Disassembling Planning of Electronic Product for Waste Recycling with China's Case

Yu Sisi Tomohiro Murata

Abstract—**According to statistics from the State Environmental Protection Administration of China, China's daily electronic waste output adds up to 3,000 tons. The accelerating technological redundancy turnaround times are making the waste problem even worse. In addition to this domestic garbage, vast amounts of overseas electronic wastes, most of them are imported officially as "secondhand goods". However, safe recycling operations are not currently viable in China. So the important thing is to make the electronic scrap recycling process profitable and safety to avoid the secondary pollution. This paper proposes a cost-efficient management of material flows which can help recycling companies obtained more achievable marginal income.**

***Keywords*—bulk recycling, electronic scraps recycling, disassembly, environmental obligation, acceptance cost**

I. Introduction

Despite the immense amount of electronic waste being generated in China, "official" recycling operations simply do not receive enough material to make recycling a profitable business. Instead, 90 percent of China's electronic waste goes to family workshops, whose manual dismantling practices create highly toxic secondary pollution.

Presently there are no regulations governing E-waste recycling in China, and there is little incentive for Chinese consumers to disposal their old electronic products in a safer manner. So if the recycling company wants to receive enough materials, it would undoubtedly push up costs to pay for consumers.

In traditional bulk recycling system, the main contribution to the objective value results from acceptance fee revenues (+). But in china, it means expense of acceptance cost (-). If Chinese enterprise wants to make profit from electrical waste recycling, they must deal with this part extra cost.

These discarded products should be recovered due to economic and ecological reasons. The paper focuses on the design and implementation of a decision support system for electronic scrap recycling companies throughout the recycling enterprise regarding chosen, disassembly and bulk recycling, a mixed-integer linear-programming (MILP) model for integrated disassembly and bulk recycling planning problems. And the optimization calculations that covering typical discarded electronic products to be recycled lead to a relevant improvement of economic success for China's recycling industry.

The recovery of electronic scrap is a multistage process. Logistic issues concern collection, grading, transport and allocation of discarded products, reusable parts and modules, as well as of recovered materials. Disassembly in order to remove hazardous substances and reusable parts is often followed by bulk recycling to gain separated material fractions that are sent to metal recycling facilities or other recycling specialists [8](Fig. 1).

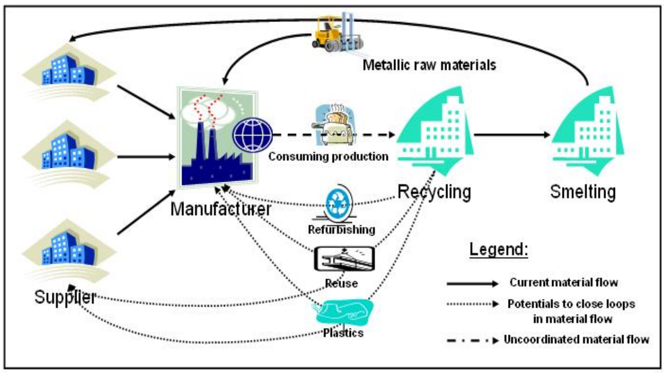

Figure 1. Material flows in closed-loop supply chains [1]

Due to high uncertainties in the amount and quality of available electronic scraps, the long term recycling schedule has to be supplemented by a detailed short term schedule at regular intervals. The recycling company regularly has to be decided on the daily recycling schedule of scrapped products, the levels of disassembly, the allocation of reusable parts and modules to producers or suppliers and the further recycling process of recoverable materials [8]. And the long term recycling schedule will be analyzed based on daily recycling schedule with inventory cost and price changing.

II. Problem Description

Model of decision problems of electronic scrap recycling companies was proposed in [9]. Decision problems of electronic scrap recycling companies refer to the chosen, disassembly and bulk recycling, the material flow throughout a typical recycling company is shown in Figure 2.

