.8	52.8	57.6	13.2	5.0	28.2
CC7	80.4	81.6	96	14.4	74.4	3.6	12.9	24
CC8	147.6	151.2	162	80.4	145.2	20.1	31.5	40.5
CC9	148.8	148.8	93.6	99.6	170.4	24.9	27.9	23.4
CC10	183.6	182.4	28.8	104.4	180	26.1	28.8	7.2
CC11	223.2	220.8	33.6	145.2	220.8	36.3	41.1	8.4
CC12	117.6	176.4	40.8	99.6	175.2	24.9	26.7	10.2

are 12 representative regions to be chosen as the collection centers, 3 small-volume transfer stations, 1 large-volume transfer station, 2 incineration plants and 1 landfill plant. Figure 2 shows the distribution of sites, and Tables 2 and 4 give the transportation distances among the nodes of the network. Other data on the collection centers are listed in Table 3.

Taking into account the practical transportation situation, the vehicles departing from the collection centers are called "collection vehicles without container", which are suitable for short-distance and small-volume transportation. This transportation mode often needs higher transportation cost, but has no fee of leasing containers. In our case study, we assume that the unit transportation cost of this mode is CI=3.7 (RMB Yuan per ton per kilometer).

For the routes in the recycling network not departing from collection centers, two other transportation modes are adopted in the same routine in this paper. The first mode's unit transportation cost is CM_1=0.3 (RMB Yuan per ton per kilometer), where the container leasing fee is 100 RMB Yuan /shipment. The second mode's unit transportation cost is

Table 3: Other parameters in collection centers.

	CC1	CC2	CC3	CC4	CC5	CC6
XC_{max_i}	40	30	30	50	70	50
β_i	15	14	15	20	8	20
μ_i	10	13	0	20	8	12
	CC7	CC8	CC9	CC10	CC11	CC12
XC_{max_i}	30	20	60	40	80	40
β_i	16	6	20	9	14	22
μ_i	9	10	10	11	15	14

Table 4: Transportation distance (kilometer).

Departure	Arrival				
	LTS1	PC1	IP1	IP2	LP1
STS1	43.2	95.2	—	—	—
STS2	48	78.2	—	—	—
STS3	20	160	—	—	—
LTS1	0	58.8	—	—	—
PC1	—	0	10.8	90.8	16.2

Table 5: Unit processing cost (RMB Yuan) and capacities (ton).

	STS1	STS2	STS3	LTS1	PC1	IP1	IP2	LP1
Cost	8	15	12	15	60	10	7	5
CAP	50	100	50	200	3000	—	—	—

CM_2=0.2 (RMB Yuan per ton per kilometer), where the container leasing fee is 300 RMB Yuan /shipment. The two modes are both suitable for long-distance transportation, but the latter one is more suitable for large-volume transportation. Denote tc, tm_1 and tm_2 the above three modes, respectively. The maximum capacities of two types of containers are supposed to be Q^{tm_1}=50(tons) and Q^{tm_2}=100(tons), respectively.

In Table 5, we present the unit management or operation fee and the capacity of each node in the recycle network. The social stock of WEEE is assumed to be equal to the total capacity of all the collection centers (540 tons).

Only the processing centers can get government subsidy in accordance to the reused quantities of WEEE. The government subsidy is 50 RMB Yuan /ton. The unrecoverable rates in collection centers to incineration plant and to landfill plant are both 10%, while the unrecoverable rates in the processing centers are both 20%. The sale price of the reusable parts from the processed WEEE is 500 RMB Yuan /ton.

The value range of each integer variable is calculated by the collected quantity divided by the unit transported quantity. Thus, in this case study, each integer variable changes in the interval $[\ulcorner 540/100 \urcorner, \ulcorner 540/50 \urcorner]$.

Consequently, in all the numerical experiments, Model (28) is involved in 148 decision variables (20 integer variables), and 118 constraints (42 equality constraints and 76 inequality constraints). We implement Algorithm 4 to solve Model (28) on the Matlab platform. The consumed time is less than 1.30s. The optimal recycling prices and the optimal recycled quantities in the 12 collection centers are presented in Table 6.

Corresponding to the optimal solution, the maximal value of the objective function is 1.6889×10^4 RMB Yuan. It is easy to see that in the 12 collection centers, 5 of them attain the maximum capacity. For the other 7 collection centers, the collected quantities of 5 collection centers are equal to their ICQ (μ_i) values, respectively. That is to say, these 5 collection centers only collect the part of WEEE in the case that the recycling price is 0 (RMB Yuan).

At this optimal solution of the model, the total cost is 1.3492×10^5 RMB Yuan, where the transportation cost (including the container leasing cost) is 5.0810×10^4 RMB Yuan. That is to say, just the transportation cost accounts for 37.66%, a critical part of the total cost in the recycling network. Clearly, due to higher recycling cost in these regions, the relevant enterprises maybe reduce the recycled quantity of WEEE in order to maximize their profits. However, such a profit-driven countermeasure is not helpful to environmental protection. Therefore, it is necessary for the government to adopt appropriate measures such that the enterprises try their best to recycle the WEEE stocked in society as much as possible. From the numerical results in our case study, we know that the recycled quantity is 345(tons) and the residual of WEEE stock in society is 255(tons).

Note that higher cost of transportation may be caused by: (1) Long distance between the collection center and the processing center; (2) Higher unit transportation cost; (3) Few transfer stations near the collection center; (4) The capacities of transfer stations are not enough. In the next section, we are going to analyze the effects of government subsidies, transfer stations, transportation cost and awareness of the public's environmental protection on performance of the recycling system.

