Reverse logistics network design considering customer convenience and low carbon emissions

Bin Wang¹,², Hao Hao² and Hehuang Li²

¹College of International Vocational Education, Shanghai Polytechnic University, 2360 Jinhai Road, Pudong New District, Shanghai, China
²School of Economics and Management, Shanghai Polytechnic University, 2360 Jinhai Road, Pudong New District, Shanghai, China
³E-mail: wangbin@sspu.edu.cn

Abstract. Reverse logistics planning has to consider operating cost, environmental cost and customer service convenience. Multi-objective programming is applied to establish reverse logistics network planning model. The objective function is to minimize the operating costs of reverse logistics enterprises, minimize carbon dioxide emissions and maximize customer convenience. Decision variables include whether the nodes in reverse logistics network are set up or not, and the volume of logistics transportation between nodes in each stage. Constraints include meeting customer needs, flow balance among logistics nodes in each stage, capacity limitation of facilities, etc. The application of this research model can effectively improve the efficiency and sustainable competitiveness of reverse logistics enterprises.

1. Introduction
Today reverse logistics network planning is receiving more attention from academia and business. For enhancing their sustainable competitiveness, reverse logistics companies not only need to reduce operating costs, but also have to bear the obligation to reduce carbon emissions, and at the same time, they must improve customer service levels.

Scholars at home and abroad have conducted extensive research on reverse logistics. Wang Shengchi et al. studied the layout of reverse logistics network for re-manufacturing of multinational enterprises with the goal of revenue and performance [1]. Zhou Yongsheng and Wang Shouyang established a reverse logistics distribution network considering both repair and re-manufacturing modes [2]. Chen Yong et al. established a multi-cycle and multi-objective reverse logistics network model for waste household appliances with the goal of maximizing corporate profits and minimizing the negative utility of recycling centers to residents [3]. Zoha. M et al. established a multi-objective planning model for a closed-loop supply chain that considers both forward logistics and reverse logistics [4]. Zarbaksh Nia. N et al. established a multi-objective planning model combining forward and reverse logistics [5]. John S T et al. focuses on the design of a multi-stage reverse logistics network for product recovery [6]. Abdallah et al. observe that efficient design of a product recovery network is one of the challenges facing the emerging field of reverse logistics [7]. Eskandarpour M et al. study the reverse logistics network design involving recycling, repairing, but re-manufacturing is not included [8]. Hatefi S M and Jolai F design a reverse logistics network design considering recycling, repairing and re-manufacturing [9]. Demirel E et al. build a multi-period reverse logistics network considering recycling, but recycling and re-manufacturing are excluded [10].
The current research on reverse logistics network design focuses on minimizing operating costs or minimizing carbon emissions, without considering customer convenience. Operating costs are visible and are short-term indicators of corporate profits. Excessive carbon emissions will lead to fines imposed by the government on enterprises, so it is also one of the short-term cost targets. The convenience of customer service is not included in the short-term profit of the enterprise, so the current research does not consider the three together. This article makes up for the shortcomings of the above studies. A multi-objective planning model for reverse logistics network design is established. In the model, the company's operating costs, environmental protection factors (carbon dioxide emission limits), and customer service convenience experience (minimize the customer's transportation distance) are systematically considered. Because of the current fierce competition in reverse logistics companies, they must establish stable strategic partnerships with customers, otherwise they will lose their customers and sustainable competitiveness.

2. Mathematical model
Reverse logistics network includes every regional collection center, centralized collection centers and re-manufacturing centers. The materials flow between every node are distributed in Figure 1.

![Figure 1. Structure of reverse logistics.](image)

Freight flows between adjacent nodes generate transportation costs, and the sum of transportation costs between different nodes is the total transportation cost. Minimizing total transportation costs is the first goal. Carbon dioxide emissions are generated by the cargo flows of adjacent nodes, and the sum of the carbon dioxide emissions between different nodes is the total emissions. Minimizing total carbon dioxide emissions is the second goal. Minimizing the distance from customers to regional collection centers is the third goal.

2.1. Parameters
$I$: Set of customers.
$A$: Set of regional collection centers.
$J$: Set of centralized collection centers.
$F$: Set of re-manufacturer centers.
$R$: Set of recycling centers.
$B$: Set of second-hand markets.
$FC_a, FC_j, FC_f$: Unit fixed cost of facility $a, j, f$, $a \in A, j \in J, f \in F$
$TC_{aj}$: Unit product shipping cost from regional collection center $i$ to centralized collection center $j$.
$TC_{jf}$: Unit product shipping cost from centralized collection center $j$ to re-manufacturer center $f$.
$TC_{fr}$: Unit product shipping cost from re-manufacturer center $f$ to recycling center $r$. 
TC: Unit product shipping cost from re-manufacturer center \( f \) to second-hand center \( r \).

EC: CO\(_2\) emissions from transporting unit products from regional collection center \( a \) to centralized collection center \( j \).

