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Study on the Recycling and Treatment of WEEE in China

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ABSTRACT

This paper investigates the regulations, recycling and treatment of WEEE (waste electrical and electronic equipment) in China. An online survey about Chinese households' treatment of WEEE is conducted. Optimization models are used to compare the performances of WEEE treatment in two different recycling networks. In the first network, WEEE is collected and sent by recycling stations to licensed WEEE recycling and treatment centers for testing and dismantling. In the second network, WEEE are tested and dismantled at small recycling workshops in residential districts, and then parts/components that require further processing are sent to licensed WEEE recycling and treatment centers. The performances of the two networks are analyzed with linear programming models. The results indicate that the second model is more effective with lower cost and higher recycling efficiency.

Keywords: WEEE; Recycling Network; China; Cost

1. Introduction

China is one of the biggest electric and electronic equipment (EEE) manufacturing countries and markets. Large volumes of electric and electronic equipment are produced and used in China. Consequently a large amount of Waste Electrical and Electronic Equipment (WEEE) is generated. However, the current recycling and treatment situation for WEEE in China has created many problems.

WEEE contains highly toxic materials, such as toxic metals, acids, plastic and plastic additives. With these hazardous elements, WEEE causes serious pollution if it is not properly disposed and treated. On the other hand, WEEE contains many precious metals and reusable materials, so it is called "Super Goldmine" if it is recycled properly. Nowadays recycling WEEE becomes a booming business in China. Unfortunately, most recycling work is done in small-scale unlicensed recycling workshops, where WEEE is disassembled manually and recycled with simplistic methods, such as directly burning WEEE and roughly extracting metals from WEEE with acid. This kind of recycling operation incurs low cost but has harmful impacts on the environment and the health of workers. On the contrary, the operation cost of licensed recycling firms is very high since they use advanced recycling technologies and proper method to protect workers and the environment. Thus licensed firms do not have much advantage over unlicensed workshops in terms of competition. According to a statistics report, there are more than 1500 unlicensed workshops and only 200 licensed WEEE recycling firms in China, and the former run a more profitable business than the latter. To improve the recycling and treatment of WEEE in China, the problems of existing recycling networks are investigated. A new system is proposed to recycle and treat WEEE for better regulations and management. The paper is organized as follows. Section 2 reviews relevant literature. In Section 3, an online survey about Chinese households' treatment of WEEE is conducted. Section 4 presents optimization models to analyze two different recycling and treatment networks. The recycling and treatment of TV sets are used as an example to compare the performances of the two networks. Section 5 concludes the findings of the research.

2. Literature Review

The environmental impact of WEEE has drawn attention of many scholars. Wäger *et al.* [1] presented the results of a combined material flow analysis and life cycle assessment study of Swiss WEEE. Lin *et al.* [2] implemented the Analytic Hierarchy Process using the information that formed an incomplete hierarchical structure to determine the priority for WEEE recycling in Taipei. Davis and Herat [3] conducted and analyzed a survey of local councils in Australia to determine the current level of understanding and action on e-waste.

A number of researchers studied the recycling and treatment of WEEE in China [4-8]. Yang *et al.* [9] identified the sources and generation of WEEE in China and recommended increasing the recycling capacity with rising quantity of WEEE. Streicher-Porte and Yang [10] analyzed the costs of collection and transport for five products, including TV sets, refrigerators, washing machines, air conditioners and personal computers, of both formal and informal recycling industries. He *et al.* [11] presented the status of WEEE and its corresponding responses adopted in 2006 in China. Chi *et al.* [12] pointed out that the key issue for China's e-waste management is how to set up incentives for informal recyclers so as to reduce improper recycling activities and divert more e-waste to the formal recycling sector.

The study on the disposal of municipal solid wastes provides good reference for dealing with WEEE. Li and Huang [13] provided an interval-based stochastic programming method for planning the municipal solid waste management with minimal system cost and environmental impact under uncertainty. Costi *et al.* [14] presented the structure and application of a decision support system designed to help decision makers of a municipality in development of incineration, disposal, treatment and recycling integrated programs. Puig-Ventosa [15] studied the charging systems and pay-as-you-throw experiences for municipal waste management in Spain.

This paper addresses the cost-saving principle and the effective recycling system and reviews the relevant papers. Chang and Chang [16] explored a new idea that an operational program in a solid waste management system should be based on not only the cost-saving principle but also the energy and material recycling requirements. Li and Zhang [17] built a cost-effective recycling model about the reverse logistic process of personal computers. Silveira *et al.* [18] proposed a deposit/refund advance-recycling fee institution which can be implemented as a voluntary industrial initiative. In this study, a new recycling and treatment network is presented based on the cost-saving principle which considers the reality and customer habits of China. This type of network has not been mentioned in past literature.

3. Situation of Recycling and Treatment of WEEE in China

The WEEE in China mainly consists of household e-products, office e-products used by enterprises and public institutions, and e-products generated in industrial production [19]. In addition, there is WEEE illegally imported to China.