Presently there are no regulations governing E-waste recycling in China, so Chinese manufacturers face a pressing cost issue in trying to make their operations more environmentally. Safe recycling of electronic wastes is expensive, so if enterprises want to make the recycling process be profitable, a detailed technical analysis of the bulk recycling process is necessary.

The recycling companies face the three levels problems. The first action is the "chosen" decision that means which products will be chosen from market, which parts of products have to be taken and recovered and which parts will be left in inventory in the considered interval planning period as seen at point (α).

The first recovery step "disassembly" is composed of manual or partly-automated processes. Mechanical assistance concerns only transportation and lifting tasks. Planning the disassembly step, the recycling companies have to determine the disassembly level at point (β) in Figure 2, taking into account that some products do not have to be disassembled at all, that the reusable part demand as well as prices change periodical and that some disassembly operations are mandatory in order to eliminate hazardous substances.

The second recovery step "bulk recycling " is designed to gain precious fractions such as ferrous and non-ferrous metals from mixed electronic scrap, using unit operations like crushing and separation steps. When planning the bulk recycling step, the recovery works manager has to decide which scrap types are to be recycled internally or are to be marketed externally as seen at point (γ) in Figure 2.

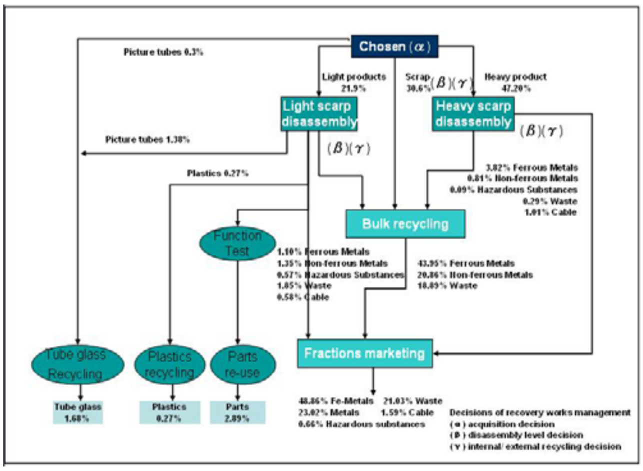

Figure 2. Material flow of a typical electronic scrap recycler [2]

This is a complex problem due to the fact that bottlenecks can appear in different units. A recycling enterprise can benefit from the blended composition of the bulk recycling input adjusted by the feed of different scrap types [8]. A detailed analysis of the disassembly and bulk recycling operations is given in following chapter.

III. OPERATION ANALYSIS

The first recovery step "disassembly" takes into account that some products do not have to be disassembled at all. But in other case the disassembly activities are necessary in order to eliminate hazardous substances shown in Figure 3. The recycling company collected the scrap 1 to be recovered, if the scrap 1 contains hazardous substances scrap 4 and scrap 7; the scrap 1 must be disassembled mandatorily through disassembly activity 1 to get scrap 3 and scrap 2, like by these operations until all the scraps do not contain hazardous substances like scrap 5 and scrap 7 in the Figure 3. The disassembly activities are end. And the scraps which do not contain hazardous substances can be blended and to be abstract the precious fractions such copper, aluminum, and ferrous metals.

