Optimizing Reverse Logistics Cost Based on Value Flow Analysis: Case Study on a Chinese Automobile Recycling Company

ZHIFANG ZHOU1,2, YANFEI CAI1, XIAOHONG CHEN2,3, HUIXIANG ZENG1*
1 Business School, Central South University, Changsha, Hunan, China
2 Collaborative Innovation Center of Resource-conserving & Environment-friendly Society and Ecological Civilization, Central South University, Changsha, Hunan, China
3 Hunan University of Commerce, Changsha, Hunan, China

ABSTRACT: The "recycling economy" has emerged in response to the necessity for mitigating the effects of climate change and minimizing the excessive consumption of resources. There is demand within the Internet of Things field for reverse logistics monitoring and environmental monitoring, particularly in terms of recycling economy practices. Integrating the material flow, value flow, and information flow in the Internet of Things can improve the efficiency of the logistics system while reducing its cost. This paper introduces a circular economy-based value flow analysis into the cost accounting, analysis, and optimization of enterprise reverse logistics. We also take into account the external costs (secondary pollution and environmental benefits of recycling) in the reverse logistics cost accounting model. Based on a case study on an automobile recycling company in Hunan Province, China, we propose an approach through which any enterprise may optimize its costs while contributing to the environmentally sustainable development of its surrounding community.

INTRODUCTION

Excessive consumption of resources and problematic environmental destruction currently pose a major threat to the sustainable development of human society, particularly in regards to their effects on the global economy. The “circular economy” or “recycling economy” concept, which is characterized by resource conservation and the recycling or reuse of materials, has become a popular research object to this effect.

Increasing public awareness of environmental issues and the general prevalence of environmental legislation across the globe has pushed more and more enterprises to practice reverse logistics. Reverse logistics can enhance the competitive advantages of participating enterprises, and are a popular approach to implementing green supply chains [1]. Mining the Internet of Things for logistics monitoring, environmental protection, and industrial monitoring becomes has emerged as a notable trend in the reverse logistics field.

As a developing country, China’s resource utilization is low and environmental pollution and ecological damage has grown severe in the country over the course of its rapid economic development in recent decades. In short: China would benefit immensely from developing a circular economy.

China is a major consumer of cars, where car ownership has grown at a remarkable rate and the number of scrapped cars per year has increased just as quickly. A successfully designed reverse logistics network decreases the environmental impact, increases the degree of social responsibility, and effectively accounts for the economic motivations of the enterprise in question [2]. Chinese enterprises tasked with the proper disposal of scrapped automobiles make an interesting example of this. Further, the Internet of Things has opened up new opportunities for tracking scrap car reverse logistics information. In 2011, Chinese citizens owned more than 100 million automobiles while more than 4 million were scrapped. By 2020, 14 million cars are expected to be scrapped per year. If they are not properly disposed of in a timely manner, these cars will represent a huge waste of resources and a massive source of environmental pollution. The Chinese government accordingly promulgated an official scrap car recycling management approach in
2001; in 2006, the NDRC and Ministry of Science and State Environmental Protection Administration jointly issued an automotive product recycling technology policy. Neither attempt has been particularly effective; however, China’s scrap car recycling market is still very complicated. The government is still introducing new incentives to help improve the efficiency of the scrap car recycling industry.

Reverse logistics have gradually attracted the attention of researchers and developers from a wide variety of disciplines. The extant research on reverse logistics is centred around the following aspects: The reverse distribution of waste materials in the supply chain and inventory management [3-5], product remanufacturing management and remanufactured product pricing strategies [6-8], and reverse logistics network design, planning, and efficiency evaluation [9-11]. Chinese scholars began exploring reverse logistics later compared to many other developed countries [12, 13]. These researchers focused more on discarded household appliances than on automobiles, and seldom brought environmental aspects into the cost accounting of reverse logistics optimization and control.

There is urgent need for further studies on environment and resource-related issues in China. With the state vigorously promoting the development of circular economies, research on the scrap car recycling industry is very relevant. Given the limitations of traditional cost accounting methods in this regard, current research on the reverse logistics of automobile recycling companies must be further refined [6, 14, 15]. Using the Internet of Things to innovate waste reverse logistics process, and establishing reverse logistics-informed processes accordingly, may be an effective approach to reducing the auto recycling industry’s operating costs while allowing for close monitoring of its environmental impact.