The recycling of WEEE in China takes two primary ways, namely door-to-door recycling by private collection peddlers, and recycling by retailers. Peddlers often sell WEEE to unlicensed workshops which repair and upgrade the equipment and sell the usable parts to rural areas or secondary e-product markets. For unusable equipment, they extract reusable metal or material from WEEE by simplistic methods (e.g. burning, extracting metals with acids). These simplistic operations cause high safety risk and pollute the environment.

To deal with the problems, the Chinese government has introduced a set of E-waste management methods. The old-for-new policy on home appliances has been effective in 27 provinces and municipalities of China since 2009. This policy has achieved remarkable success. According to the Commerce Department statistics, 62.113 million sets had already been collected by July 28, 2011. Four pilot projects were launched to gain institutional and technical experiences in regulation preparation and recycling network design [12]. Some licensed recycling firms have been built to improve WEEE processing technology and reduce environmental pollution. However, according to the survey, these licensed recycling and treatment firms collect WEEE far lower than their design capacity allows. Due to the high cost of WEEE processing facilities and the complex processing procedure, these firms make very low profits or even losses. The recycling behavior of consumers is one of the important reasons for this situation.

Thus, an online survey was conducted to investigate the recycling behavior of consumers in China. The questionnaire contained 23 questions, entitled "Disposal of Home Appliances (WHA) by Consumers". The survey randomly selected consumers in China and 104 completed questionnaires were collected.

Every family has a variety of home appliances. **Figure 1** shows the numbers of obsolete home appliances. TV sets and washing machines are two widely used domestic electrical appliances in China. When the respondents were asked what home appliances they had discarded, 68.32% said they generally sold their TV sets because most of them were made in the 1980s and were replaced after 2000. Thus, in the following section TV sets will be used as an example for analysis. It is expected that home appliances such as air conditioners and refrigerators will be replaced soon with the economic development and the improvement in the living standard of China. All this will further exacerbate the WEEE problem.

When asked about how to dispose unwanted home ap-

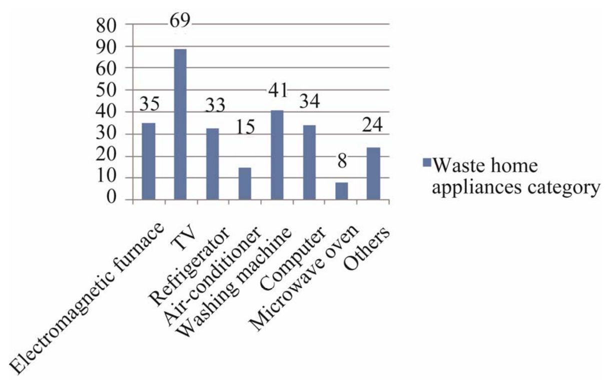

Figure 1. Waste home appliances category.

pliances, 59.6% of the respondents said that they sold them to private collection peddlers, 28.8% just left them at home, 9.7% gave them to their friends, and only 1.9% sent them to government recycling stations (**Figure 2**). Obviously collection peddlers are more popular since they are more convenient to the customers and operate at lower costs. The recycling efficiency can be improved if the recycling system consists of these collection peddlers. However, most private collection peddlers sell WEEE to unlicensed recycling workshops since they offer higher prices. It is obvious that a large number of obsolete e-products go to unlicensed workshops, which triggers the problem of WEEE collection.

When the respondents were asked who should pay the recycling cost of e-products, 62% agreed that producers and distributors should pay the recycling cost, and 38% replied that recycling peddlers should pay. Most consumers thought that manufacturers, recycling peddlers and the government should pay the disposal costs since they are the main beneficiaries of e-products. In fact, consumers are users of the e-products and also beneficiaries. They should also pay part of the recycling cost.

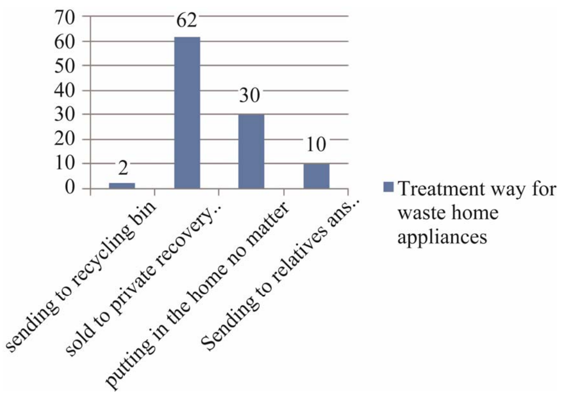

Figure 2. Treatment way for waste home appliances.

When the respondents were asked whether consumers supported the program of building a large WEEE treatment center in their cities, 85% were in favor of and 15% against. Most consumers recognize that WEEE is harmful to the environment. However, some think that the WEEE treatment center will pollute their living environment.