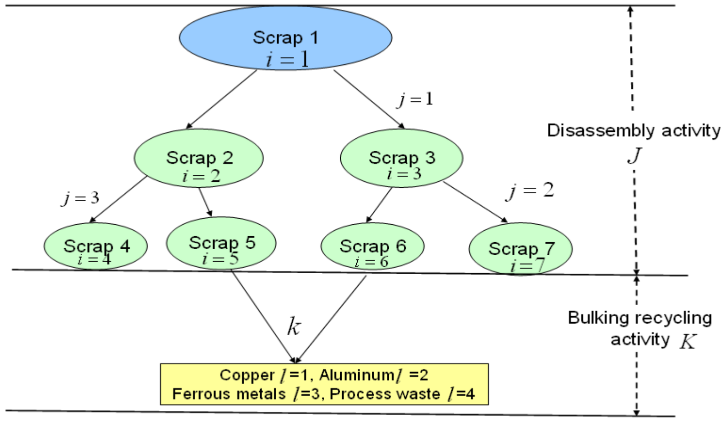

Figure 3. The concept of the disassembly operations structure

An example of the disassembly operations structure is depicted in Figure 4. A refrigerator (i=1) chosen from the discarded products range (i=1…3) must be opened and the harmful part Freon (i=2) has to be removed (disassembly activity j=1). The resulting by-products are refrigerator without Freon (i=3). The disassembly option to remove pump oil (i=4) through disassembly activity j=2. The output of activity of pump oil removal is refrigerator without Freon and pump oil (i=5) from refrigerator without Freon (i=3), which can be recycled in the steel industry.

Disassembly output has to be directed towards external or internal treatment. In case of external treatment, the output is collected in boxes and marketed externally, e.g. as spare parts or in order to be treated by recycling specialists. Alternatively, the disassembled parts can be recycled internally in a bulk recycling facility where they are mixed with other products and parts [9]. The flow sheet of the bulk recycling step is shown in Figure 5.

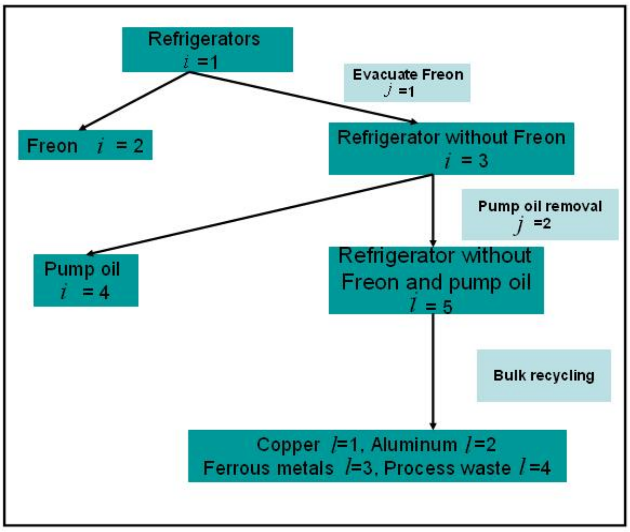

Figure 4. Example of the disassembly operation of a refrigerator

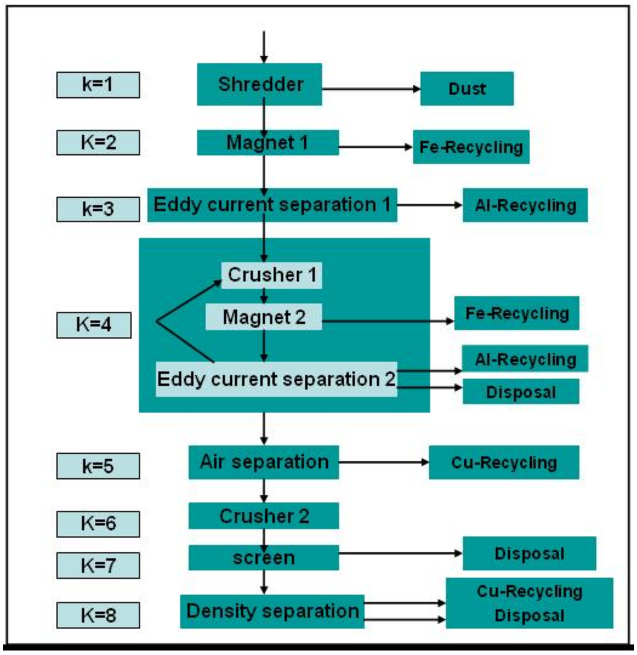

Figure 5. Bulk recycling process [9]

IV. FORMULATION OF A MILP-MODEL

A. *Activity analysis based on model description*

The model formulation is based on the linear activity analysis [4] that permits a model formulation of recovery planning problems [6], [7]. The activity analysis based model description is shown in Figure 6.

