Assessing the Recycling Efficiency of Resource in E-Waste Based on MFA of Reverse Logistics System

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Abstract. The waste electrical and electronic equipment (WEEE, e-waste) has caused many issues, such as waste of resource and environmental pollution. This paper applied material flow analysis (MFA) method to analyze the flows of recycled resource from WEEE and process of reverse logistics from recycling to reuse. And analyzed the discarded TV data in K company (a leading television producer in China), and calculated the recycling efficiency of metals. The research showed that recycling efficiency of the metals from discarded TV in K company is 12.3%, which is far below the criterion (In Japan, the "Household appliance recycling and reuse" recycling efficiency of useful resource from discarded television by the television manufacturers must be above 55%). At last, we gave some suggestions for developing recycling efficiency of manufacturing enterprises and recovery enterprises in China: (1) Improving the recycling efficiency of manufacturer, retailer and consumer can contribute to improve the recycling efficiency in the whole reverse logistics system; (2) Improving the technological level of decomposition and dismantling of e-waste in the recycling process can increase the recycled material; (3) Manufacturing enterprises should have the green production concept and the participants in the supply chain should follow the concept of EPR (Extended Product Responsibility).

Keywords: Reverse logistics · Recycling efficiency · MFA · WEEE

1 Introduction

WEEE is the waste of electrical or electronic products, it covers a wide spectrum ranging from consumer goods such as discarded refrigerators, air conditioners, washing machines, televisions and computers, mobile phones to capital goods such as some unqualified products, parts and scraps in the production and repair processes [6].

Because of containing precious metals (such as gold, copper, aluminum and silver) and plastic, the reutilization of WEEE has magnificent recovery value and

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environmental protection advantages. Recycling resource from the WEEE has long-term strategic significance, not only can reduce the waste of resource, promote social development and regional economic growth, but also can reduce the serious threat from toxic and harmful substances in e-waste to the environment and human health.

Many researchers have made a large amount of researches on the recycling in reverse logistics system and e-waste recycling. In the aspect of reverse logistics system mainly focused on architecture design for the network, model establishing and waste management in reverse logistics system. Reverse logistics network can be divided into different branches according to the type of goods in reverse logistics system, applying the mixed-integer linear program (MILP) or integrating the analytical hierarchical process (AHP) can address the complex network configuration of a reverse logistics system [2,9,11]. In order to design the network of reverse logistics system, the capacities of each nodes and the number of recycling facilities should be considered. By applying some models can minimize the costs, and simultaneously can consider green and social issues to design a reverse logistics network [10]. In addition, establishing the model of reverse logistics also can solve some practical problems, for instance Ehab Bazan established the model based on the economic order/production quantity (EOQ/EPQ) and the joint economic lot size (JELS) settings for reverse logistics inventory systems [5]. Waste management is an important part in reverse logistics system, and waste recycling is a multi-disciplinary problem, a holistic view and viewpoints from different decision levels should be considered when modelling a reverse logistics system for waste management [7]. Setting up the waste management strategies can help firms to reduce waste and have a healthy reverse logistics system [15]. In the aspect of e-waste recycling, developing model and applying method can analyze the WEEE based on a real world case. For instance, Ayvaz, B created the two stage stochastic programming model provides acceptable solutions to make efficient decisions for reverse logistics network design of e-waste [4]. By applying the material flow analysis method can make a detailed analysis for recycling and stock of e-waste, as well as the recycling efficiency assessment and optimization in the closed-loop supply chain [1,14].

This paper combine recovery system with material flow analysis method in reverse logistics system and analyze the process of resource recycling of e-waste. Take recovery of discarded televisions of K company (a leading television producer in China) as an example in this thesis, its recycling efficiency of metal in the discarded television is calculated and assessed, based on that we gave some suggestions for the manufacturing enterprises and recovery enterprises in China.

2 Theory and Methodology

2.1 Reverse Logistics and Reverse Logistics Network

A complete definition of reverse logistics is put forward by the European Working Group on Reverse Logistics, and is formulated as follows: "The process of planning, implementing and controlling backward flows of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution or use node, to a node of recovery or node of proper disposal" [3].