When the respondents were questioned why they did not sell WEEE to licensed recycling firms, 67% replied that the recycling price offered by licensed firms was low and 33% replied that the recycling channel was not clear. In most cities, there are a variety of recycling channels, such as door-to-door recycling by peddlers, "old-for-new change" in big electronic shopping malls, and home appliances recycling in the second-hand market. Among the recycling channels, recycling prices vary greatly. Therefore, it is imperative to set up a unified WEEE collection system in China.

4. Analysis of WEEE Recycling and Treatment Network

There are two existing WEEE recycling and treatment networks in China. One is a formal network, and the other is informal. The existing WEEE networks are shown in **Figures 3** and **4**. In the formal network (**Figure 3**), WEEE is collected by licensed recycling stations set up by the government and sent to licensed recycling and treatment firms for dismantling and recycling. The processing entails fuel cost, labor cost, management cost, disposal cost, etc. The cost is high due to the technology required and safety and environmental regulations. In the informal network (**Figure 4**), WEEE is collected by recycling vendor and then sent to unlicensed recycling workshops for dismantling and recycling. Theses workshops do not use expensive technology and proper equipment, and thus their processing cost is low. Due to

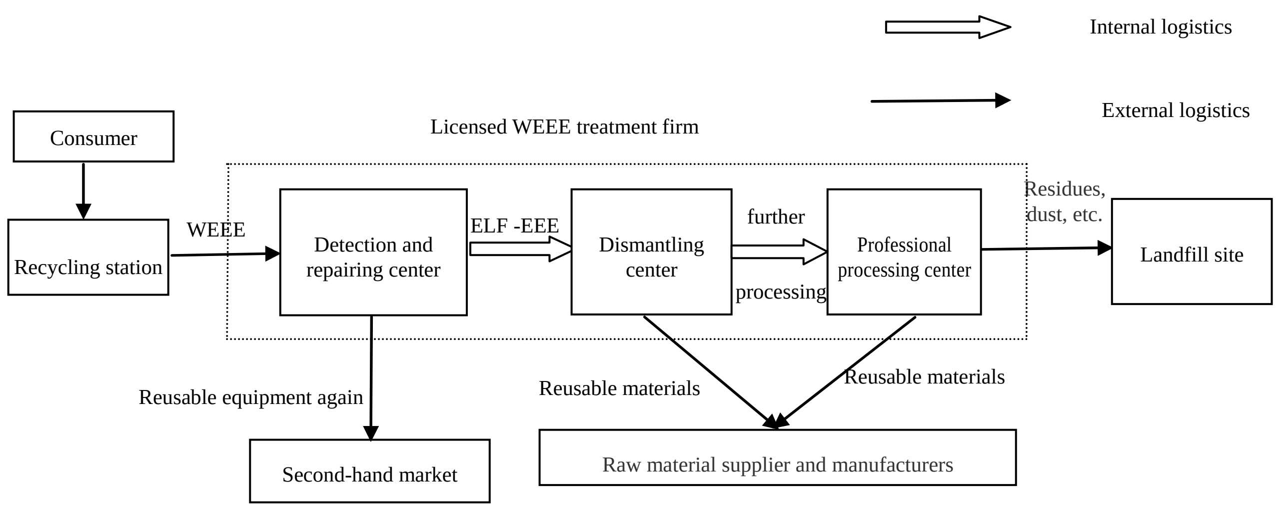

Figure 3. Formal WEEE recycling and treatment network.

the low cost, they can offer much higher purchase prices for used equipment than formal collection stations and most of the used equipment is sold to unlicensed firms. However, the simplistic methods and inappropriate processing cause serious pollution problems. At the same time, since most of the WEEE goes to the informal network, licensed recycling firms do not have enough business to cover the high investment cost of facilities and equipment.

In order to reduce pollution and increase the recycling volume of licensed recycling firms, we propose a new network, which uses the convenient collection system of recycling peddlers, and the neatly dismantling skills in unlicensed dismantling workshops to reduce the operation cost. The new network allows small dismantling workshops to disassemble WEEE. We suggested that parts or components that need further processing will be sent to professional treatment firms. The new network is shown in **Figure 5**. In the next section, the existing network will be compared with the proposed network by mathematical models.

4.1. Model for the Existing Formal Network

In the existing formal network, recycling stations deliver WEEE to licensed recycling firms which consist of a detection and repairing center, a professional dismantling center, and a further processing center. Before presenting our model, the following notations are defined:

h: the index of WEEE recycling station, $h = 1, \cdots, H$.

c: the index of a WEEE recycling firm, $c = 1, \cdots, C$.

u: the index of a WEEE landfill, $u = 1, \cdots, U$.

i: the index of a home appliance, $i = 1, \cdots, I$.

j: the index of a material derived from WEEE, $j = 1, \cdots, J$.

s: the index of a component containing harmful material, $s = 1, \cdots, S$.

k: the index of processing equipment, $k = 1, \cdots, K$.