Before the end of this section, to further show the advantages of our Model (28) and Algorithm 4, we apply them into the management problem of recycling WEEE in the Region of Central Macedonia, Greece, studied in [19]. The relevant data and the choices of model parameters are same as in [19]. However, unlike the model in [19], we modify this model as a special case of Model (28). For example, we need to consider the recycling price, the new nodes of secondhand markets, landfill and incineration plants, and the subsides from government. Additionally, hybrid transportation mode is also adopted for this WEEE recovery network, smaller-volume containers is introduced with 1.5 times of the unit transportation cost and 0.5 times of leasing fee, compared with those of the larger-volume containers used in [19]. Then, we implement Algorithm 4 to solve the modified model. The obtained numerical results demonstrate that:

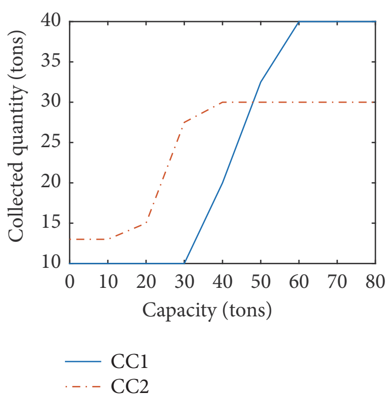
(1) Unlike the assumption in [19] that all the WEEE must be collected and processed, the WEEE collection rate given by our model is 93.44% with the maximal profit of 2.1784×10^6 (€). In [19], the minimal recovery cost is 1.11×10^6 (€).

(2) Owing to the hybrid transportation mode in our model, the proportion of the transportation cost in the total cost is 35.70%, far less than 63% in [19].

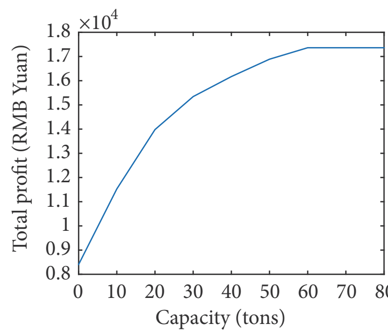
The results suggest that paid recovery and government subsidy can facilitate a satisfactory recovery rate, as well

Table 6: Optimal solution of model.

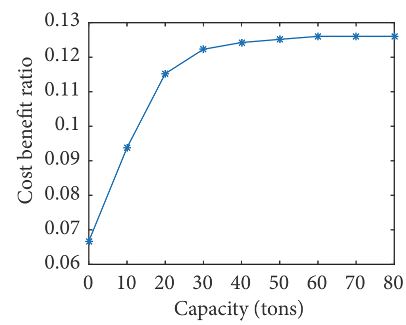
collecting centers	quantity (ton)	capacity (ton)	μ_i	recycling price(Yuan)
CC1	32.5000	40.0000	10.0000	1.5000
CC2	30.0000	30.0000	13.0000	1.2143
CC3	30.0000	30.0000	0.0000	2.0000
CC4	20.0000	50.0000	20.0000	0.0000
CC5	70.0000	70.0000	8.0000	7.7500
CC6	50.0000	50.0000	12.0000	1.9000
CC7	30.0000	30.0000	9.0000	1.3125
CC8	10.0000	20.0000	10.0000	0.0000
CC9	10.0000	60.0000	10.0000	0.0000
CC10	33.5000	40.0000	11.0000	2.5000
CC11	15.0000	80.0000	15.0000	0.0000
CC12	14.0000	40.0000	14.0000	0.0000



(a) Impact on collected quantity



(b) Impact on profit



(c) Suitable capacity of STS1

Figure 3: Impacts of capacity in transfer station STS1.

as being two appropriate incentive measures such that the households willingly, rather than compulsively, participate in the WEEE recovery. Hybrid transportation mode can reduce the total transportation cost and its proportion in the total recovery cost.

5. Sensitivity Analysis

In this section, by sensitivity analysis, we intend to investigate the impacts of model parameters on performance of the recovery system.

From the numerical results in Section 4, it is clear that the collected quantities in the collection centers 1,4,8,9,10,11, and 12 are quite less than their maximum capacities due to the high recycling costs. In other words, on the one hand, there is large overcapacity for the existent collection centers. On the other hand, a great number of WEEE in society has not been collected and then properly handled. Therefore, it is valuable to investigate efficient measures to improve the performance of WEEE recovery system. In this paper, we attempt to answer how the transfer stations, the government subsidy, the reduction of transportation cost and the public's environmental awareness improve this performance.