EC: CO\(_2\) emissions from transporting unit products from centralized collection center \( j \) to re-manufacturer center \( f \).

EC: CO\(_2\) emissions from transporting unit products from re-manufacturer center \( f \) to recycling center \( r \).

EC: CO\(_2\) emissions from transporting unit products from re-manufacturer center \( f \) to second-hand market \( b \).

C: Cost of a unit of product purchased from customer \( i \).

PC: Cost of processing unit product at regional collection center \( a \).

PC: Cost of processing unit product at centralized collection center \( j \).

PC: Cost of processing unit product at re-manufacturer center \( f \).

Q: Number of products offered by customer \( i \).

D: Distance from customer \( i \) to regional collection center \( f \).

C\(_\text{min}\): Capacity of facility \( k \), \( k = a, j, f \).

\( \lambda \): Proportion of products that can be sold to the secondary market after processing in re-manufacturing center \( f \).

M: Large enough positive number.

2.2. Decision variables

\( X_k \): \( X_k = 1 \) means facility \( k \) on operation; \( X_k = 0 \) means facility \( k \) on non-operation; \( (k = a, j, f) \)

\( X_{ia} \): \( X_{ia} = 1 \) means customer \( i \) is distributed to regional collection center \( a \); \( X_{ia} = 0 \) means customer \( i \) is not distributed to regional collection center \( a \);

\( Q_{aj} \): Number of product shipments from regional collection center \( a \) to centralized collection center \( j \).

\( Q_{jf} \): Number of product shipments from centralized collection center \( j \) to re-manufacturer center \( f \).

\( Q_{rb} \): Number of product shipments from re-manufacturer center \( j \) to recycling center \( r \).

\( Q_{fb} \): Number of product shipments from re-manufacturer center \( f \) to second-hand market \( b \).

\( D_{\text{max}} \): Upper limit of distance from a customer to a regional collection center.

2.3. Objective function

Objective function 1:

\[
\text{Min} Z_i = FC + VC + CC + SC
\]  

Objective function 1 is to minimize the operational cost of reverse logistics.

\[
FC = \sum_a FC_a X_a + \sum_j FC_j X_j + \sum_f FC_f X_f
\]  

\( FC \) shows the establishment cost of each regional collection center, centralized collection center and re-manufacturing center.

\[
VC = \sum_i \sum_a PC_a Q_{ia} X_{ia} + \sum_a \sum_j PC_j Q_{aj} + \sum_j \sum_f PC_f Q_{jf}
\]  

3
VC shows product processing costs for each regional collection center, centralized collection center, and re-manufacturing center.

\[ CC = \sum_i C_i Q_i \]  

(4)

CC shows the cost of collection at each customer.

\[ SC = \sum_a \sum_j TC_{aj} Q_{aj} + \sum_j \sum_f TC_{jf} Q_{jf} + \sum_f \sum_r TC_{fr} Q_{fr} + \sum_r \sum_b TC_{rb} Q_{rb} \]  

(5)

SC shows the total transportation cost of each customer to each regional collection center, each regional collection center to each centralized collection center, each centralized collection center to each secondary market, and each centralized collection center to each recycling center.

Objective Function 2:

\[ \text{Min} Z_{E2} = \sum_a \sum_j EC_{aj} Q_{aj} + \sum_j \sum_f EC_{jf} Q_{jf} + \sum_f \sum_r EC_{fr} Q_{fr} + \sum_r \sum_b EC_{rb} Q_{rb} \]  

(6)

Objective function 2 minimizes the sum of carbon dioxide emissions from each regional collection center to each centralized collection center, each centralized collection center to each re-manufacturing center, each re-manufacturing center to each recycling center/second-hand market.

Objective Function 3:

\[ \text{Min} Z_{E3} = D_{\text{max}} \]  

(7)

Objective function 3 minimizes the longest distance from a customer to a regional collection center.

2.4. Constraints

\[ \sum_a X_{ia} \geq 1 \quad \forall a \in A \]  

(8)

Constraint (8) indicates that at least one regional collection center is operational.

\[ \sum_j X_{ij} \geq 1 \quad \forall j \in J \]  

(9)

Constraint (9) indicates that at least one centralized collection center is operational.

\[ \sum_f X_{jf} \geq 1 \quad \forall f \in F \]  

(10)

Constraint (10) indicates that at least one re-manufacturing center is operational.

\[ \sum_a X_{ia} = 1 \quad \forall i \in I \]  

(11)

Constraint (11) indicates that any customer is assigned to one and only one regional collection center.

\[ \sum_i X_{ia} \leq MX_a \quad \forall a \in A \]  

(12)

Constraint (12) indicates that customers can be assigned to a regional collection center only when it operates.

\[ D_{ia} X_{ia} \leq D_{\text{max}} \quad \forall i \in I, a \in A \]  

(13)

Constraint (13) indicates the distance-limit of any customer to its assigned regional collection center.

