The Evaluation of Energy Consumption of Scrap Automotive Parts' Recycling

——Take the Power Seat as an Example

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Abstract. An evaluation model was established in this paper according to the mutual mapping relationships among material and energy consumption in the scrap recycling process of automotive parts. The model provides a new computing method for evaluating the energy consumption quantity in this process. Then this model was applied to a power seat for empirical research, whose data was plugged into the model to conduct the analysis, which verifies the feasibility of the model and the valuable evaluation results were obtained.

1 Introduction

So far, there have been many studies on the life cycle assessment of the automotive products, however, the scrap recycling process was not included in most of them, which led to incomprehensive evaluation results. On the other hand, some scholars have focused on the problems related to the end-of-life vehicles, including the reverse logistics network design, eco-study and technology of remanufacturing[1][2][3], etc. However, the studies on the energy consumption of scrap recycling were relatively rare. Hence, based on the researches of Chen[4] and Tu[5] and other scholars, in this paper, by analyzing the mutual mapping relationships among the material and energy consumption in scrap recycling process, an evaluation model was established, which could be used to compute the quantity of energy consumption of scrap recycling of an automotive part.

2 Establishing Energy Consumption Evaluation Model

Scrap vehicle parts are processed according to the flow chart of automotive products' recycling [6][7], as shown in Fig. 1. Firstly, they are transported through the recycling system to the designated facility, for dismantling, sorting and testing, which is called the dismantling stage. Then the dismantled components are handled with appropriate treatments. Among them, remanufacturing and recycling are referred as the resourcing stage; all the transportation processes are referred as the transportation stage, while disposing of the waste is called the waste disposal stage.

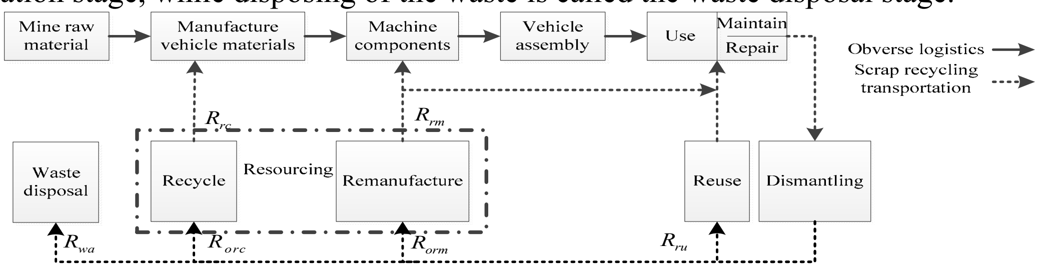


Fig. 1 Flow chart of scrap automotive parts' recycling.

2.1 Materials Mass Model

In order to evaluate the energy consumption, the mass of the materials obtained in the recycle process must be calculated first. Thus, the materials mass model was established to describe the mass of materials and components from the different stages in the automotive parts' recycle process, as shown in Fig.1.

(1) Automotive Parts Mass Matrix

The mass matrix M_1 was set up to describe the components and materials contained in automotive product as follows:

$$M_1 = (m_{1,ij})_{k \times n} \tag{1}$$

Where, k stands for the types of components; n stands for the types of material; $m_{1,ij}$ stands for the mass of the j-th material contained in i-th components.

(2) Material Obtaining Matrices

The material obtaining matrices were set up to calculate the mass of components and materials obtained in scrap recycling, which were divided into the following two cases:

(a) Reusable and remanufactured components are calculated by quantity. After dismantling stage, each kind of component has a ratio, which decides the quantity to be remanufactured, and the k order diagonal matrix R_{orm} can be established by using these ratios as elements; after remanufacturing, each kind of component has a ratio that decides the restored value in use, then the k order diagonal matrix R_{rm} can be established by using these ratios as elements. Eventually, the mass matrix of remanufactured components can be expressed as follow:

$$M_{rm} = R_{rm} \cdot R_{orm} \cdot M_1 \tag{2}$$

The k order diagonal matrix R_{ru} can be established by using the reusable ratio of each kind of component as elements as follow:

$$M_{ru} = R_{ru} \cdot M_1 \tag{3}$$

(b) The recycled and waste disposal material is calculated by mass. After recycling stage, each kind of material has a ratio which decides the quantity to be recycled, the n order diagonal matrix R_{orm} can be established by using these ratios as elements; after being recycled， each kind of material has a ratio which decides the restored value in use, the n order diagonal matrix R_{orm} can be established by using these ratios as elements. Eventually, the mass matrix of recycled materials can be expressed as follow:

$$M_{rc} = M_1 \cdot R_{orc} \cdot R_{rc} \tag{4}$$

The n order diagonal matrix R_{wa} can be established by using the waste disposal ratios of each kind of material as elements as follow:

$$M_{wa} = M_1 \cdot R_{wa} \tag{5}$$

2.2 Energy Consumption Model

(1) Energy Consumption Matrix of Dismantling Stage E_d

The energy consumption matrix of dismantling stage can be established by multiplied mass matrix M_1 by energy consumption intensity matrix EI_d as follow:

$$E_d = M_1 \cdot EI_d \tag{6}$$

$$EI_d = [ei_{d,ij}]_{n \times r} \tag{7}$$

Where, r stands for the types of energy consumed in scrap recycling process, $ei_{d,ij}$ stands for the quantity of the j-th energy consumed in processing the unit mass of i-th material. Other energy consumption intensity matrices have a similar structure as this one.

(2) Energy Consumption Matrix of Resourcing Stage E_{rs}

The mass matrices M_{rm} and M_{rc} are multiplied respectively by energy consumption intensity matrices of remanufacturing and recycle EI_{rm}, EI_{rc}, the results are energy consumption matrices of the remanufactured components E_{rm} and the recycled materials E_{rc}, as following:

$$E_{rm} = M_{rm} \cdot EI_{rm} = R_{rm} \cdot R_{orm} \cdot M_1 \cdot EI_{rm} \tag{8}$$

$$E_{rc} = M_{rc} \cdot EI_{rc} = M_1 \cdot R_{orc} \cdot R_{rc} \cdot EI_{rc} \tag{9}$$

The energy consumption matrix E_{rs} of resourcing stage can be expressed by superimposing the two matrixes above:

$$E_{rs} = E_{rm} + E_{rc} \tag{10}$$

(3) Energy Consumption Matrix of Waste Disposal Stage E_{wa}

The mass matrix M_{wa} is multiplied by energy consumption intensity matrix of waste disposal stage

EI_{wa}; the result is energy consumption matrix E_{wa} of this stage as follow:

$$E_{wa}=M_{wa} \cdot EI_{wa} \tag{11}$$

(4) Energy Consumption Matrix of Transportation Stage E_{tr}

The energy consumption matrix E_{tr} of transportation stage can be expressed as follows：

$$E_{tr}=M_{tr} \cdot T_{tr} \cdot EI_{tr} \tag{12}$$

$$M_{tr} = (m_{tr,ii})_{l\times l} \tag{13}$$

$$T_{tr} = (t_{tr.ij})_{l\times g} \tag{14}$$

$$EI_{tr} = (ei_{tr.ij})_{g\times r} \tag{15}$$

Where, Eq.13 stands for the mass matrix of different kinds of transportation material (the same kind refers to the material that has same transportation distance); Eq.14 stands for the distances of different kinds of material transported by different transportations, g stands for the types of transportation; Eq.15 stands for the energy consumption intensity matrix of transportation stage, $ei_{tr;ij}$ stands for the quantity of energy consumed in transporting the unit mass material through unit distance by different transportations.