In this study, we applied the concept of value flow in the circular economy to an innovative reverse logistics cost and analysis method. The proposed method was designed specifically to balance economic and environmental benefits via reverse logistics management – we sought to establish a technique for supporting reverse logistics management and decision-making to reduce costs and improve operational efficiency. The proposed method was applied to a domestic scrap car recycling enterprise as a case study, and its ability to enhance the enterprise’s resource use efficiency, reduce its environmental impact, and promote sustainable social, economic, and environmental development within the surrounding community were analysed as discussed below.

2. Enterprise reverse logistics based on circular economy value flow

2.1 Value flow analysis of the circular economy

Professor Xu Xiao led the value flow analysis of the circular economy and guided the integration of environment and ecological concerns into the economic system. A given circular economy value flow analysis system assigns value to resources based on how efficiently they are utilized, how much it costs to waste them, the amount of environmental damage they cause, and their value added. Value accounting of the resource flow is conducted based on how efficiently they are utilized, how much it costs to waste them, the amount of environmental damage they cause, and their value added. Value accounting of the resource flow is conducted based on the material flow; material flow analysis is based on the principle of balancing the material circulation and tracking input and output volumes to improve resource use efficiency and conserve energy.

Resource flow value accounting must include information regarding material and energy investment, production, consumption, and transfer into products in the manufacturing process. Well-established cost management techniques can be used to track changes in the quantity and value of physical resources throughout manufacturing. Value flow accounting for circular economies is more easily fine-tuned to sustainable development models than traditional accounting techniques; this type of value flow accounting uses the resource output direction and flow of qualified products and waste to establish the distribution of the resource flow, and further, whether resources are truly being utilized effectively.

Enterprise resource flow can move in a forward direction (“positive flow”) or in the reverse (“counter current”), constituting a bidirectional structural analysis model depicted in Figure 1.
As shown in Figure 1, the resource flow can be subdivided into two categories: Forward resource flows (solid lines) and the reverse (dashed lines). Forward resource flow describes a model through which disposable resources are consumed or transformed into products in the production process straightforwardly. Initial investment in the process includes natural ore, fuel, and other raw auxiliary materials ($Y_i$) and energy ($E_i$). A reverse resource flow describes a model through which resources re-flow across production systems or natural systems; this category includes renewable resource streams, secondary resource flow ($R_s$), and wasted resource flow ($R_w$). These can be further subdivided into the consumption of renewable resources ($R_c$) from outside the enterprise and renewable resources produced inside ($R_p$), which include the manufacturing return resource flow ($R_m$) and the functional return resource stream ($R_u$).

The manufacturing return flow of resources includes products, semi-finished products, and scrap materials. Remanufacturing practices are important in terms of enhancing resource utilization efficiency. Functional return resource streams mean that medium-class resources have a fixed and single function that does not change as the process changes, but can be reused; these include water return or secondary-use streams, which can lower both material consumption and costs. The consumption of renewable resources also includes integrating resources that had been scrapped after circulation and consumption by a separate (external) source. Effectively utilizing these means can conserve valuable resources in addition to manufacturing costs and further, they contribute to the establishment of a functional circular economy and sustainable community.

The closed-loop supply chains characteristic of a circular economy can be divided into forward logistics and reverse logistics categories that should be optimized to ensure the most efficient and sustainable use (and reuse) of resources. The resource value flow analysis model can be used to track a given enterprise’s generation of waste, the cost of disposing waste, and their recycling practices. The model can also be adapted to meet the requirements for reverse logistics cost accounting.

### 2.2 Connotation of reverse logistics based on the circular economy

A reverse logistics system concerns product return, material substitution, recycling, waste disposal, and re-manufacturing information. Per its namesake, it moves in the opposite direction as conventional, forward logistics. As discussed in the Introduction, reverse logistics is now a popular research object under increasing pressure for economic and environmental sustainability in China and abroad.

A supply chain is constituted by forward logistics and reverse logistics which together form a closed-loop structure including internal and external components. As shown in Figure 2, forward logistics...
solid line) represents normal demand and commodity-trading activities through procurement, production, distribution, and consumption to meet the needs of consumers. This is the main channel of the logistics flow. As discussed above, logistics can also flow in the reverse (dashed line).