Reverse logistics network is the nodes distribution and the arrangement of transportation routes between each node in the reverse logistics system. Typical reverse logistics network is shown in Fig. 1.

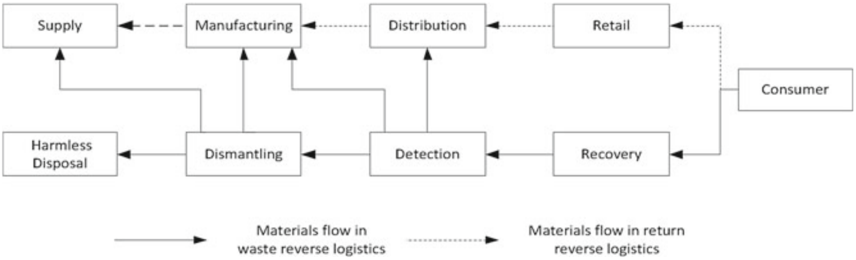

Fig. 1. Typical reverse logistics network

2.2 Material Flow Analysis

Material flow analysis (MFA) is "a systematic assessment of the flows and stocks of materials within a system predefined in space and time". The method mainly

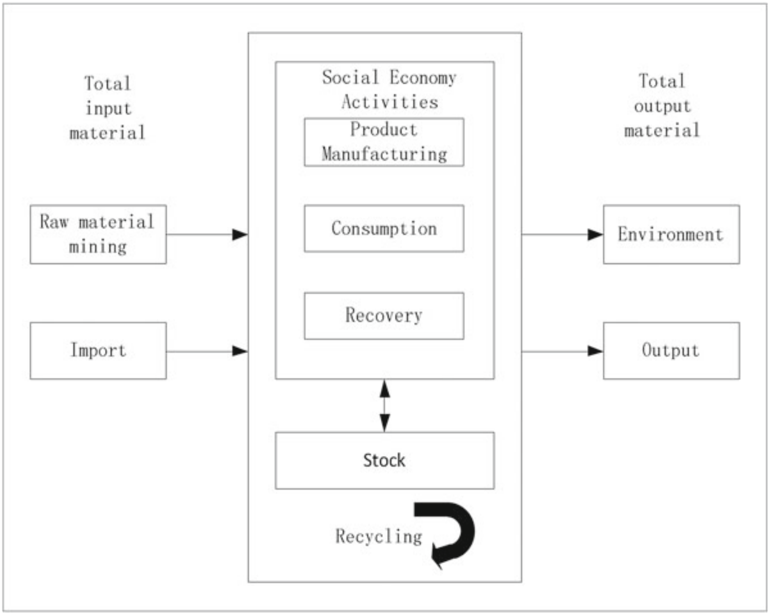

Fig. 2. The basic framework of material flow analysis method

involved the material inputs, outputs, and inventories [8]. According to the law of conservation of mass, MFA could get an ultimate conclusion that indicates the status of material input, stock and output in each stage of life cycle. It is based on the material balance theory (Total material input = Total material output + Stock), by means of material flow analysis, we can estimate and evaluate the condition of development, utilization and waste management of natural resources and various substances. The basic framework of material flow analysis method is shown in Fig. 2.

2.3 Material Flow Analysis of Reverse Logistics System

MFA of reverse logistics system is the main methodology in this paper which is a way to analyze the material flow of e-waste in reverse logistics system.