It is assumed that a number of different discarded products, parts and materials *i= 1,…, I* are available in the in the discarded market at a given acceptance price. And the recycling companies choose some products to be recovered and the others will be left in inventory for next period. These *I* scrap types can be disassembly by the application of *j=1, …, J* different disassembly activities. And the disassembly output will be recycled externally or internally. These *I* scraps which are recycled internally can be processed by a bulk recycling plant using *k=1, …, k* process units to gain material *l=1, …, L.*

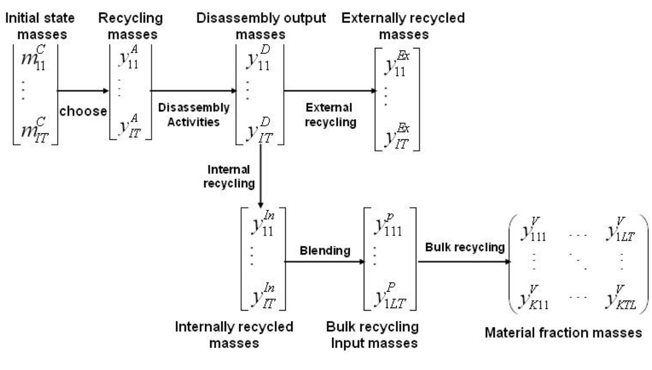

Figure 6. Activity analysis based model description

B. *Notation*

Indices:

i : Index of scrap types: products, parts, materials $i \in \{1,\dots,I\}$

j : Index of disassembly activity $j \in \{1,\dots,J\}$

k : Index of unit operation $k \in \{1,\dots,K\}$

l : Index of material $l \in \{1,\dots,L\}$

Parameters and Coefficients:

a_{il} : Composition factor that disposes scrap type i composition to material component $[kg/kg]$ $(0 \le a_{il} \le 1)$

c_k^p : Bulk recycling cost factor for unit k $[Yuan/kg]$

c^z : Disassembly labor cost factor $[Yuan/Kg]$ represents labor cost

e_{it}^A : Acceptance cost factor for scrap type i $[Yuan/Kg]$ in period t

c_i^h : The inventory holding cost of scrap type i in the collection center $[Yuan/Kg]$

e_{klt}^V : Recycling material sale price factor of isolated fraction l in the collection center $[Yuan/Kg]$

e_{it}^{EX} : Price factor for scrap type i $[Yuan/Kg]$ to external recycling in period t

m_i : Mass of one piece of scrap type i $[Kg]$ $(m_i \ge 0)$

t_j^Z : Disassembly time needed for one application of activity j $[j/act]$

v_{ij} : Disassembly activity coefficient for the input (-) or output (+) masses of scrap type i caused by one application of activity j $[Kg/act]$

u_{kl}^P : Transformation coefficient for unit operation k $[Kg/Kg]$ $(0 \le u_{kl}^P \le 1)$

Limits:

$T^{\max}$:Limit for disassembly labor time $[h]$

$m_{it}^{C,\max}$: Limit for masses of scrap type i that is available to be taken $[Kg]$ in period t

$Y_{it}^{Ex,\max}$: Limit for sale capacity of scrap type i to external recycling $[Kg]$

$Y_{klt}^{P,\max}$: Limit for equipment capacity of separation unit k $[Kg]$

$Y_{klt}^{V,\max}$: Limit for sale capacity of isolated material fraction l separated by separation unit k $[Kg]$

ISBN: 978-988-17012-7-5

$m_{it}^{C,\min}$: The lowest level of the mass of scrap type i should be obtained from market, environmental obligation