2.3 Constitution of reverse logistics costs based on circular economy

Reverse logistics costs include the expense and material consumption incurred throughout manufacturing, as well as expenses incurred by environmental protection measures; included in these calculations are costs that arise from recycling, reuse, and reasonable disposal of materials, as well as substandard materials, packaging materials, and original use-values. Traditionally, the costs of reverse logistics include: recovery; detection and classification; product disassembly; remanufacturing; waste disposal; transportation and management. Management costs contain the publicity expenses of making the reverse logistics run smoothly, office expenses, travel expenses, and labour costs (base salaries, bonuses, allowances, employee benefits, etc.) as well as expenses incurred in the collection, consolidation, analysis, and transmission of logistics information. In a circular economy, the reverse logistics motto “reduce, reuse, recycle” creates wider implications including the value gains of reduction in environmental damage provided by recycling and the environmental costs of secondary pollution. Recycling waste materials is beneficial both environmentally and economically on the whole, but also produce secondary pollution and must be accounted for accordingly.

3. Optimizing enterprise reverse logistics cost based on circular economy value flow analysis

To meet the requirements of a circular economy, an enterprise must reduce resource consumption while reducing waste emissions so as to operate in an environmentally sustainable manner. Internal damage assessment can assist in this process. In the cost accounting of reverse logistics, to adapt to the requirements of circular economy, resource-saving and environmental benefits resulting from effective reverse logistics planning can be considered revenue. The reverse logistics system can be integrated into a traditional binary accounting and analysis model to calculate the value of environmental damage caused by the enterprise, as well as the value of resources it depletes, waste it emits, and resources it wastes.

First, it is necessary to calculate the cost of each cost center. Positive and negative product costs are equal to each unit price multiplied by the number of units purchased. Waste disposal costs equal the unit price of disposal multiplied by the amount of waste disposed. The amount of waste multiplied by its environmental impact factor coefficient yields the external damage value of waste. The difficulty in external environmental damage value accounting lies in determining the units of the loss. After a comprehensive comparison of available environmental impact assessment methods, we selected LIME, a life-cycle impact assessment method based on endpoint modeling.

The reverse logistics chain is divided into two parts within the closed-loop value chain as a whole: Resource recycling logistics of internal production, and the logistics of consumers recycling the product externally. We assume that both reverse logistics chains necessitate a processing center for resource recycling, testing, and reproduction. Nodes of the reverse logistics chain include collection centers, disassembly centers, remanufacturing centers, and waste disposal centers. The process is illustrated in Figure 3.

As discussed above, the factors which comprise the reverse logistics value flow analysis system include resource consumption, environmental impact, and economic performance. The system can be employed to manage these factors appropriately to promote sustainable development.

3.1 Reverse logistics cost calculation
The proposed cost accounting model is formulated according to the composition and characteristics of reverse logistics as follows:

\[ TC = TC_1 + TC_2 + TC_3 + TC_4 + TC_5 + TC_6 + TC_7 - TR_9 \] (1)

where \( TC_1 \) is collection cost, \( TC_2 \) is test cost, \( TC_3 \) is takedown cost, \( TC_4 \) is remanufacturing cost, \( TC_5 \) is waste disposal cost, \( TC_6 \) is transportation cost, \( TC_7 \) is fixed cost, \( TC_9 \) is the cost of environmental damage due to waste, and \( TR_9 \) denotes environmental benefits.

(1) The reverse logistics process starts with recycling, the cost of which is represented by \( TC_1 \). We examine two scenarios related to this variable: Internal resource recycling logistics, in which the logistics of consumers recycling the product outside of the enterprise. We calculate this as follows:

\[ TC_1 = \sum C_i \cdot N_i \] (2)

where \( C_i \) represents unit operating costs (RMB/T) in the recycling collection center \( i \); \( N_i \) represents the recycling quantity (T).

(2) Testing costs are calculated as follows:

\[ TC_2 = \sum \sum C_j \cdot N_j \] (3)

where \( C_j \) represents the unit operating costs (RMB/T) of detection center \( j \); \( N_j \) represents the number of items from collection center \( p \) center \( i \) to the testing center \( j \).

(3) Takedown costs are calculated as follows:

\[ TC_3 = \sum \sum C_r \cdot N_r \] (4)

where \( C_r \) is the unit operating costs (RMB/T) of takedown center \( r \); \( N_r \) represents the number of items from testing center \( j \) to disassembly center \( r \).