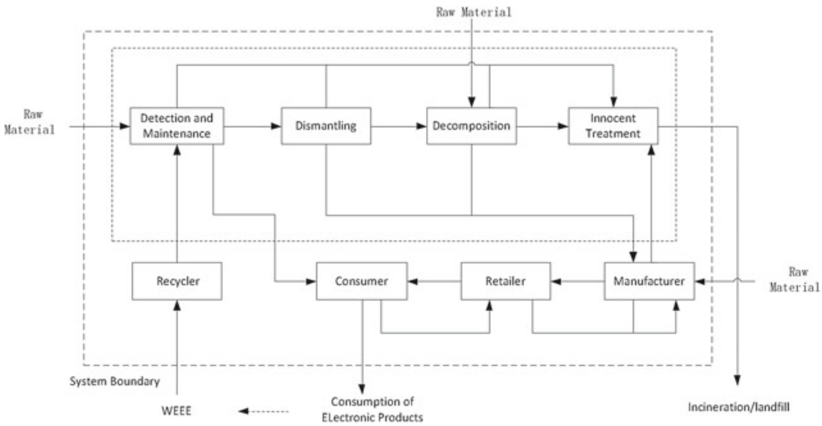

Fig. 3. The material flow analysis frame of the reverse logistics system

As shown in Fig. 3, participants in the frame are recycler (which mainly responsible for four recycling process: detection and maintenance, dismantling, decomposition and innocent treatment), manufacturer, retailer and consumer.

3 Analysis and Discussion

3.1 Reverse Logistics Process for the WEEE

As a special kind of reverse logistics, the recovery process for e-waste includes five aspects. Figure 4 shows the principal stages in the recovery process.

(1) Recovery

Recovery phase is the first and most important stage in the whole recovery process. At present, the main sources and recovery channels of e-waste in China are shown in Table 1.

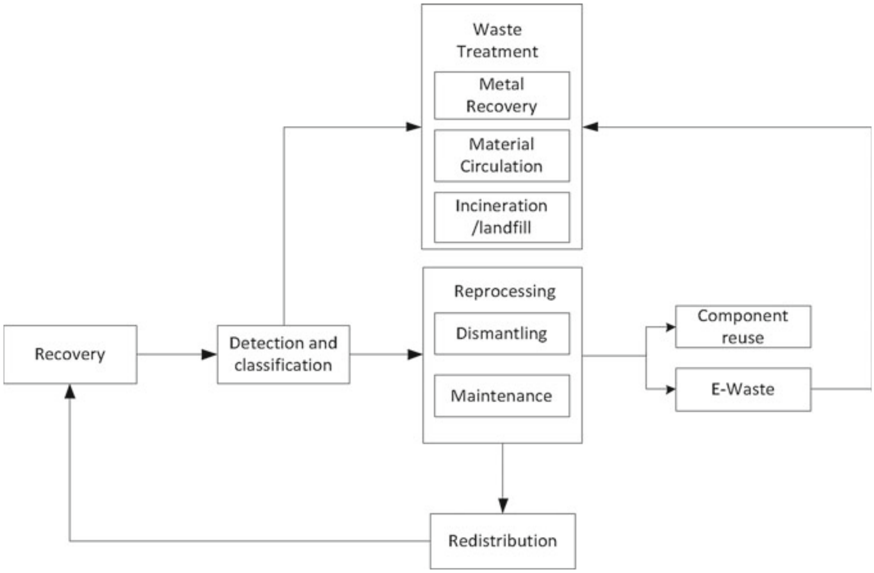

Fig. 4. Recovery process for the WEEE

Table 1. The main sources and recovery channels for e-waste

Category	Comment
Main source	The daily life of the residents; Electronic products and household appliances manufacturers and sellers; Illegal imports of e-waste from abroad.
Recovery channel	Door-to-door recovery; For trading-in old one for new one in the Shop; Flea Market of electronic products and household appliances; Garbage recycling by government/The glean and collect scrap man; After-service station

(2) Detection and Classification

E-waste has a wide variety of categories, and each category can be divided into small classes and the corresponding value of it is different. Therefore, the work that must be done is rigorous detection and classification for the recycling of e-waste according to their characteristics such as structure or components function to determine the subsequent process, such as after maintenance to resale, reuse the parts after dismantling, material recycling after decomposition or waste treatment.

(3) Reprocessing

In the reprocessing stage, e-waste can be reacquired the value that reuse, remanufacture or recycle through reasonable reprocessing for recycled products or parts. Reuse only aims at the recycled products can be used directly through cleaning or simple maintenance, such as the toner cartridge which can be used again through the simple work. Remanufacturing aims at the e-waste can enter the manufacturing stage again after dismantling, replace or repair. And the recycle aims at the parts, glass and plastic in the recycled e-waste.