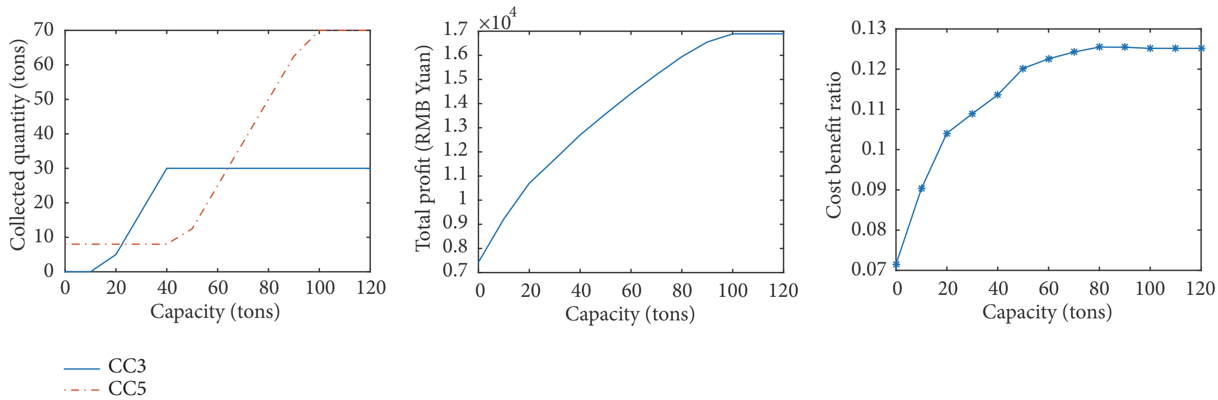
5.1. Effects of Transfer Stations. We first show that the transfer stations play an important role in improving the performance of the WEEE recovery system. For this, we change the capacity of the transfer stations to see how the optimal decision and the optimal recovered quantities of WEEE are affected.

As the capacity of STS1 changes from 0(not be established) to 80(tons), the total collected quantity also changes, and the change of capacity in STS1 only affects the collected quantities in the collection centers CC1 and CC2 (see Figure 3(a)).

Furthermore, from Figure 3, the following is revealed.

(1) From Figure 3(a), the collected quantity in the collection center CC2 increases from 13(tons) to 27.5(tons) as the capacity of STS1 changes from 0 (equivalent to be not established) to 30(tons). As the capacity of STS1 increases from 30(tons) to 60(tons), both collection centers CC1 and CC2 are all fully collected without any space left. It says that 60 (tons) is a better storage capacity for the transfer station STS1.

(2) From Figure 3(b), the profit of the recovery system increases continuously till the capacity of STS1 increases to 60(tons). From Figure 3(c), it is clear that in accordance



(a) Impact on collected quantity (b) Impact on profit (c) Suitable capacity of STS2

Figure 4: Impacts of capacity in transfer station STS2.

Table 7: Impacts of capacity of STS3 on transportation assignment.

	$CAP_{STS_3}=0$		$CAP_{STS_3}=10$		$CAP_{STS_3}=20$		$CAP_{STS_3}=30$	
	STS3	LTS1	STS3	LTS1	STS3	LTS1	STS3	LTS1
CC10	0	8.8	0	8.8	8	0.8	8.8	0
CC11	0	12	10	2	12	0	12	0
CC12	0	11.2	0	11.2	0	11.2	9.2	2

with larger capacity, for example, in the interval $[30, 60]$, there exists an optimal cost benefit ratio (0.1260) for the increasing capacities. Thus, considering from the view point of environmental protection and operational efficiency of the recovery network, the optimal capacity of STS1 is 60(tons).

(3) In virtue of the proposed model and algorithm in this paper, an optimal capacity of the transfer station can be computed to obtain a preferred profit or collected quantity.

Similarly, we can get the results on the other three transfer stations (see Figures 4, 5 and 6). Specifically, dilatation of STS2 generates a positive impact on the collected quantities of the collection centers CC3 and CC5. That of STS3 positively influences those of CC10, CC11 and CC12, and that of LTS1 positively affects those of the collection centers CC7 and CC10. The recycled quantity of each collection center and the profit change as indicated in Figures 4, 5 and 6.

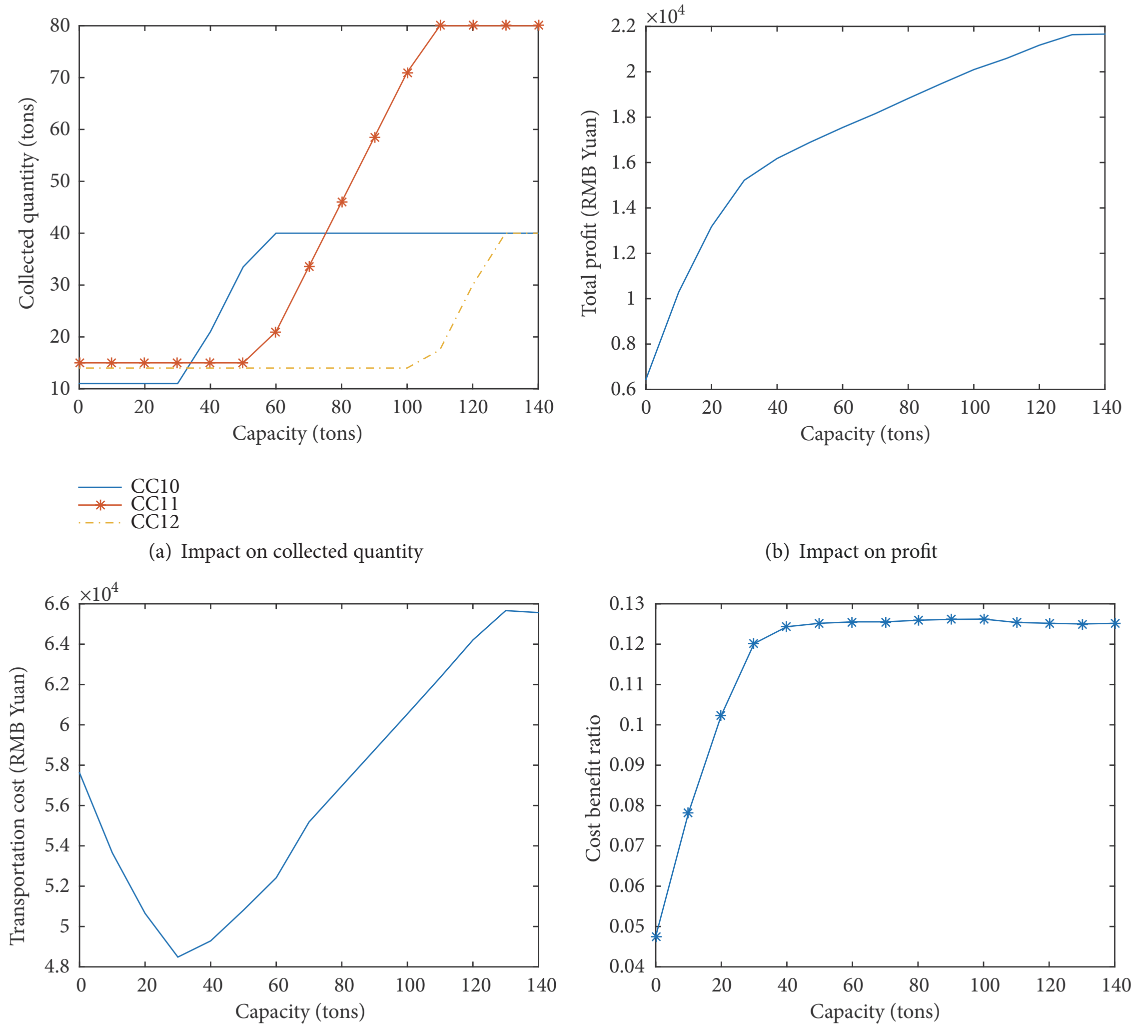
As seen from Figures 4(a) and 4(b), the collected quantity in the collection center CC3 increases from 0(ton) to 30(tons) as the capacity of STS2 changes from 0(equal to be not established) to 40(tons). As this capacity increases from 40(tons) to 100(tons), both of the collection centers CC3 and CC5 are all fully collected and the profit of recovery system increases continuously. However, just shown in Figure 4(c), there exists an optimal cost benefit ratio (0.1255) in the interval $[60, 90]$ for the increasing capacity of STS2, rather than at the largest capacity (100(tons)). Of course, from the view point of environmental protection, 100(tons) is the best capacity for the transfer station STS2 since a preferred profit is also obtained simultaneously.