D_{hc}: the distance between h and c (km).

D'_{cu} : the distance between c and u (km).

U_{hc}: the unit transportation cost for delivering WEEE from h to c (¥/ton·km).

U'_{cu} : the unit transportation cost of discarded refuse from c to u (¥/ton·km).

c_i: the unit recycling cost of WEEE i (¥/unit).

c'_i : the unit detection cost of WEEE i (¥/unit).

c''_{is} : the unit processing cost of component s containing harmful material in WEEE i (the average fee of breaking, magnetic desperation, etc) (¥/ton).

J_i: the unit manual dismantling cost for WEEE i (¥/unit).

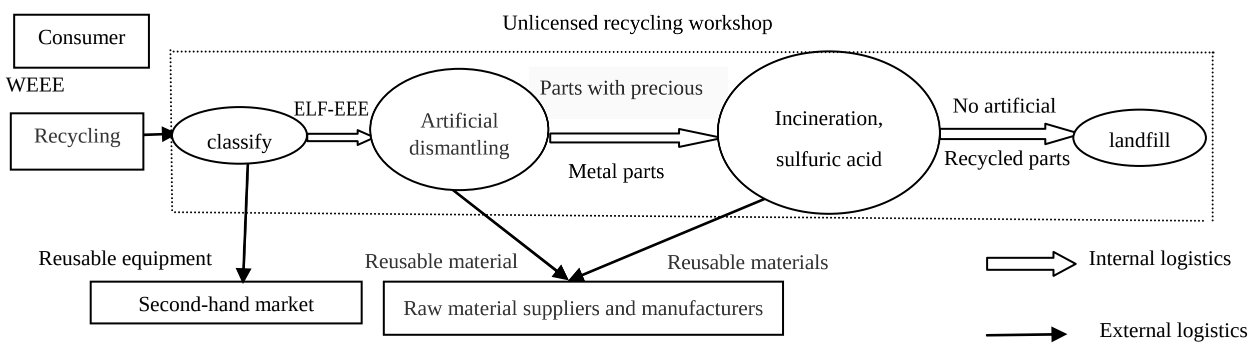

Figure 4. Informal WEEE recycling and treatment network.

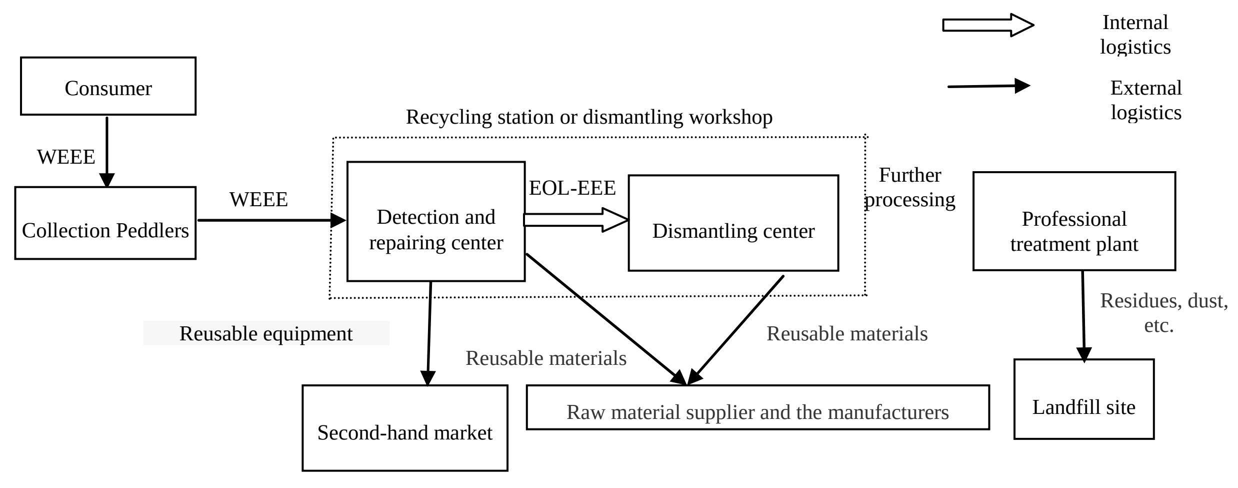

Figure 5. New recycling and treatment network.

w_i: the average weight of WEEE i (kg).

Y_j: the unit sale price for material j (¥/ton).

$W^{''}_{hc}$: the total weight of WEEE sent to c from h (ton).

T_u: the unit landfill price for discarded refuse at landfill site u (¥/ton).

Y_i: the unit sale price for WEEE i repaired that can be used again (¥/unit).

β_{ij}: the percentage of recycled material j derived from WEEE i.

z_{is}: the percentage of component s containing harmful material in WEEE i.