(4) Redistribution

The recycled e-waste can be as commodity to reuse and enter the consumer market or donate to the consumers in poor areas directly after the inspection and reprocessing stage. In this stage, distribution is the most important work, which can make the entire recovery process for the WEEE operate efficiently.

(5) Waste Treatment

For the e-waste that has no circular economic value or can bring large harm to the environment, the available material in them can as the recycling resources to be reused through the reasonable treatment, such as dismantling, melting, refining and electrolysis. While for the e-waste cannot be reused, the disposing is partitioned in two ways, one which is stored them in landfills; the other approach is sent them to an incinerator.

3.2 MFA in Reverse Logistics System for E-Waste

(1) Date Acquisition

In this paper, according to the MFA of reverse logistics system, we built a reverse logistics system for e-waste based on the self-operated recovery system of the K television manufacturing company in China. Take the recycling efficiency of the metal resources (copper, aluminum, iron) of the company as the concrete calculation example. Through collecting television sales data of the company over the years and applying the market supply method A [12] to forecast the amount of discarded TV of the K television manufacturing company in 2016.

Through the existing research [13] can get the duration of use and the waste rate of the television is shown in Table 2.

Table 2. The duration of use and the waste rate of the television

Duration of use(year)	< 8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	> 16
Waste rate	6%	6%	10%	13%	15%	15%	13%	10%	6%	6%

The sales date of K television manufacturing company over the years is shown in Table 3.

The market supply method A formula as follows:

$$Q = \sum S_i \times P_i, \quad (1)$$

Table 3. Sales of television over the years

Year	Sales (Million)
2000	1.06
2001	1.09
2002	1.63
2003	2.41
2004	2.43
2005	3.99
2006	3.99
2007	3.54
2008	4.01
2009	5.8
2010	6.02
2011	6.41
2012	7.56
2013	8.05
2014	9.67
2015	9.92

where, Q represents the amount of discarded televisions a year, S_i represents the sales of televisions i years ago (assuming all the sales of televisions are used), P_i is the waste rate represents the proportion of the discarded television in sales i years ago.

By using this model, it can be concluded that the amount of waste television in 2016 is 2.12million. Combining with the relevant information from the related industry, 50% of discard television can be recovered, and the dismantling rate (after dismantling can be recycled parts ratio) is set to 35%, and the decomposition and utilization rate is set to 56%. The average weight of a television is 20 kg, the content of copper in a television is 5.4%, the content of aluminum in a television is 5.4%, and the content of iron in a television is 5.3% [18]. Because the resource loss of recycled metal to the environment in each stages, and in order to facilitate the research, so the following assumptions are given:

(1) The structure of resource recycling in reverse logistics system is a closed loop network, all the discarded television after disposing would return to manufacturer;
(2) The return production from consumer must be sent to the manufacturer for processing;
(3) The product could be reused after detection and maintenance would be resold and enter the consumer market;
(4) All the discarded television (which could be recycled) must be recycled by the recycler.

Therefore, the amount of recycled metal from discarded television is 3413.2 tons. The specific data are shown in Fig. 5.

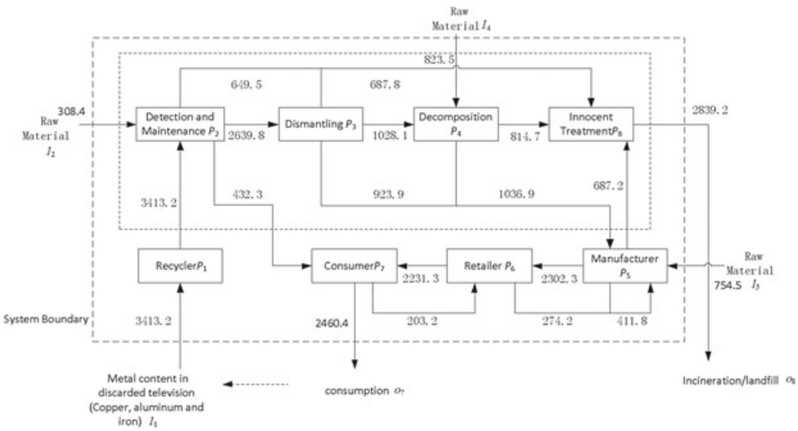

Fig. 5. The specific data in reverse logistics system of discarded television. All units measures in tons

(2) Empirical Analysis

According to the data in Fig. 5, the input-output table of reverse logistics system of discarded television is shown in Table 4.