(4) The cost of remanufacturing is calculated as follows:

\[ TC_4 = \sum \sum C_h \cdot N_h \] (5)

where \( C_h \) is the unit operating costs (RMB/T) of remanufacturing center \( h \); \( N_h \) represents the number of items from takedown center \( r \) to remanufacturing center \( h \).

(5) Waste disposal costs are calculated as follows:

\[ TC_5 = \sum \sum C_g \cdot N_g + \sum \sum C_{rg} \cdot N_{rg} + \sum \sum C_{rh} \cdot N_{rh} \] (6)

where \( C_g \) represents the unit cost of waste disposal (RMB/T); \( N_{rg} \) represents the amount of waste that cannot be recycled as-detected at the testing center; \( N_{rh} \) represents the amount of waste that cannot be recycled after demolition; \( N_{rg} \) expresses the amount of newly-generated waste in remanufacturing center \( h \).

(6) Transportation costs are calculated as follows:

\[ TC_6 = \sum \sum DC_j \cdot N_j + \sum \sum DC_{rg} \cdot N_{rg} + \sum \sum DC_{rh} \cdot N_{rh} \] (7)

where \( DC_{ji} \) represents unit transportation costs (RMB/T) from collection center \( i \) to testing center \( j \); \( DC_{rg} \) represents unit transportation costs from testing center \( j \) to disassembly center \( r \); \( DC_{rh} \) represents unit transportation costs from disassembly center \( r \) to remanufacturing center \( h \); \( DC_{rg} \) represents unit transportation costs from takedown center \( r \) to waste disposal center \( g \); \( DC_{hg} \) represents unit transportation costs from remanufacturing center \( h \) to waste disposal center \( g \).

(7) Fixed costs are calculated as follows:

\[ TC_7 = \sum (FC_i + FC_j + FC_r + FC_g) \] (8)

where \( FC_i \) represents fixed costs (RMB) of collection center \( i \); \( FC_j \) represents fixed costs of detection center \( j \); \( FC_r \) represents fixed costs of disassembly center \( r \); \( FC_g \) represents fixed costs of remanufacturing center \( h \).

(8) External environmental damage cost due to waste is calculated as follows:

\[ TC_8 = L \times \left( \sum \sum c_{ji} \cdot N_{ji} + \sum \sum c_{rg} \cdot N_{rg} + \sum \sum c_{rh} \cdot N_{rh} \right) \] (9)

where \( L \) is a comprehensive evaluation factor of the environmental impact (RMB/T).

(9) Gains resulting from the reduction in environmental damage through recycling are calculated as follows:

\[ TC_9 = L \times \left( \sum \sum c_{ji} \cdot N_{ji} - \sum \sum c_{rg} \cdot N_{rg} - \sum \sum c_{rh} \cdot N_{rh} \right) \] (10)

By considering a variety of factors affecting cost in the reverse logistics system, a control and decision model can be established to assist the enterprise in determining economically and environmentally beneficial solutions.

3.2 Optimization of reverse logistics cost in value flow analysis of circular economy

In the construction of reverse logistics, the position of the various nodes has a pronounced impact on operating efficiency. To ultimately help enterprises make better decisions, we reformulated the reverse logistics cost optimization model to minimize total operational costs according to various impact factors. The optimal cost plan can be
identified after accounting for and analyzing every factor in the reverse logistics chain.

To simplify the model, we make the following assumptions:

(1) The quantity of waste products recycled, the processing capacity of various facilities, and investment/operation/transportation costs across various facilities are known.

(2) Material loss in the process of recycling is negligible.

(3) The expansion of logistics facilities occurs not only at the enterprise itself, but also includes inputs helpful to improving productivity such as production lines and new technologies.

(4) New logistics facilities are set in known alternative geographic locations.

(5) Fixed costs include storage charges, utility bills, and other items generated by the logistics node facility.