From Table 7 and Figure 5, it follows that:

(1) From Figure 5(a), as the storage capacity of the transfer station STS3 rises from 0(ton) to 30(tons), the collected quantity of the network is not increasing, but the profit of the total network increases obviously by choosing an optimal transportation assignment. Actually, in Table 7, we list the transportation assignment of the collected quantities, the quantities transported from CC10, CC11 and CC12 to the transfer stations, respectively. From Table 7 and Figure 5(c), we know that the dilatation of STS3 from 0(ton) to 30(tons) generates the change of transportation assignment of the WEEE collected by the collection centers CC10, CC11 and CC12 such that more profit is obtained by reducing the transportation cost. Thus, the dilatation of STS3 is helpful to the increment of the recycled WEEE quantities, as well as optimization of transportation assignment.

(2) As the storage capacity of STS3 attains 130(tons), the recycled quantities of CC10, CC11 and CC12 reach their maximum capacities and we get a higher profit of the recovery system as 2.1635×10^4 RMB Yuan. However, from Figure 5(d), the optimal cost benefit ratio is obtained in the interval $[30, 50]$ with enlarging the capacity. Thus, it is not true that the more quantity to be collected, the higher cost benefit ratio is obtained. Taking into consideration the environmental protection, an optimal capacity of STS3 should be 130(tons). But there exists a capacity in the interval $[30, 50]$ which ensures the highest operational efficiency.

Figures 6(a) and 6(b) demonstrates that dilatation of LTS1 brings more recycled quantities and higher profits. At the beginning, the collected quantity of the collection center CC7 increases gradually up to its maximum capacity. Then, CC10 begins to increase its recycled quantity, but this quantity does not change at 33.5(tons), instead of reaching the maximum collection capacity of 40(tons). Recall that Figure 5 has shown that the recycled quantity of CC10 can reach to the maximum



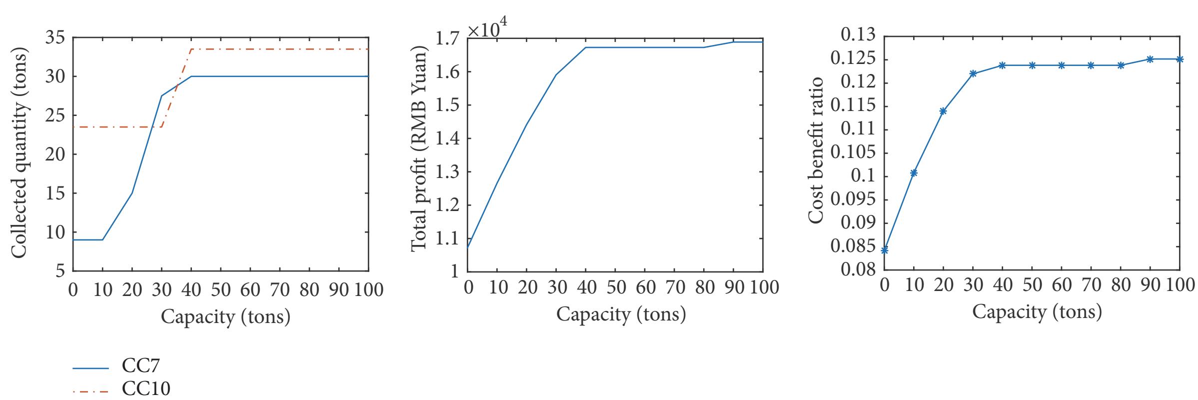
(a) Impact on collected quantity

(b) Impact on profit

(c) Impact on transportation cost

(d) Suitable capacity of STS3

Figure 5: Impacts of capacity of transfer station STS3.