Table 4. The input-output table. All units measures in tons.

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	I_0
P_1	0	0	0	0	0	0	0	0	3413.2
P_2	3413.2	0	0	0	0	0	0	0	308.4
P_3	0	2639.8	0	0	0	0	0	0	0
P_4	0	0	1028.1	0	0	0	0	0	823.5
P_5	0	0	923.9	1036.9	411.8	274.2	0	0	754.5
P_6	0	0	0	0	2302.3	0	203.2	0	0
P_7	0	432.3	0	0	0	2231.3	0	0	0
P_8	0	649.5	687.8	814.7	687.2	0	0	0	0
O_0	0	0	0	0	0	0	2460.4	2839.2	0

In order to quantify the relationship of various stages of metal cycle in reverse logistics system, we give the mathematical expression of input-output relationship based on material balance theory as Eqs. (1) and (2), x_k is the total flow in P_k, f_{kj} is the flow of P_j to P_i.

$$x_k = \sum_{i=1}^{n} f_{kj} + I_k \qquad k = 1, 2, \cdots n, \tag{2}$$

$$x_k = \sum_{i=1}^{n} f_{ik} + O_k \qquad k = 1, 2, \cdots n. \tag{3}$$

According to the Eqs. (2) and (3), the total flow of each node is shown in Table 5. In order to assess the overall recycling efficiency of the system, we give the mathematical expression Eq. (4)–(6).

Table 5. The total flow of each node

Node	Amount (tons)
P1	3413.2
P2	3721.6
P3	2639.8
P4	1851.6
P5	2989.5
P6	2505.5
P7	2663.6
P8	2839.2

$$n_i = \frac{I_i + \sum_{j=1}^{n} f_{ij}}{o_i + \sum_{j=1}^{n} f_{ji}}, \tag{4}$$

$$R_i = \frac{n_i - 1}{n_i}, \tag{5}$$

where, n_i is the relation of the input and the final output of a single node. When $n_i = 1$ indicates that the recycled metal resources through the node i, but not returned to the node i for recycling. When $n_i > 1$ indicates that the recycled metal resources through the node i, and returned to the node for recycling with a direct or indirect way.

n_i is recycling efficiency of a single node. When $R_i = 0$ indicates the flow of the recycled metal resources through the node i is unidirectional. When $R_i > 0$ indicates the recycled metal resources through the node i can return the node for circulating and using.

Table 6. The calculation results of n_i and R_i

	1	2	3	4	5	6	7	8
n_i	1	1	1	1	1.14	1.09	1.19	1
R_i	0	0	0	0	12.30 %	8.30%	16%	0

The calculation results of n_i and R_i are shown in the following Table 6.

According to weighted method, we use the recycling efficiency of each node can get the overall recycling efficiency C in the system.

$$C = \frac{s_c}{s} = \frac{\sum_{i=1}^{n} R_i \times x_i}{\sum_{i=1}^{n} x_i} = \frac{1001.841}{8158.6} \approx 12.3\%, \tag{6}$$

where, S_c is the total recycling flow, S is the overall flow of nodes which the recycling efficiency of a single node is not equal to zero [16].

Therefore, the overall recycling efficiency of the system is 12.3 %. That is the recycled metal resources after the whole recovery process, 12.3% metal resources in discarded television can be reused.

4 Conclusions

According to the analysis and discussion above, we concluded that the recycling efficiency of metal resources in waste television of K television manufacturing company which is representative in the television industry, so the recycling efficiency has a certain reference value for home appliance manufacturing industry in China.