The reverse logistics cost control model is as follows:

\[
\begin{align*}
\min Z &= \sum_{i} C_i \cdot N_i + \sum_{j} J_j, \\
&= \sum_{i} C_i \cdot N_i + \sum_{j} J_j + \sum_{r} R_r + \sum_{h} H_h + \sum_{g} G_g,
\end{align*}
\]

s.t: 

\[
\begin{align*}
\sum_{j} N_{jr} &= (1-\alpha) \sum_{i} N_i, \\
\sum_{r} N_{ir} &= (1-\beta) \sum_{j} N_j, \\
\sum_{j} N_{jr} &= \alpha \sum_{i} N_i, \\
\sum_{r} N_{ir} &= \beta \sum_{j} N_j, \\
\sum_{k} N_{hk} &= \mu \sum_{r} N_{rk}, \\
L_i &\leq \sum_{j} N_{jr} \leq U_i, \\
L_j &\leq \sum_{r} N_{ir} \leq U_j, \\
L_R &\leq \sum_{j} N_{jr} \leq U_R, \\
L_h &\leq \sum_{r} N_{ir} \leq U_H, \\
L_G &\leq \sum_{j} N_{jr} + \sum_{r} N_{ir} + \sum_{k} N_{hk} \leq UG_g, \\
\sum_{i} y_i &\leq I, \\
\sum_{j} y_j &\leq J, \\
\sum_{r} y_r &\leq R, \\
\sum_{k} y_k &\leq H, \\
\sum_{g} y_g &\leq G, \\
y_i, y_j, y_r, y_k, y_g &\in [0,1], \\
i &\in I, j &\in J, r &\in R, h &\in H, g &\in G, \\
N_i, N_j, N_r, N_k, N_g &\geq 0.
\end{align*}
\]

Target formula (11) means maximizing profits in enterprises with reverse logistics; constraint equations (12)-(16) describe the flow conservation conditions; formulas (17)-(21) limit the capacity of logistics facilities; formulas (22)-(26) indicate the limit on the number of logistics facilities; formulas (27)-(29) provide for the range of each variable.

(1) Decision variables
\(y_i, y_j, y_r, y_h,\) and \(y_g\) are 0-1 variables that indicate whether new or expanded nodes exist: Yes means 1, no means 0.

(2) Parameter description

\(\alpha\) represents the scrap rate in a given testing centre; \(\beta\) represents the scrap rate of a demolition centre; \(\mu\) represents the waste generation rate of a remanufacturing centre; \(I, J, R, H,\) and \(G\) are the maximum number of collection, detection, manufacture, and waste processing centres, respectively; \(P_i\) is the purchase price of waste recycling products.

\(L_i\) and \(U_i\) represent the minimum and maximum processing capacity of collection center \(i;\) \(L_j\) and \(U_j\) represent the minimum and maximum processing capacity of center \(j;\) \(L_r\) and \(U_r\) denote the minimum and maximum processing capacity of disassembly center \(r;\) \(L_h\) and \(U_h\) denote the minimum and maximum processing capacity of remanufacturing center \(h;\) and \(L_g\) and \(U_g\) denote the minimum and maximum processing the capacity of waste disposal center \(g.\)

The model above is a mixed integer linear programming model that can be solved in LINGO software, a program for solving linear programming problems. By solving the model, we can derive the optimal cost of reverse logistics planning and then implement a further cost estimation to obtain binary values that include the internal and external costs of consumption. The cost-optimized operating mode can then finally be selected to maximize economic and environmental benefits.

4. Case study

We were assisted by professional scrap car recycling company D from Hunan Province, China, to test the proposed model on its reverse logistics decisions. The primary services offered by Company D include recycling, dismantling, and remanufacturing waste cars. It can be regarded as a third-party logistics enterprise. Company D intends to further utilize the portion of its business that is currently disposed as waste to respond to the government’s call for resource and energy conservation. The company has signed a recycling contract with a local car manufacturer that is responsible for the recycling, dismantling, and disposal of scrap cars (Figure 4). This enterprise strips and crushes scrap cars before sending the material to two recycling centers and a center for disassembly and metal grinding. The company has signed a cooperation agreement with a manufacturer and metal processing plant that will utilize their metal components and parts. The company currently recycles 5,000 tons of used cars every year, at an annual total cost of RMB 11,105,875.50 (after adjustment for the value of the external environmental damage).

Fig. 4 Scrap car dismantling process

Due to the increase in discarded vehicles mentioned in the Introduction section, Company D’s operating facilities can no longer meet the demand for their services. The company has decided to expand their production capacity by adding logistics services in the local region by either building out the original facility or constructing some new facilities in a new location. In calculating the actual operational processes of the company, we adjusted the previous cost control model appropriately, adding a metal grinding center instead of a testing center, counting only the relevant freight of remanufacturing and waste treatment sectors and not counting operating and fixed costs. After dismantling about 40% of the scrap cars and sending them into the remanufacturing process, and sending 50% into the metal grinding process, the solid waste output rate of dismantling and crushing vehicles is 10%. The company can use the adjusted cost control and decision model to re-plan the structure of its scrap car recycling logistics and optimize its total logistics costs.