M_c: the maximum capacity of WEEE recycling firm c (ton) per year.

$M^{'}_u$: the maximum capacity of landfill site u (ton) per year.

Q_{hi}: the total quantity of WEEE i recycled at recycling station h (unit).

N_c: the number of workers who operate the equipment at recycling firm c.

P_c: the annual salary of a worker who operates the equipment at recycling firm c.

ε_c: the percentage of harmful material to be land filled at recycling firm c.

u_{ci}: the upper bound of α_{ci}, $0 < u_{ci} < 1$.

d_{ci}: the lower bound of α_{ci}, $0 < d_{ci} < u_{ci} < 1$.

There are four decision variables for the problem:

W_{hci}: the total weight of WEEE I sent to c from h.

$W^{'}_{cu}$: the total weight of discarded refuse sent to u from c.

S_{hci}: the quantity of WEEE i sent to c from h.

α_{ci}: the percentage of WEEE i that can be used again at recycling firm c.

F_{ck}: the consumption cost of equipment k at recycling firm c.

The following values are calculated and used in the objective function:

- The total income of the recycling firm:

$$E = \sum_c \left(E_{c1} + E_{c2} \right)$$

where E_{c1} is the total income gained from second-hand home appliances sales at recycling firm c:

$$E_{c1} = \sum_h \sum_i S_{hci} \alpha_i Y_i \ .$$

E_{c2} is the total income gained from recyclable materials sales at recycling firm c:

$$E_{c2} = \sum_h \sum_i \sum_j w_i S_{hci} \left(1 - \alpha_i \right) \beta_{ij} Y_j \ .$$

- The total transportation cost :$T = T_1 + T_2$, where T_1 is the total transportation cost from h to c:

$$T_1 = \sum_h \sum_c \sum_i W_{hci} D_{hc} U_{hc} \ .$$

T_2 is the total transportation cost from c to u:

$$T_2 = \sum_c \sum_u W^{'}_{cu} D^{'}_{cu} U^{'}_{cu} \ .$$

- The total operation cost of all the recycling firms:

$$O = \sum_c \left(O_{c1} + O_{c2} + O_{c3} + O_{c4} + O_{c5} \right),$$

where O_{c1} is the operation cost of the detection center at recycling firm c (including recycling fee and detection fee):

$$O_{c1} = \sum_h \sum_i S_{hci} \left(c_i + c^{'}_i \right).$$

O_{c2} is the operation cost of the dismantling center at recycling firm c:

$$O_{c2} = \sum_h \sum_i S_{hci} \left(1 - \alpha_i \right) J_i \ .$$

O_{c3} is the operation cost of the professional treatment center at recycling firm c:

$$O_{c3} = \sum_h \sum_i \sum_s S_{hci} w_i \left(1 - \alpha_i \right) c^{''}_{is} z_{is} \ .$$

O_{c4} is landfill cost paid by recycling firm c:

$$O_{c4} = \sum_u W^{'}_{cu} T_u \ .$$

O_{c5} is the total salary for all the workers who operate the equipment at recycling firm c: $O_{c5} = N_c P_c$.

- The total fixed cost of all the recycling firms:

$$F = \sum_c \sum_k F_{ck} \ .$$

The objective function is to maximize the profit, which equals the total income, after subtracting the total transportation cost, the total operation cost and the total fixed cost.

Problem (4.1)

$$\text{Max } E - T - O - F$$

Subject to:

$$\sum_h \sum_i S_{hci} w_i \le M_c, \forall i, c, h \quad (1)$$

$$\sum_c W^{'}_{cu} \le M^{'}_u, \forall c, u \quad (2)$$

$$\sum_u W^{'}_{cu} = \varepsilon_c \sum_h W^{''}_{hc}, \forall c, u, h \quad (3)$$

$$\sum_c S_{hci} = Q_{hi}, \forall c, h, i \quad (4)$$

$$d_{ci} \le \alpha_{ci} \le u_{ci}, \forall c, i \quad (5)$$

Equivalent conversion

$$\left. \begin{array}{c} W^{''}_{hc} = \sum_i W_{hci}, W_{hci} = S_{hci} w_i \\ Q_{hi}, W^{''}_{hc}, M^{'}_u, W^{'}_{cu}, M_c, w_i, S_{hci} \ge 0, \\ \forall c, u, h, i \end{array} \right\} \quad (6)$$

The objective function is to maximize the profits of the recycling firm. Constraint (1) shows that the total amount accepted by the recycling firm should be less than or equal to the maximum allowable operating capacity of the recycling firm. Constraint (2) fixes the maximum capacity for the landfill site. Constraint (3) requires that all wastes produced are correctly disposed. Constraint (4) is a balance equation: all recycled WEEE has to be finally detected and disposed in recycling firms. Constraint (5) fixes the range of WEEE that can be used again. All the decision variables are required to be non-negative in Equation (6).