(a) Impact on collected quantity

(b) Impact on profit

(c) Suitable capacity of LTS1

Figure 6: Impacts of capacity in transfer station LTS1.

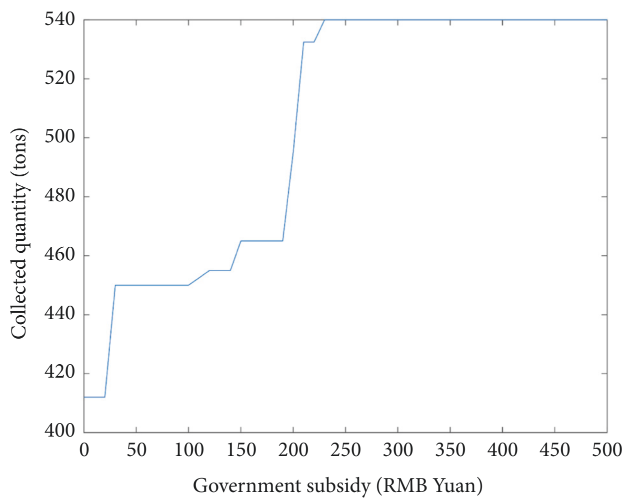


FIGURE 7: Impacts of government subsidy on the total collected quantity.

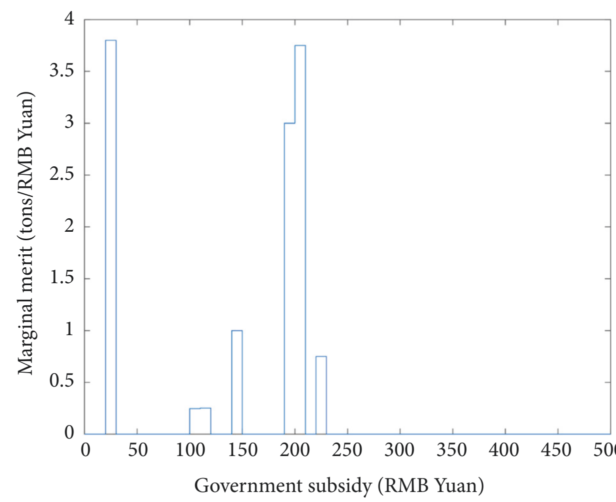


FIGURE 8: Impacts of government subsidy on the marginal merit.

capacity (40(tons)) by the dilatation of STS3. Therefore, although the collected quantity of CC10 is also affected by LTS1 (see Figure 6), its effect is less than that generated by STS3 (83.75% versus 100% of recycling rates).

When the storage capacity of LTS1 is larger than 40(tons), the collected quantity of the collection center CC7 reaches its maximum capacity, while CC10 only has a fixed collected quantity (33.5 tons less than its maximum capacity). However, as seen in Figure 6(c), 40(tons) is an optimal capacity of LST1 environmentally and economically.

The numerical results shown in Figures 3, 4, 5 and 6 suggest that the preferred recycled quantities of WEEE, the generous profits and the operational efficiency of the recovery network can be attained by choosing appropriate capacities of the transfer stations.

In conclusion, apart from improving profit of recovery, transfer stations play an important role in alleviating both overcapacity and insufficient recovery of WEEE.

5.2. Impacts from Government Subsidies. Owing to social and environmental benefits of recycling the WEEE, government subsidy may be a positive incentive to the recovery system. Interesting issues are to address what are the impacts of governmental subsidies on the collected WEEE quantity? How to search for an optimal subsidy to attain a preferred marginal merit of the recovery system? We next answer these questions by numerical analysis.

As studied in Section 5.1, it is seen that the collection centers CC1, CC10, CC11 and CC12 can reach their capacities by changing the capacities of the transfer stations, but the capacities of the other three collection centers (CC4, CC8, CC9) are still fully unused.

We now change the subsidy in Model (28) by step length increment of 10 (RMB Yuan) and implement Algorithm 4 to solve the corresponding models. Change of the total collected quantity is presented in Figure 7.

From Figure 7, it is clear that with the increment of subsidies, there are several jumps for the recycled quantities at some critical values of subsidy. For the government, larger subsidy investment undoubtedly attracts more capital into the industry of WEEE recovery. However, the subsidies generate greater financial burden for the government as well. We now attempt to find an optimal government subsidy by its marginal merit for recycling WEEE.

As the governmental subsidy increases, the marginal merit of subsidy increases at some critical points (see Figure 8). Specifically,

(1) As the subsidy is in the interval $[20, 30]$, we got the maximum marginal benefit of 3.8 tons/RMB Yuan. The desired subsidy is at least 30 RMB Yuan /ton, considering both the environmental effects and the government burden.

(2) From the view point of environmental protection, an optimal government subsidy should be 210 RMB Yuan /ton or so. Actually, if it is in $[190, 200]$, its marginal merit is 3.00 tons/RMB Yuan. If it is in $[200, 210]$, its marginal merit is up to 3.75 tons/RMB Yuan.