(5) Total Energy Consumption Matrix E of Scrap Recycling

Because of the different column amount in energy consumption matrices of every stage, the energy consumption matrices should be translated into matrices of 1 row and r columns by column addition. Then we add the translated matrices to get the total energy consumption matrix as follow:

$$E=[\sum_{i=1}^{k}E_{d,i1}\cdots\sum_{i=1}^{k}E_{d,ij}\cdots\sum_{i=1}^{k}E_{d,ir}]+[\sum_{i=1}^{k}E_{rs,i1}\cdots\sum_{i=1}^{k}E_{rs,ij}\cdots\sum_{i=1}^{k}E_{rs,ir}]+[\sum_{i=1}^{l}E_{tr,i1}\cdots\sum_{i=1}^{l}E_{tr,ij}\cdots\sum_{i=1}^{l}E_{tr,ir}]+[\sum_{i=1}^{k}E_{wa,i1}\cdots\sum_{i=1}^{k}E_{wa,ij}\cdots\sum_{i=1}^{k}E_{wa,ir}] \tag{16}$$

3 Empirical Research

3.1 Empirical Research Object

A power seat was selected as the empirical research object to study the energy consumption of its scrap recycling. There are 14 types of components (length of be confined to, only 4 of them were listed) and 9 types of materials (ferrite and aluminum alloy are relatively less than other material, so ferrite is treated as steel and aluminum alloy is treated as aluminum) in the seat. Table 1 shows the list of components and materials in the power seat. The mass matrix of the seat M_1 can be established according to the list.

Table 1 List of components and materials in the power seat （kg）

	Copper	Steel	Aluminum	PP	PCB	PU	Fabric
Vertical Motor	0.100	0.900	0.360	0.060	0	0	0
Horizontal Motor	0.050	0.358	0.	0.030	0	0	0
Seat Support	0	10.2	0	0	0	0	0
Head Pillow	0	0.430	0	0.015	0	0.180	0.050
…	…	…	…	…	…	…	…
Summation	0.295	21.798	0.410	1.955	0.090	2.380	0.900
Mass Rate	1.06%	78.33%	1.47%	7.03%	0.33%	8.55%	3.23%
Gross Mass	27.828						

3.2 Evaluation and Results

In this paper, a thorough basic data list was collected and substituted into the assessment model to calculate the various stages and the total energy consumption of scrap recycling process.

The data sources include the Gabi database, life cycle inventory data of BJUT for typical energy production, statistical data from authorities like metallurgy and energy, domestic and international literatures, etc. In addition, besides the direct energy consumption as electricity and diesel, the model also considered the upstream energy consumption. Three main types of non-renewable primary energy were focused in this paper, that are raw coal, natural gas and crude oil.

In actual production practice, taking into account the cost of production, maturity of technology and other issues, the metallic components in the seat were to be directly remelted, not for reuse and remanufacturing; and plastic (PP), PCB, foam (PU), and fiber materials were to be disposed with advanced incineration for power generation and production of hot steam, the actual scrap recycling path of the power seat was as shown in Fig. 2.

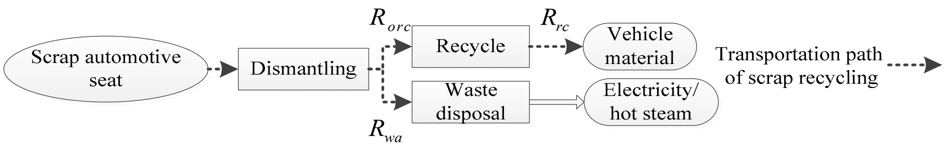


Fig.2 Scrap recycling path of the power seat

(1) Material Obtained

According to the collected data, the matrices R_{orc} and R_{rc} were established and plugged into Eq.4 to calculate the quantity of recycled material. Table 2 showed the comparison between the recycled materials by scrap recycling and the original materials of the seat.