4.2. Case Study

In order to simplify the model, the following assumptions are made:

- Unit operating cost in the model is the average value of fuel cost, power cost, labor force cost, water and electricity cost, etc.
- Two formal WEEE recycling firms, five recycling stations and two landfill sites are chosen in Shanghai's Pudong New Area. Due to the different distances between the recycling firms and the landfill sites and the different transport ways, the corresponding unit freight among them is different.
- According to the investigation, the recycling rate n is more than 95% of the total recycling volume in the recycling firm, it is assumed that there is always 5% of the total weight to be land filled, namely, $\varepsilon_c = 0.05$.
- The detection, dismantling, processing costs are the same for the two recycling firms, and the scrap rates of the two processing factories are also constant. The data are obtained from China Economic Herald (2011) and the internet.
- The WEEE recycling volume is proportional to the number of consumers. Along with implementation of the "old-for-new" policy, the recycling amount in Pudong New Area is about 163,000 sets, 80% of which are TVs (130,000 sets). The recycling and treatment of TV sets is used as an example.

The average unit recycling price of an obsolete TV is about ¥ 60. If a TV is repaired properly, which can still be used for some time, it can be sold for ¥ 90. The unit artificial dismantling cost for an EOL-TV is ¥ 10. The average weight of a TV set is about 30 kg, (50% glass, about 16% metal and 20% plastic) with harmful material accounting for about 0.4%. Two components with harmful substances in a TV set are the CRT tube and the circuit board, whose unit further processing fees are ¥120 /ton and ¥100/ton, respectively. The maximum treatment capacities of the two recycling firms are 3500 ton and 3000 ton, respectively. There are 70 workers operating the equipment at the two recycling firms and the per capita annual salary is about ¥ 20,000. The maximum landfill volumes of the two landfill sites are 100 ton and 110 ton per year, respectively. The other relevant data is listed in the Appendix.

The LINGO software is used to solve the above linear programming problem. The total profit of the two recycling firms is ¥5,664,162, where E = ¥16,770,000, T = ¥394222.5, O = ¥10,043,616. The price of a piece of PCB recycling treatment equipment is about ¥2.1 million and the price of other equipment is about ¥716,000. Therefore, ¥5.632 million is needed for the treatment equipment of EOL-TVs at the two recycling firms. Hence, the total profit obtained from processing TVs can only make up the equipment cost. The break-even point is 33,730 sets. According to the budget, a bigger recycling amount can generate bigger revenue as shown in **Figure 6**, which show the total profit is increasing due to the rising of recovery amount.

4.3. The Model for the New Network

In the existing formal network, the actual recycling volume of WEEE in the licensed recycling center is far lower than the break-even point. Thus, the operation cannot optimize the utility of resources. To solve the problem, a new network (**Figure 5**) is suggested. Its main difference from the existing formal network is that WEEE is first sent to a small dismantling workshop for dismantling and recycling, and only components with harmful materials are sent to professional treatment firms. This network uses the convenient collection network provided by recycling peddlers and the cheap operation cost of small dismantling workshops. As a result, the operation cost is reduced without causing pollution to the environment.

Some notations are added to the new model:

L_s: the unit treatment fee of component s at the recycling firm (¥/ton).

S_{hi}: the amount of WEEE i recycled at recycling station h.

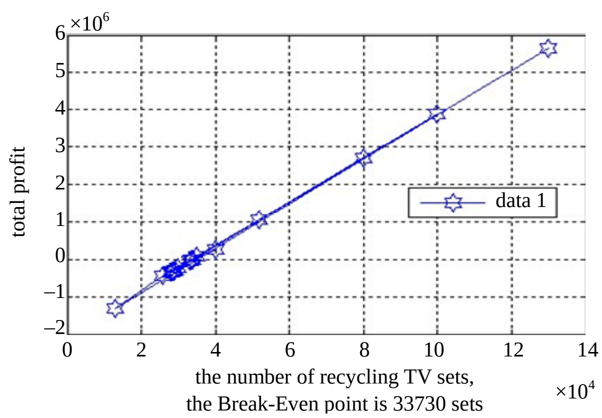

Figure 6. Total profit changing chart with the increasing recovery amount.

B_{is}: the percentage of component s requiring further processing in WEEE i.

z_{sj}: the percentage of material j derived from component s in component s.

u_{hi}: the upper bound of α_{hi}, $0 < u_{hi} < 1$.

d_{hi}: the lower bound of α_{hi}, $0 < du_{hi} < u_{hi} < 1$.

M''_{hi}: the total weight of WEEE i at recycling station/dismantling workshop h.

F_{ck}: the annual consumption cost of equipment k at recycling firm c.

Four direct decision variables are defined for the problem:

W_{hcs}: the total weight of component s sent to c from h.

α_{hi}: the percentage of WEEE i that can be used again at dismantling workshop h.

W'_{cu}: the total weight of discarded refuse sent to u from c.