Decision Variables:

x_{jt} : Integer decision variable for the number of applications of disassembly activity j in period t

y_{it}^{A} : Decision variable for the mass of scrap type i to be taken for recycling from inventory in period t $[Kg]$

y_{it}^{D} : Decision variable for the mass of scrap type i after disassembly in period t $[Kg]$

y_{it}^{Ex} : Decision variable for the mass of scrap type i to external recycling in period t $[Kg]$

y_{it}^{In} : Decision variable for the mass of scrap type i to internal recycling in period t $[Kg]$

y_{klt}^{P} : Decision variable for the mass of material component l in the mixture that is treated in separation unit k in period t $[Kg]$

y_{klt}^{V} : Variable for the mass of isolated material fraction l separated by separation unit k in period t $[Kg]$

y_{it}^{C} : Variable for the mass of scrap type i in inventory in period t $[Kg]$

m_{it}^{C} : Variable for the mass of collected scrap type i in period t $[Kg]$

C. Objective Function:

$$\max_{\substack{y_{11}^A,\ldots,y_{IT}^A\\ x_1,\ldots,x_J\\ y_{11}^{In},\ldots,y_{IT}^{In}}} \sum_{i=1}^{I}\sum_{t=1}^{T} y_{it}^{Ex}\cdot e_{it}^{Ex} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} y_{klt}^{V}\cdot e_{klt}^{V} - \sum_{j=1}^{J}\sum_{t=1}^{T} x_{jt}\cdot t_j^z\cdot c^z$$

$$-\sum_{k=1}^{K} c_k^P\Big(\sum_{l=1}^{L}\sum_{t=1}^{T} y_{klt}^{V}\Big) - \sum_{i=1}^{I}\sum_{t=1}^{T} y_{it}^{A}\cdot e_{it}^{A} - \sum_{i=1}^{I}\sum_{t=1}^{T} c_i^h\cdot y_{it}^{C} \quad (1)$$

The objective function (1) maximizes the total achievable marginal income subject to mass balance equations and capacity and market restrictions. The four periodical term decision questions are depicted by the decision variables "mass of collected scrap type i in period t (m_{it}^{C})", "mass of scrap type i to be taken (y_{it}^{A}) in period t", "number of applications of disassembly activity j (x_{jt}) in period t" and "mass of scrap type i directed to internal recycling (y_{it}^{In}) in period t". The values of other variables are determined by the constraints. The total achievable marginal income results from disassembly output revenues/costs, bulk recycling output revenues/cost, variable disassembly costs, acceptance costs and variable process costs.

D. Restrictions

Subject to

$$y_{it}^{D} = y_{it}^{A} + \sum_{j=1}^{J} x_{jt}\cdot v_{ij} \qquad i = 1,\ldots,I \qquad (2)$$

The chosen products, parts and materials can be depicted by an initial state vector $y_t^A = \left[y_{1t}^A \ldots y_{It}^A\right]$ in period t that contains the masses y_{it}^{A} of every taken scrap type and every period t. For every scrap type i the material flow throughout the recovery enterprise can be described. Disassembly operations are modeled with linear input-output coefficients v_{ij} that represent the input and output masses of every scrap type in one disassembly activity and the number of applications of the disassembly of this x_{jt} in period t (2).

$$y_{it}^{D} = y_{it}^{Ex} + y_{it}^{In} \qquad i = 1,\ldots,I \qquad t = 1,\ldots,T \qquad (3)$$

The obtained disassembly output y_{it}^{D} has to be directed either to external or to internal treatment (3).

$$y_{klt}^{V} = u_{kl}^{P}\cdot y_{klt}^{P} \qquad k = 1,\ldots,K \qquad l = 1,\ldots,L \qquad (4)$$

The coefficient u_{kl}^{P} represents the share of the available material l in the input of the unit k that is directed in material fraction l of this unit (4).