There is not a sound assessment standard to evaluate the recycling efficiency in China, so this paper take Japanese experience as reference. In Japan, the "Household appliance recycling and reuse" started from 2001 specifies that the recycling efficiency of useful resource (metal in the majority) from discarded television by the television manufacturers must be above 55% [17]. Obviously, the recycling efficiency of the television company was hard to reach the criterion with the present resource recycle level, so it is feasible to make optimization for reverse logistics recycling system of e-waste in China, and improve circulation efficiency of the recycling system, so we give the following suggestions:

(1) From the above calculation process, the overall recycling efficiency lever mainly depends on P_5, P_6 and P_7 (Fig. 5). Thus, we can increase the numerical value of P_5, P_6 and P_7 (Table 6) to increase the overall recycling efficiency, that means improving the flow of manufacturers, retailers and consumers is the key problem to improve the recycling efficiency of the system.

(2) Improving the secondary utilization ratio of the material in the recycling system, such as improving the technological level of decomposition and dismantling of e-waste in the recycling process, the recycled material in e-waste can be increased, but the input of raw material can be reduced, and then minimize the wastage of resource from the external environment.

(3) Chinese electronic products and household appliances manufacturing enterprises should have the green production concept to decrease the amount of waste that can't be reused. In addition, the participants in the entire supply chain should follow the concept of EPR (Extended Product Responsibility). That means not just the manufacturer, the distributor, retailer and consumer should also strengthen mutual cooperation and bear their respective responsibilities, for the purpose of promoting the level of reuse and recycling of resources.

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References

1. Agamuthu P, Kasapo P, Nordin NAM (2015) E-waste flow among selected institutions of higher learning using material flow analysis model. Resour Conserv Recycl 105:177–185
2. Alshamsi A, Diabat A (2015) A reverse logistics network design. J Manufact Syst 37:589–598
3. Alumur SA, Nickel S et al (2012) Multi-period reverse logistics network design. Eur J Oper Res 220(1):67–78
4. Ayvaz B, Bolat B, Aydin N (2015) Stochastic reverse logistics network design for waste of electrical and electronic equipment. Resour Conserv Recycl 104:391–404
5. Bazan E, Jaber MY, Zanoni S (2015) A review of mathematical inventory models for reverse logistics and the future of its modeling: an environmental perspective. Appl Math Model 40(5–6):4151–4178
6. Bertram M, Graedel TE et al (2002) The contemporary european copper cycle: waste management subsystem. Ecol Econ 42(1–2):43–57
7. Bing X, Bloemhof JM et al (2015) Research challenges in municipal solid waste logistics management. Waste Manag 48:584–592
8. Brunner PH, Rechberger H (2006) Practical handbook of material flow analysis. Int J Life Cycle Assess 10(9):293–294
9. Galvez D, Rakotondranaivo A et al (2015) Reverse logistics network design for a biogas plant: an approach based on MILP optimization and analytical hierarchical process (AHP). J Manufact Syst 37:616–623
10. Govindan K, Paam P, Abtahi AR (2016) A fuzzy multi-objective optimization model for sustainable reverse logistics network design. Ecol Ind 67:753–768
11. Mangla SK, Govindan K, Luthra S (2016) Critical success factors for reverse logistics in indian industries: a structural model. J Clean Prod 129:608–621
12. Simon W, Noel D, Matt C (2001) Waste from electrical and electronic equipment. US Environmental Protection Agency
13. Song X (2008) Establishment and economic analysis of the standardized recycling system for waste and used home applications. Doctoral dissertation
14. Su LX, Wang ZH et al. (2012) MFA-based resource cycling efficiency analysis for a closed-loop supply chain system. Ind Eng J

15. Van Der Wiel A, Bossink B, Masurel E (2012) Reverse logistics for waste reduction in cradle-to-cradle-oriented firms: waste management strategies in the Dutch metal industry. Int J Technol Manage 60(1/2):96–113
16. Wu Z (2013) Reverse logistics management ł the WEEE as the research objects. Science Press in Beijing
17. Yu P (2012) An analysis of Japan's home appliance recycling. Contemporary Economy of Japan
18. Zeng X (2008) Mechanism and technology of nonferrous metals recycling from typical e-waste parts. Doctoral dissertation