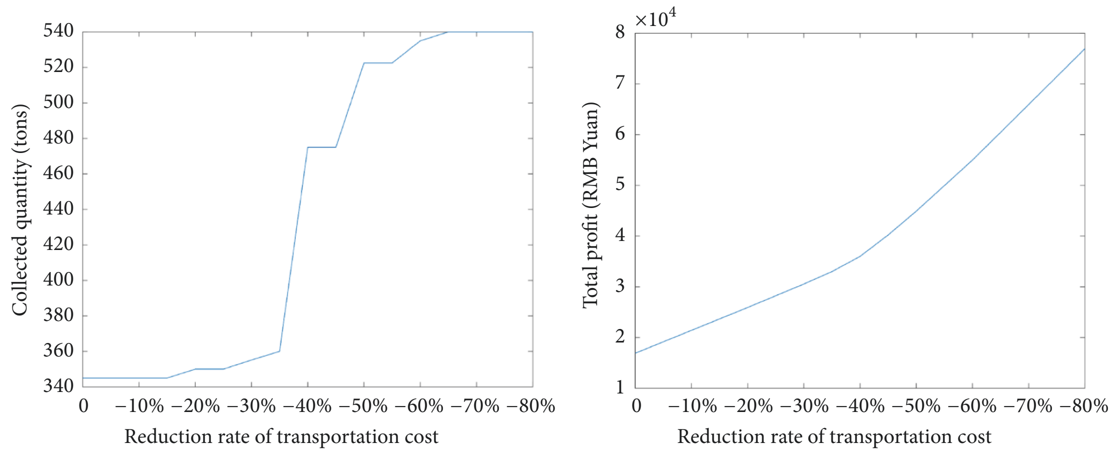
5.3. Impacts of Transportation Modes. To investigate the impacts of different transportation modes, we need the following setting on the transportation modes in recovery network:

Γ: The set of the routines not departing from collection centers, where two different transportation modes are permitted in the same routine.

Δ: The set of the routines departing from collection centers, where only one transportation mode is permitted in the same routine.

tm_1: A transportation mode with medium-size vehicles, which is suitable for long-distance and medium-volume delivery with higher unit delivery cost and lower unit leasing fee of containers on the routines in Γ.

tm_2: A transportation mode with large-size vehicles, which is suitable for long-distance and large-volume delivery



(a) Impact on collected quantity

(b) Impact on profit

Figure 9: Impacts of transportation cost CI.

with lower unit delivery cost and higher unit leasing fee of containers on the routines in Γ.

tc: A transportation mode with "collection vehicles without container", which is suitable for short-distance and small-volume delivery without leasing fee of containers on the routines in Δ. Its unit delivery cost is the highest among the three modes.

As done in the case study, the unit transportation costs for the three transportation modes tc, tm_1 and tm_2 are supposed to be $CI = 3.7$, $CM_1 = 0.3$, $CM_2 = 0.2$, respectively.

5.3.1. Impacts of Unit Transportation Cost CI. By sensitivity analysis, we first investigate what are the effects of cost reductions of CI on the profits and on the collected quantity of WEEE, and whether an appropriate choice among different transportation modes is a critical way to reduce the cost of the recovery system, or not?

We change the value of unit transfer cost coefficients CI in Model (28) by step length of -5% increment and implement BNB algorithm to solve (28). Based on the analysis of the numerical results, we find that the transportation cost greatly influences the optimal solution. Numerical results are presented in Figure 9.

Figure 9(a) indicates that when the cost reduction rate changes to 20%, the recycled WEEE quantity begins to rise from 345(tons) to 350(tons) and then reaches to the maximum recycling capacity quantity 540(tons) as this reduction rate is 65%. Thus, we get the threshold value of the unit transport cost CI in the interval [3.7×(1-0.65),3.7×(1-0.2)]. With this threshold, the collected quantity decreases companied with the increment of CI. We also note that existence of the integer variables makes the change of the optimal solution discontinuous.

From Figure 9, the following follows:

(i) In Figure 9(a), the decline in cost is also helpful to the growth of recycled quantity in the network. It suggests that reducing the transportation cost is an efficient strategy for increasing the total recycled quantity. In particular, we have summarized that subsidy can generate great financial burden for the government to reach the same result.

(ii) In Figure 9(b), the decline in cost brings profit growth. The profit growth rate contributed by transfer cost CI is increasing, in other words, as the CI's reduction rate increases, the marginal effect of transfer cost increases and tends to be stable.

(iii) Reducing transportation cost for recycling WEEE is the most useful way to increase the recycled quantity and get more profit. Thus, we suggest the policy makers try to minimize transportation cost which largely influences the optimal options. In other words, for recovering the WEEE, the unit transportation cost is a key effective factor and negotiating with a third party transportation company to reduce the unit transportation costs or improving the modes of transport, such as switching to energy-efficient vehicles, is the preferred way to increase the recycled quantity and profit.

5.3.2. Impacts of Unit Transportation Cost CM. We next study whether the choice among different transportation modes is a critical way to reduce the cost of the recovery system or not.

We compare the transportation costs in the routines of Γ and its proportion in the total recovery cost corresponding to three transportation modes: one hybrid mode (tm_1,tm_2) and two single modes (tm_1 or tm_2). We present the numerical results by solving Model (28) as the three different transportation modes are adopted.

From the results in Table 8, it follows that the hybrid transportation mode can reduce the total transportation cost in the routines of Γ, and its proportion in the total recovery cost is the lowest (4.25%), as well as the profit of recovery system is the highest among the three modes. It is concluded that the choice of different transportation modes plays a critical role in reducing the cost of the recovery system.

TABLE 8: Comparison among three transportation modes.