$$y_{klt}^{P} = \begin{cases} \sum_{i=1}^{I} a_{il}\cdot y_{it}^{In} & k = 1 \\ y_{(k-1)lt}^{P} - y_{(k-1)lt}^{V} & k = 2,\ldots,K \end{cases}$$
$$i = 1,\ldots,I \qquad t = 1,\ldots,T \qquad (5)$$

It is assumed that disassembly output to internal treatment y_{it}^{In} is completely processed in the bulk recycling units. The input of the bulk recycling process is blended by a mixture of disassembly output parts and discarded products in the feed of the process. In the first unit, the input masses y_{klt}^{P} result from the composition of y_{it}^{In} in period t. At the moment of destruction in the first unit shredder the composition coefficients a_{il} dispose the scrap types i to a material component l. The input masses of the other units can be calculated by the following mass balance equations for each unit (5).

$$y_{it}^{C} = \begin{cases} m_{it}^{C} - y_{it}^{A} & t = 1 \\ y_{i(t-1)}^{C} + m_{it}^{C} - y_{it}^{A} & t = 2,\ldots,T \end{cases}$$
$$i = 1,\ldots,I \qquad (6)$$

In initial state, the amount of scraps in collection center equal to the amount of collected products. From initial state, the amount of scraps in collection center equal to the difference between the whole scrap amount in collection center and the scrap amount will be taken in period t (6).

$$y_{it}^{In} = \begin{cases} = 0 \\ \geq 0 \end{cases} \quad \text{If } i \text{ contains hazardous substances or not} \quad i = 1,\ldots,I \quad t = 1,\ldots,T \qquad (7)$$

The removal of hazardous substances in disassembly is mandatory before the treatment in bulk recycling. In this model, this can be achieved by the setting $y_{it}^{In} = 0$ in period t initiating external treatment if a scrap type i that contains hazardous substances is not disassembled (7).

$$y_{it}^{C} \geq 0 \qquad i = 1,\ldots,I \qquad t = 1,\ldots,T \qquad (8)$$

$$y_{it}^{D} \geq 0 \qquad i = 1,\ldots,I \qquad t = 1,\ldots,T \qquad (9)$$

$$y_{klt}^{V} \geq 0 \qquad k = 1,\ldots,K \qquad l = 1,\ldots,L \qquad (10)$$

The positive variables are y_{it}^{C}, y_{it}^{D} and y_{klt}^{V} (8) (9) (10).

$$y_{klt}^{V} \leq Y_{klt}^{V,\max} \qquad k = 1,\ldots,K \qquad l = 1,\ldots,L \qquad (11)$$

$$\sum_{l=1}^{L} y_{klt}^{P} \leq Y_{klt}^{P,\max} \qquad k = 1,\ldots,K \qquad l = 1,\ldots,L \qquad (12)$$

$$m_{it}^{C,\min} \leq m_{it}^{C} \leq m_{it}^{C,\max} \quad i = 1,\ldots,I \quad t = 1,\ldots,T \qquad (13)$$

$$y_{it}^{Ex} \leq y_{it}^{Ex,\max} \qquad i = 1,\ldots,I \qquad t = 1,\ldots,T \qquad (14)$$

$$\frac{y_{it}^{A}}{m_i};\frac{y_{it}^{Ex}}{m_i} \in IN_0 \quad i = 1,\ldots,I \qquad t = 1,\ldots,T \qquad (15)$$

$$x_j \in IN_0 \qquad j = 1,\ldots,J \qquad (16)$$

$$\sum_{j=1}^{J} x_{jt} \cdot t_j^{Z} \leq T^{\max} \quad i = 1,\ldots,I \qquad t = 1,\ldots,T \qquad (17)$$

And the very important point is the recycling company must satisfy the environmental obligation level, $m_{it}^{C} \geq m_{it}^{C,\min}$ (13). Capacity restrictions represent input supply (13) as well as output sales capacity (11), (14). Bottlenecks in bulk recycling can appear in every unit due to variations in feed composition. Thus, capacity constraints must be depicted by limits for every unit, too (12). The disassembly capacity restriction refers to a maximum of labor time of the available workers (17).