W''_{hc}: the total weight of components sent to c from h.

The following values are defined and used in the objective function:

- The total income of recycling stations/dismantling workshops and the recycling firm:

$$E = \sum_h E_h + \sum_c E_c ,$$

where E_h is the income of recycling station/dismantling workshop h:

$$E_h = E_{h1} + E_{h2} .$$

E_{h1} is the total income gained from the second-hand home appliances sales at recycling station/dismantling workshop h:

$$E_{h1} = \sum_i S_{hi} \alpha_{hi} Y_i .$$

E_{h2} is the total income gained from recyclable materials sales at recycling station/dismantling workshop h:

$$E_{h2} = \sum_j \sum_i S_{hi} \left(1 - \alpha_{hi}\right) \beta_{ij} Y_j .$$

E_c is the income of recycling firm c:

$$E_c = \sum_h \sum_s \sum_j W_{hcs} z_{sj} Y_j .$$

- The total transportation cost: $T = T_1 + T_2$, where T_1 is the total transportation cost from h to c:

$$T_1 = \sum_h \sum_c D_{hc} U_{hc} W''_{hc} .$$

T_2 is the total transportation cost from c to u:

$$T_2 = \sum_c \sum_u D'_{cu} U'_{cu} W'_{cu}$$

- The total operation cost:

$$O = \sum_h O_h + \sum_c O_c ,$$

where O_h is the operation cost of recycling station h: $O_h = O_{h1} + O_{h2}$. O_{h1} is the detection and recycling cost at recycling station/dismantling workshop h:

$$O_{h1} = \sum_i S_{hi} \left(c_i + c'_i\right) .$$

O_{h2} is the manual dismantling cost of EOL-EEE at recycling station/dismantling workshop h:

$$O_{h2} = \sum_i S_{hi} \left(1 - \alpha_{hi}\right) J_i .$$

O_{c1} is the processing cost for components for further processing at recycling firm c:

$$O_{c1} = \sum_h \sum_s W_{hcs} L_s .$$

O_{c2} is the annual salary of workers who operate the equipment at recycling firm c: $O_{c2} = N_c P_c$.

- The total fixed cost:

$$F = \sum_c \sum_k F_{ck} .$$

Problem (4.3)

The objective function is to maximize the total profit of the recycling station/dismantling workshop and the recycling firm. The total profit equals the total income, after subtracting the total transportation cost, the total operation cost and the total fixed cost.

$$\text{Max } E - T - O - F$$

Subject to

$$\sum_h W''_{hc} \le M_c \quad (6)$$

$$\sum_c W_{hcs} = \sum_i S_{hi} \left(1 - \alpha_i\right) w_i \beta'_{is} , \quad (7)$$

$$\sum_c W'_{cu} < M'_u \quad (8)$$

$$\sum_u W'_{cu} = \varepsilon_c \sum_h W''_{hc} \quad (9)$$

$$d_{hi} < \alpha_{hi} < u_{hi} \quad (10)$$

Equivalent conversion:

$$\left.\begin{array}{c} \sum_c W''_{hc} = \sum_i \sum_s M'_{hc} \left(1 - \alpha_i\right) \beta'_{is} \\ M''_{hi} = S_{hi} w_i , W''_{hc} = \sum_s W_{hcs} . \\ Q_{hi}, W''_{hc}, M'_u, W'_{cu}, M_c, w_i, S_{hci} \ge 0, \\ \forall c, u, h, i \end{array}\right\} \quad (11)$$

The objective function is to maximize the total profit. Constraint (6) indicates that the total weight of parts/components accepted by the recycling firm should be less than or equal to its maximum allowable operating capacity. Constraint (7) fixes the maximum capacity of the landfill site. Constraint (8) requires that all the components containing toxic materials must be correctly disposed in the formal processing center. Constraint (9) shows that all the refuse produced in the treatment center should be disposed at the landfill site. Constraint (10) fixes the range of WEEE that can be used again. All the decision variables are required to be non-negative in Equation (11).

The same data is used as in Section 4.2. The total profit is ¥7,190,320. The overall operation cost is reduced by ¥601,660. The break-even point is about 17,000 sets (**Figure 7**), which is far lower than the break-even point of the existing model (**Figure 6**). Compared to the model in Section 4.2, the value of a TV is unchanged, which means *E* is the same. However, the weight sent to the specialized disposal plant reduces, and the total freight is reduced by ¥251999.1. Meanwhile, because of cheap methods and low cost employed by small dismantling workshops, dismantling efficiency is improved, the unit manual dismantling cost for EOL-TV is reduced by 20%, and the total manual dismantling cost can be saved up to ¥208,000. Since only components containing harmful substances need further processing, they are transported to professional recycling firms. Hence, part of WEEE processing can be done at dismantling workshops, and the rest can be treated at licensed recycling firms which can make full use of the previously established recycling treatment systems. Since there are at least 5 million EOL-TV sets in China, we can save at least ¥58.7 million. The cooperation between dismantling workshops and professional recycling firms reduces not only cost but also pollution. In the new network, we emphasize the cooperation between dismantling workshops and the professional recycling firms.