	Transportation cost in Γ	Total cost of recovery	Proportion	Profit of system
(tm_1,tm_2)	5.7285×10^3	1.3492×10^5	4.25%	1.6889×10^4
tm_1	7.0844×10^3	1.3505×10^5	5.20%	1.5521×10^4
tm_2	5.8563×10^3	1.3628×10^5	4.34%	1.6761×10^4

TABLE 9: Unit transportation cost and leasing fee.

	$Unit\ cost\ j \longrightarrow k$	$Unit\ cost\ k \longrightarrow l$	$Unit\ cost\ l \longrightarrow u$	$Unit\ cost\ k \longrightarrow p$	$Unit\ cost\ k \longrightarrow r$	$Unit\ cost\ k \longrightarrow s$	$Leasing\ fee$
o_1	0.4	0.2	0.5	0.5	0.5	0.5	0
t_1	0.4	0.2	0.5	0.5	0.5	0.5	50
t_2	0.3	0.1	0.35	0.35	0.35	0.35	100

TABLE 10: Comparison among different transportation modes.

Mode	Transportation cost	Total recovery cost	Proportion
(t_1,t_2)	1.0827×10^5	2.1977×10^6	4.93%
t_1	1.5703×10^5	2.2465×10^6	6.99%
t_2	1.0836×10^5	2.1980×10^6	4.93%

5.3.3. Improvement of Other Recovery Network. To show that the presented hybrid transportation mode in this paper can also reduce the total transportation cost of other recovery networks, we apply this mode into recovery network of end-of-life vehicles (ELV) studied in [31], where the case study was conducted for recycling the ELVs in Ankara, Turkey. However, in [31], only one transportation mode (o_1) is considered and the transportation cost depends on the distances and transported quantities, without any choice of transportation modes.

Inspired by the strategy of hybrid transportation mode, we now suppose that there are three different transportation modes available for the ELV recovery network in [31]: a hybrid mode (t_1,t_2), two single modes without or with leasing fee of containers, denoted by t_1 and t_2, respectively. The unit transportation costs and leasing fee for each mode are given in Table 9, referring to the setting in [31]. Then, we modify the proposed optimization model in [31] by incorporating the design variables of transportation modes into its objective function and the constraints, and solve the models corresponding to the different transportation modes by the GAMS-CPLEX, an popular solver of mix linear programming problems. Numerical results are reported in Table 10.

The results in Table 10 indicate that for the other recovery network, the hybrid transportation mode can also reduce the total transportation cost and its proportion in the total recovery cost. Actually, for the hybrid transportation mode, all of the transportation cost, the total cost of the recovery system and the proportion in the total cost are the lowest among the three modes.

5.4. Impacts of the Public's Environmental Awareness. We finally investigate what are the impacts of the public's awareness of environmental protection on the decision-making of the WEEE recovery system?

Since both of SCRP (β_{iw}) and ICQ (μ_{iw}) in (2) represent the status of the public's environmental awareness in managemental practice, we are now going to analyze their effects on the collected quantity, the total recycling cost and the total maximum profit.

We change the values of β_1 in Model (28) and observe the corresponding change of the collected quantities (for example, that in the collection center CC1). Numerical results are reported in Figure 10.

From Figure 10, it follows that:

(1) With an increasing value of β_1, the collected quantity of CC1 increases, and is up to its maximum capacity as $\beta_1 = 1.1$.

(2) Owing to existence of integer variables, the collected quantity may have great jumps at some points.

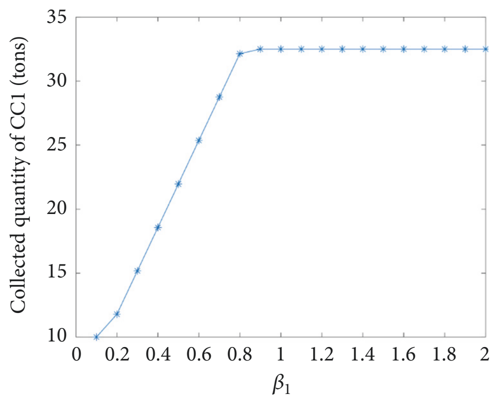
(3) Since larger value of SCRP (β_{iw}) implies stronger awareness of environmental protection, improving this awareness is helpful to an efficient system of recycling WEEE.

Next, we analyze impacts of another type of model parameters to describe the public's environmental awareness ICQ (μ_i). We consider two practical scenarios specified by smaller and larger $\mu_{iw}(w = 1)$, respectively. Actually, smaller μ_i implies lower awareness of environmental protection, and often occurs in undeveloped and developing regions, such as some undeveloped rural areas. In these areas, the public is more sensitive to the recycling price of WEEE.

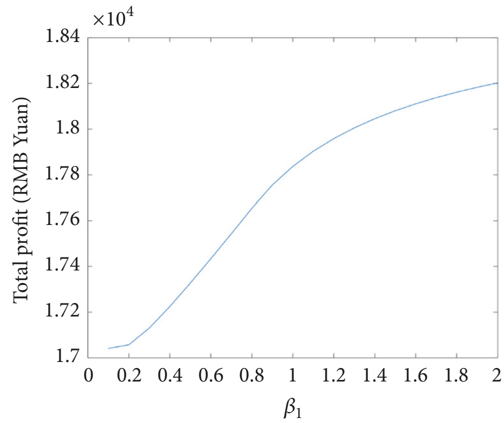
In Figure 11, we present the numerical results in the case that $\mu_3 = 0$ or $\mu_3 = 15$. For the lower ($\mu_3 = 0$) or higher ($\mu_3 = 15$) public's environmental awareness, we observe how the increment of the collected quantity of Collection center 3 changes for the different values of β_3.