Disassembly activities as well as the number of discarded products and parts are modeled as integer variables (15) (16).

V. RESULTS AND INTERPRETATION

The basic scenario can be described that the acceptance cost of all the three kinds of products decrease to the lowest in the June and back to the normal level in December. And the metal price decrease to the lowest point in the June and back to normal level in December.

The decision concerning internal or external recycling of scrap types is influenced strongly by the market situation including materials price in metal market and the scarps price in spare market. When the bulk recycling output revenues is increasing, scrap types which have high metal composition should be recycled internally. Scrap types with low material value, for instance telephone parts, are recycled externally in order to gain more profit.

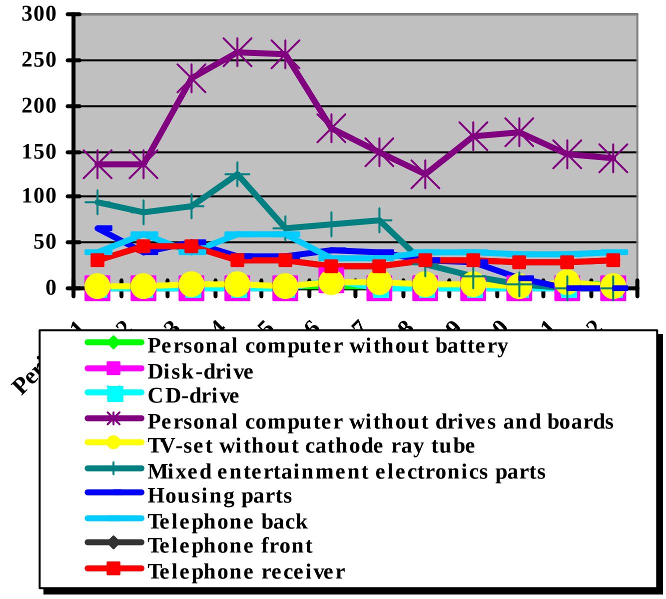

Figure 6. Internal recycling mass decision variable y_{it}^{In} result

The interpretation of the solution for the considered periodical planning model reveals bottlenecks and risks concerning the presented recovery system. Recommendations for future planning can be derived, including design improvement hints and promising strategic positions for the recycling company. For that purpose, the system behaviors under changing conditions has been analyzed by the assessment of different scenarios.

Price variations have been examined as seen in Figure 7. With regard to the choosing of scrap, all acceptance cost are changed to half and to double of the basic scenario respectively. The volatility of material markets is considered by changing the prices to half and to double value. The prices of scraps markets also change to half and to double value.

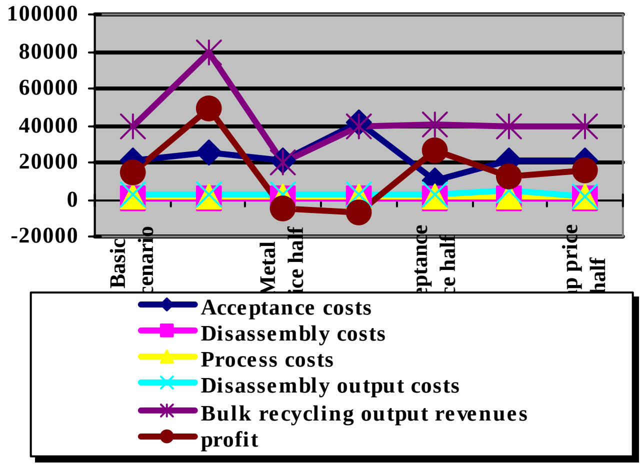

Figure 7. Effect of different scenarios concerning prices

As shown in Figure7, the metal price has the highest impact on the objective value. The share of the bulk recycling output revenues is the only one positive value in this recycling process. The other factor which has the high impact on the objective value is acceptance cost. When the acceptance cost changed to double, the profit almost changed twice profit in basic scenario. When the acceptance cost changed to half, the objective value changed to double also. The recycling company can not control the materials prices in market. So the recycling company should concentrate on acceptance cost more. Changes in scrap prices have been analyzed as well, but the related impacts are very small.