Table 2 The compassion between the recycled and original materials （kg）

	Copper	Steel	Aluminum
Recycled materials	0.221	18.136	0.352
Original materials	0.295	21.798	0.410

(2) Energy Consumption

Due to the length restriction, in this paper we only listed the process of using the model to calculate the energy consumption in the resourcing stage. The processes of computing energy consumption of other stages were similar. Because there was none remanufactured components, the E_{rs} could be expressed as followed:

$$E_{rs} = E_{rm} + E_{rc} = E_{rc} = M_{rc} \cdot EI_{rc} \quad (13)$$

The matrix EI_{rc} could be established as followed, the unit is MJ/kg:

$$EI_{rc} = \begin{bmatrix} 6.6330 & 0.1666 & 2.6223 \\ 12.0856 & 7.4096 & 0.4463 \\ 0.7593 & 4.1544 & 0.4699 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

According to Eq.8, we could compute the energy consumption of obtaining the three kinds of recycled metal in the resourcing stage, as shown in Table 3.

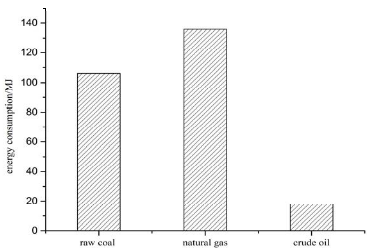
Table 3 Energy consumption in resource stage

Energy consumption / Recycled material	Raw coal （MJ）	Natural gas （MJ）	Crude oil （MJ）
copper	1.464	0.037	0.579
Steel	219.186	134.382	8.094
Aluminum	0.267	1.460	0.165
Summation	220.917	135.879	8.838

In transportation stage, the transported material were divided into three categories including the electric seat, recyclable materials and waste, the corresponding transportation distance included from collection point to dismantling centers, from dismantling centers to recycle centers and from dismantling centers to waste disposal centers. In waste disposal stage, burning the materials like PP and fabric would generate electricity and hot steam. Depending on the relevant database, we calculated the quantity of these three types of primary energy consumed to generate the equivalent electricity and hot steam, and defines the obtained energy as negative (the consumed energy is defined as positive). The negative quantity was actually the energy obtained in the waste disposal stage.

Fig. 3 and Fig. 4 showed the energy consumption of different types in scrap recycling, and the comparison of energy consumption in various stages. The total consumption is 259.932MJ, in which the natural gas consumption accounted for the most up to 135.898MJ; raw coal and crude oil consumption were 106.219MJ and 17.815MJ respectively.

The energy consumption of the resourcing stage is 365.634MJ, the highest among all stages, and the consumption of raw coal and natural gas in this stage are much higher than other stages. The energy consumption in disposal waste stage is -130.581MJ, which can offset 36% of energy consumption in resource stage, while the non-metallic materials' mass only equals 25% of metal materials'. In recycling stage, compared with two other types of primary energies, raw coal has been consumed the most, which is mainly related to China's power structure. The crude oil has been consumed the most in transportation stage for 11.150MJ, 8.838MJ in the resourcing stage.



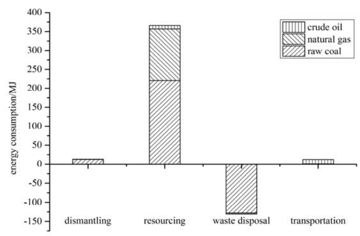


Fig.3 Comparison of different types of energy consumption
Fig.4 Energy consumption in various stages

4 Conclusion

On the basis of preliminary studies, an energy consumption evaluation model was established for scrap recycling of auto parts by constructing the materials mass matrices and the energy consumption matrix, and the model was verified through an empirical research on an auto power seat. The model could be used to accurately calculate the auto parts' consumption of the three main primary energy (raw coal, natural gas, crude oil) in various stages of scrap recycling process (including transportation stage). The evaluation results could provide useful references on improving the energy saving effect and green design level for related enterprises.

5 Acknowledgement

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