From Figure 11, the following is clear:

(1) Increment of the collected quantity is more sensitive to the change of SCRP (β_3) at the beginning in the scenario with lower environmental awareness. In contrast, in the areas with larger value of inherent collected quantity (ICQ) μ_3, the public is not sensitive to the SCRP due to higher



(a) Impact on collected quantity



(b) Impact on profit

FIGURE 10: Impacts of SCRP β_1.

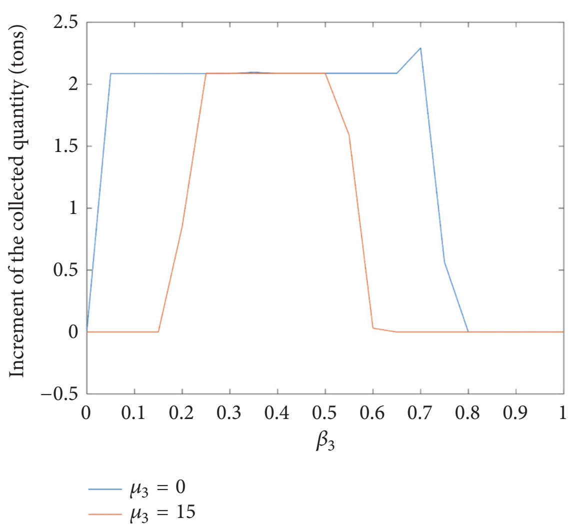


FIGURE 11: Impacts of SCRP (β_3) and ICQ (μ_3).

environmental awareness. Thus, the collected quantity does not increase until SCRP (β_3) increases to critical value.

(2) When the value of SCRP (β_3) increases to 0.8, the increment of the collected quantity decreases to 0 in the scenario with low inherent collected quantity (ICQ) ($\mu_3 = 0$). On the contrary, when the value of SCRP (β_3) increases to 0.65, the increment of the collected quantity decreases to 0 in the high ICQ scenario ($\mu_3 = 15$). Obviously, the threshold value of SCRP (β_3) in low ICQ scenario is more than that in higher ICQ case. Actually, the increment of the collected quantity decreases to 0 when the collection center gets to the maximum capacity. Thus, the collected quantity is easier to get to the maximum capacity in those regions with higher ICQ values.

In conclusion, we need to pay attentions at the differences caused by different awareness of environmental protection when we make an optimal decision in the management problems of recycling WEEE.

6. Conclusions and Directions of Future Research

We have proposed mixed integer nonlinear programming model for designing a WEEE recovery system with stronger applicability, where recycling prices and transportation modes are regarded as its endogenous variables, and the roles of government subsidy, transfer stations and environmental protection awareness in optimizing WEEE recovery system are studied. An efficient branch and bound algorithm has been developed to solve the built model. By numerical experiments and sensitivity analysis, a number of valuable managemental implications have been revealed from the proposed optimization model. In summary,

(i) Transfer stations play an important role in improving the performance of the WEEE recovery system by eliminating both overcapacity and insufficient recovery of WEEE, as well as increasing profit. Appropriate capacities of transfer stations can be provided by the proposed model in this paper in order to design an environmentally and economically efficient system of recycling WEEE.

(ii) For the WEEE recovery system, suitable governmental subsidies can be computed by marginal merit analysis. As the subsidy increases, the collected quantities become larger for a part of collection centers. From application of the proposed model, it follows that an optimal subsidy can be obtained (at least 30 RMB Yuan /ton in our case study) when both the environmental effects and the government burden are considered. If only the environmental protection is considered, another optimal government subsidy can be provided by our model for the WEEE recovery system (210 RMB Yuan /ton or so in our case study).

(iii) For recycling WEEE, reducing transportation cost is the most useful way to increase the recycled quantity and get more profit. Thus, introduction of a third party logistics may be a more efficient mean to improve the performance of recycle system of WEEE.

(iv) Improving the transportation modes, such as switching to energy-efficient vehicles, is the preferred way to increase the profit and the recycled quantities of WEEE. The choice among different transportation modes is a critical way to reduce the cost of the recovery system.

(v) The public's awareness of environmental protection seriously affects performance of the WEEE recovery system. Preferred environmental protection awareness can increase the profit and the recycled quantities of the recovery network, as well as reducing the recovery costs. Therefore, we should pay great attention to the improvement of the environmental protection awareness for seeking to scientific management of recycling WEEE.

In the future research, our results can be modified in the following aspects:

(i) The recovery network can be modified such that it satisfies the practical situation in different regions.

(ii) For a long plan, location of different recycling nodes are important to improve the performance of the recycling network. Thus, it is significant to develop an integrated model which is involved in all of location, production and transportation.

(iii) For the large scale optimization model, a more efficient algorithm needs to be further investigated.

(iv) As shown in this paper, the public's awareness of environmental protection seriously affects the decision making for recycling WEEE. Thus, it is an interesting issue to address how the government countermeasures, such as propaganda guide, funds and policy support, affect the environmental protection awareness such that the performance of WEEE recovery system is improved.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that all the authors have no conflicts of interest about submission and publication of this paper.

Authors' Contributions

Zhong Wan conceived and designed the research plan and wrote the paper; Yanan Bo and Yanqi Wang performed the mathematical modelling and numerical analysis and wrote the paper. Yanan Bo and Yanqi Wang equally contributed to this research.

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