Compared with the exiting formal network, the new network can reduce the total social cost, increase the profit of licensed recycling firms and ensure the health of the staff in the dismantling workshops. It can also remove the existing illegal informal network. Currently a large number of unlicensed recycling workshops run business across the country. More manpower, financial and material resources are needed to manage unlicensed

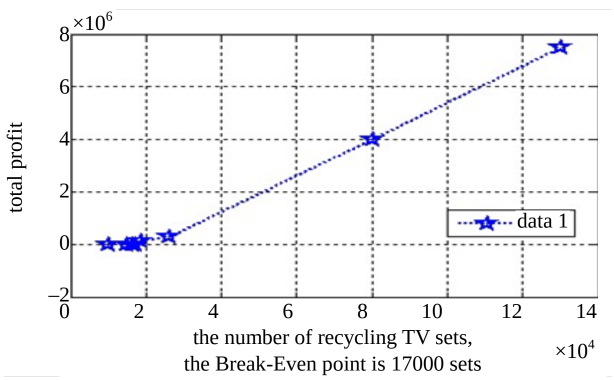

Figure 7. Total profit changing chart with the increasing recovery amount.

workshops. It is estimated that at least 500 people should be hired to handle unlicensed workshops. The salary of each supervisory staff member is at least ¥500 per month and the total investment in supervising workshops will be about ¥3 million per year. In the new network, no attempts are made to close down small dismantling workshops and they are allowed to do dismantling work of parts without harmful material, and parts/components with harmful material are sent to professional recycling firms for further processing. As a result, workers in small workshops can keep their jobs and WEEE can be processed in a proper and healthy way.

5. Conclusion

The impact of WEEE on the environment has become a global issue. The situation in China is particularly serious. The recycling and treatment of WEEE in China just begins and needs improving. There are formal and informal recycling networks in China. Both of them have drawbacks. Our proposed new network uses the convenient collection system of recycling peddlers and the cheap operation of small dismantling workshops, and ensures parts/components containing harmful material are sent to professional recycling firms for processing. This new network also combines the advantages of both the formal and informal networks. Linear programming models are used to analyze and compare the networks. This research proves that this new network can improve environment protection and also reduce operation cost. It also provides valuable advice for establishing WEEE recycling and treatment management policies in China.

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Appendix

Table 1. Distance from *h* to *c* (km).

*c**h*	*h*1	*h*2	*h*3	*h*4	*h*5
*c*1	10	6	30	24	21
*c*2	4	16	30	20	20

Table 2. Unit transportation cost from *h* to *c* (¥/ton·km).

*c**h*	*h*1	*h*2	*h*3	*h*4	*h*5
*c*1	8	12	9	7	6
*c*2	8	6	8	5	4

Table 3. Distance from *c* to *u* (km).

u/c	*c*1	*c*2
*u*1	20	19
*u*2	31	3

Table 4. Unit transportation cost from *c* to *u* (¥/ton·km).

u/c	*c*1	*c*2
*u*1	8	7
*u*2	6	9

Table 4. Unit transportation cost from *c* to *u* (¥/ton·km).

u/c	*c*1	*c*2
*u*1	8	7
*u*2	6	9

Table 5. Unit landfill cost (¥/ton).

Landfill site	*u*1	*u*2
T_u	200	210

Table 6. Unit cost of recycled materials derived from EOF-TV (10,103 ¥/ton).

Materials	Glass	Plastic	Copper	Iron	Aluminum	Lead	Phosphor
Y_j	0.012	0.6	4	0.3	1.6	1.5	0

Table 7. Percentage of components with harmful materials to the environment.

S	s_1	s_2
w_s	0.2	0.25

Table 8. Recycling amount of every recycling station (10,103 sets).

Recycling bin	*h*1	*h*2	*h*3	*h*4	*h*5
Recycling amount Q_{hi}	3	4	2	1	3

Table 9. Equipment cost in one professional treatment plant.

Equipment name	Television dissembling line	HA shell crusher	Electronic glass to be automatic cutting machine for CRT	Heater strip	Full set of processing equipment for circuit board	Explosion-proof belt
Unit cost	168,000 (¥/set)	168,000 (¥/set)	260,000 (¥/set)	300 (¥/kg)	2,100,000 (¥/set)	120,000 (¥/set)
Life spans	About 7 (years)	About 8 (years)	About 13 (years)	500 CRT tube handled by 1 kg Heater strip	About 10 (years)	About 6 (years)
Fee for every year	24,000 (¥/year)	21,000 (¥/year)	20,000 (¥/year)	(the number of the TV/500) ×300	2,100,00 (¥/year)	20,000 (¥/year)