If the company concentrate on the acceptance cost, and the masses of products that can be collected from market. As a result, the recycling companies should get the long term contracts in fixed quantity of collected products and at fixed acceptance price in order to avoiding the uncertainties in the extent market which may be will increase the companies' whole recycling process cost.

The factor that is the biggest share of the recycling companies' profit is materials price. Uncertainly factors in the metal markets can not be avoided by fixed-price contracts. And the recycling company can not control the uncertainly material prices. So the company should focus on the output side of recycling. However, the delivery of reusable parts for spare parts management and as-to-new-pats for the use in production processes are a practical way to secure output proceeds.

VI. CONCLUSION

In this paper, an integrated periodical term recycling planning problem for electronic scrap has been analyzed and formulated as mixed-integer linear programming model, based on the linear activity analysis. The purpose of this periodical operational management task is to get an optimal choice of recovered products for disassembly and bulk recycling as well as an optimal allocation disassembly operations in every period with the price of metals and scraps changing.

In this paper, it is the specific case for China's electronic scraps recycling industry. The most different situation is the acceptance fee, in other countries, the users who want to discard the used-product should pay the relevant fee, but in China, if the recycling companies want to receive enough used-product they must pay for the end-user. So in China, it is means acceptance costs. Thus the recycling companies in China face the more pressure on cost control. While safe recycling operations are not currently viable in China, it is hoped the recycling companies can get profit from recycling process through controlling the total cost or expecting the other financial subsidies.

Compared with the models found before, the presented model has important specific characteristics: It is the periodical planning problem of electronic scraps recycling; the models found before, the model is the daily recovery program but not considering the price changing of scraps and metal materials, and inventory cost.

REFERENCES

[1] Hesselbach, J., Spengler, T., Graf, R., Ploog, M., 2001, Materialkreisläufe schließ VDI Umwelt 4/5, 37-39.
[2] Ploog, M., Spengler, T., 2002, Integrated Planning of Electronic Scrap Disassembly and Bulk Recycling, Proceedings of the IEEE International Symposium on Electronics and the Environment, San Francisco, 263-268
[3] Spengler, T., Püchert, H., Penkuhn, T., Rentz O., 1997, Environmental integrated production and recycling management. European Journal of Operational Research, 97, 308-326.
[4] Meier-Staude, R., Mersmann, A., 1997, Cost-Structure and Cost Factors for Mechanical Processing of Electro-Scrap. Aufbereitungstechnik, 6,287-296.
[5] Koopmans, T.C., 1951, Efficient Allocation of Resources, Econometrica 19, 455-465.
[6] Souren, R., 1996, Theorie betrieblicher Reduktion: Grundlagen, Modellierung und Optimaierungsansätze stofflicher Entsorgungsprozesse (Heidelberg: Physica-Verlag).
[7] Spengler, T., 1998, Industrielles Stoffstrommanagement, Betriebswirtschaftliche Planung und Steuerung von Stoff-und Energieströmen in Produktionsunternehmen(Berlin: Erich-Schmidt-Verlag).
[8] Thomas Spenler, Martin Ploog, and Marcus Schröter, OR spectrum (2003) 25:413-442, Intergrated planning of acquisition, disassembly and bulk recycling: a case study on electronic scrap recovery
[9] Thomas Spengler 2002, IEEE, Decision of Material Flow in Closed-Loop Supply Chains, Decision Support System for Electronic Scrap Recycling Companies

ISBN: 978-988-17012-7-5