There are four alternative recycling locations currently: \(I_1\) and \(I_2\) are the original collection centers that can be extended, and \(I_3\) and \(I_4\) are candidate sites for new collection centers. There are four alternative dismantling centers: \(J_1\) and \(J_2\) are the existing scrap vehicle dismantling centers that can be expanded and \(J_3\) and \(J_4\) are candidates for new dismantling centers. There are three alternative metal grinding centers, where \(R_1\) considers the expansion of the existing metal grinding center and \(R_2\) and \(R_3\) can be considered new metal grinding centers. Remanufacturer \(H\) and metal processing
plant $M$ will join in the cooperation. Solid waste is transported to state-sponsored waste disposal site $G$.

It is difficult to set parameters such as unit operational costs directly from reported statistical data because most business records are confidential. All the related parameters were filled in here through what data was gathered and estimated based on interviews with relevant personnel. In general, the environmental impact evaluation coefficient $L$ has estimated an value of 650 (LIME value here is calculated using the weighted average of the original model’s standards with appropriate adjustments). Other estimated parameters are as follows.

### Table 1 Scrap car recycling capacity of each expanded or newly-built collection center (Ni) Unit: T

<table>
<thead>
<tr>
<th>Collection center</th>
<th>$I_1$</th>
<th>$I_2$</th>
<th>$I_3$</th>
<th>$I_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2037</td>
<td>2437</td>
<td>3000</td>
<td>2718</td>
</tr>
</tbody>
</table>

### Table 2 Minimal processing capability ($L_{ij}$) and maximum processing capacity ($U_{ij}$) for each expanded or newly-built dismantling center Unit: T

<table>
<thead>
<tr>
<th>Dismantling center</th>
<th>$I_j$</th>
<th>$I_2$</th>
<th>$I_3$</th>
<th>$I_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{ij}$</td>
<td>1600</td>
<td>2100</td>
<td>2500</td>
<td>3800</td>
</tr>
<tr>
<td>$U_{ij}$</td>
<td>1900</td>
<td>2700</td>
<td>4500</td>
<td>5100</td>
</tr>
</tbody>
</table>

### Table 3 Minimum processing capacity ($L_{ij}$) and maximum processing capacity ($U_{ij}$) for each expanded or newly-dismantled metal-grinding center Unit: T

<table>
<thead>
<tr>
<th>Metal grinding center</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{ij}$</td>
<td>1600</td>
<td>2200</td>
<td>2900</td>
</tr>
<tr>
<td>$U_{ij}$</td>
<td>1600</td>
<td>2600</td>
<td>5800</td>
</tr>
</tbody>
</table>

### Table 4 Unit transport costs from recycling center to dismantling center Unit: RMB/T

<table>
<thead>
<tr>
<th>Dismantling center</th>
<th>$I_j$</th>
<th>$I_2$</th>
<th>$I_3$</th>
<th>$I_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_1$</td>
<td>12</td>
<td>17</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>$J_2$</td>
<td>18</td>
<td>16</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>$J_3$</td>
<td>10</td>
<td>8</td>
<td>26</td>
<td>15</td>
</tr>
<tr>
<td>$J_4$</td>
<td>32</td>
<td>15</td>
<td>24</td>
<td>30</td>
</tr>
</tbody>
</table>

### Table 5 Unit transportation costs from dismantling center to metal-grinding center Unit: RMB/T

<table>
<thead>
<tr>
<th>Metal grinding center</th>
<th>$I_j$</th>
<th>$I_2$</th>
<th>$I_3$</th>
<th>$I_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_1$</td>
<td>825000</td>
<td>900000</td>
<td>290000</td>
<td>825000</td>
</tr>
<tr>
<td>$J_2$</td>
<td>107500</td>
<td>125000</td>
<td>113000</td>
<td>156000</td>
</tr>
<tr>
<td>$J_3$</td>
<td>140000</td>
<td>150000</td>
<td>140000</td>
<td>150000</td>
</tr>
</tbody>
</table>

### Table 6 Unit transportation costs from dismantling center to remanufactured center Unit: RMB/T

<table>
<thead>
<tr>
<th>Remanufacturer center</th>
<th>$J_1$</th>
<th>$J_2$</th>
<th>$J_3$</th>
<th>$J_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>30</td>
<td>7</td>
<td>44</td>
<td>23</td>
</tr>
</tbody>
</table>

### Table 7 Unit transportation costs from metal-crushing center to metal-processing plants Unit: RMB/T

<table>
<thead>
<tr>
<th>Metal processing plants</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>14</td>
<td>17</td>
<td>27</td>
</tr>
</tbody>
</table>

### Table 8 Unit transportation costs from dismantling center to waste-disposal site Unit: RMB/T

<table>
<thead>
<tr>
<th>Waste disposal site</th>
<th>$J_1$</th>
<th>$J_2$</th>
<th>$J_3$</th>
<th>$J_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>18</td>
<td>20</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>17</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>

### Table 9 Fixed costs and unit operation costs for each expanded or newly-build center Unit: RMB

<table>
<thead>
<tr>
<th>Center</th>
<th>$I_j$</th>
<th>$I_2$</th>
<th>$I_3$</th>
<th>$I_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC$_1$</td>
<td>87500</td>
<td>80000</td>
<td>910000</td>
<td>825000</td>
</tr>
<tr>
<td>C$_1$</td>
<td>113000</td>
<td>125000</td>
<td>1300</td>
<td>950</td>
</tr>
<tr>
<td>FC$_2$</td>
<td>107000</td>
<td>125000</td>
<td>113000</td>
<td>156000</td>
</tr>
<tr>
<td>C$_2$</td>
<td>140000</td>
<td>150000</td>
<td>140000</td>
<td>150000</td>
</tr>
<tr>
<td>FC$_3$</td>
<td>140000</td>
<td>150000</td>
<td>140000</td>
<td>150000</td>
</tr>
<tr>
<td>C$_3$</td>
<td>500</td>
<td>430</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

The LINGO software yielded results suggesting the expansion of collection centers $I_1$ and $I_2$, removal of center $J_2$, and establishment of new dismantling center $J_3$ and new metal-grinding center $R_2$. According to the new operating program, the largest operational capacity reached was 9,474 tons – an increase of 89% over the original. The minimum added cost is RMB 7,466,430, an increase of only 67% over the original. The traffic volume between the various selected locations was determined as shown in Figure 5.

![Fig. 5 Logistics processes and volume of company D](image)

The total added cost was indeed reduced by introducing the environmentally friendly benefits described above. These results may serve as a reference for future government subsidy policies. It is worth noting that operational costs comprised the majority of the total recycling cost, and that the operational cost of the dismantling center comprised the majority of the operational cost (nearly 47%); therefore, the most efficient way to reduce the system’s total cost is to reduce the operational cost of the dismantling center.

### 5. Conclusions

Reverse logistics represents an innovative approach to sustainable development in regards to
both the economy and the environment. It is readily applicable not only to circular economies, but to supply chain logistics process visualization as-assisted by the Internet of Things. In this study, concepts related to the value flow accounting of circular economies were introduced into a reverse logistics cost calculation process; the ultimate goals were to 1) properly account for internal cost and external damage value factors in a typical reverse logistics management scenario, and 2) to formulate an effective reverse-flow logistics model based on the circular economy value flow analysis. We utilized a scrap car recycling business as a case study to test the proposed method and found that by redesigning the reverse logistics network to optimize costs, the enterprise’s expenses and environmental impact can be reduced in such a way that benefits both the economy and the community.

Methods for integrating the Internet of Things into real-world enterprises in regards to material flow and value flow merit further research. The system discussed in this study needs fine-tuning before it can be applied to existing supply chain enterprises, and the advantages inherent to the Internet of Things must be exploited properly to fully realize the potential economic and environmental benefit.

6. Acknowledgements

I would like to thank all the seminar participants at Central South University for their valuable comments throughout our discussions. My thanks also to the two anonymous reviewers who provided much sound advice on this paper. I would like to thank my wife for her work editing this paper. All remaining errors are my own.

This research was supported by the National Natural Science Funds of China (No. 71303263), the Major Program of the National Social Science Fund of China (11&ZD166, 15ZDA020), the State Key Program of National Natural Science of China (No. 71431006), the Innovation Driven Program of Central South University (2015CX010), the Doctoral Fund of the Ministry of Education (20130162120045) and the Research and Innovation Project for Postgraduate in Hunan Province of China (CX2016B036).

7. REFERENCES