\[ \sum_i Q_{ai} X_{ia} = \sum_j Q_{aj} \quad \forall a \in A \]  

(14)

Constraint (14) indicates that the product inflow and outflow balance for any regional collection center.

\[ \sum_a Q_{aj} = \sum_f Q_{jf} \quad \forall j \in J \]  

(15)

Constraint (15) indicates that the product inflow and outflow balance for any centralized collection center.
\[
\lambda_f \left( \sum_j Q_{jf} \right) = \sum_b Q_{fb} \quad \forall f \in F 
\]  

(16)

Constraint (16) indicates that the product flow balance from any centralized collection center to the secondary market.

\[
(1 - \lambda_f) \left( \sum_j Q_{jf} \right) = \sum_r Q_{jr} \quad \forall f \in F 
\]  

(17)

Constraint (17) indicates that the product flow balance from any centralized collection center to recycling center.

\[
\sum_i Q_{ia} X_{ia} \leq C_a^{\text{max}} X_j \quad \forall a \in A 
\]  

(18)

Constraint (18) indicates the capacity limit of each regional collection center.

\[
\sum_a Q_{aj} \leq C_j^{\text{max}} X_j \quad \forall j \in J 
\]  

(19)

Constraint (19) indicates the capacity limit of each centralized collection center.

\[
\sum_f Q_{jf} \leq C_f^{\text{max}} X_f \quad \forall f \in F 
\]  

(20)

Constraint (20) indicates the capacity limit of each re-manufacturing center.

\[
Q_{aj}, Q_{jf}, Q_{jr}, Q_{fb}, D_{\text{max}} \geq 0 \quad \forall a \in A, j \in J, f \in F, r \in R, b \in B 
\]  

(21)

Constraint (21) indicates non-negative constraint on any variable.

3. Numerical examples

In the following numerical example, we use the data of Shanghai Conway Logistics Company as the model parameter. The company's main business is to collect used tires. The data are list below. \( I = 20 \), \( A = 8 \), \( J = 4 \), \( F = 2 \), \( R = 3 \), \( B = 2 \). The demand of each customer is 50, and the fixed cost of each regional collection center is 100 yuan. \( Q_i = 50 \), \( C_i = 15 \), \( C_a^{\text{max}} = 150 \), \( FC_a = 100 \), \( PC_a = 80 \), \( C_j^{\text{max}} = 400 \), \( FC_j = 200 \), \( PC_j = 100 \), \( C_f^{\text{max}} = 600 \), \( FC_j = 300 \), \( PC_j = 250 \). The unit transportation cost from each regional collection center to each centralized collection center is 50 yuan. The unit transportation cost from each centralized collection center to re-manufacturing center \( f_1 \) is 50 yuan, to the re-manufacturing center \( f_2 \) is 40 yuan. The unit transportation cost from each re-manufacturing center to recycling center \( r_1 \) is 45 yuan, to \( r_2 \) is 50 yuan, and to \( r_3 \) is 55 yuan. The unit transportation cost from each re-manufacturing center to the secondary market \( E \) is 0.7. The distance from everybody customer to every regional collection center is shown in below. \( D_{ia} = 29(a = 1, \ldots, 8) \), \( D_{ia} = 32(a = 1, \ldots, 8) \), \( D_{ia} = 36(a = 1, \ldots, 8) \), \( D_{ia} = 45(a = 1, \ldots, 8) \), \( D_{ia} = 52(a = 1, \ldots, 8) \), \( D_{ia} = 43(a = 1, \ldots, 8) \), \( D_{ia} = 52(a = 1, \ldots, 8) \), \( D_{ia} = 57(a = 1, \ldots, 8) \), \( D_{ia} = 69(a = 1, \ldots, 8) \), \( D_{ia} = 70(a = 1, \ldots, 8) \), \( D_{ia} = 71(a = 1, \ldots, 8) \), \( D_{ia} = 74(a = 1, \ldots, 8) \), \( D_{ia} = 35(a = 1, \ldots, 8) \), \( D_{ia} = 73(a = 1, \ldots, 8) \), \( D_{ia} = 41(a = 1, \ldots, 8) \), \( D_{ia} = 79(a = 1, \ldots, 8) \), \( D_{ia} = 43(a = 1, \ldots, 8) \), \( D_{ia} = 70(a = 1, \ldots, 8) \), \( D_{ia} = 40(a = 1, \ldots, 8) \), \( D_{ia} = 72(a = 1, \ldots, 8) \). The model in this paper is solve by the e-constraint method. For multi-objective programming model,

\[
\min(f_1(X), \ldots, f_p(X)), \text{ subject to } X \in S, 
\]

Following single objective programming models are firstly solved

\[
\min f_i(X), \text{ subject to } X \in S, (i = 1, \ldots, p) 
\]
$Z_i$ is value of their objective functions. Then the single objective programming model is solved.

$$\min f_i(X), \quad \text{subject to} \quad f_j(X) \leq \varepsilon_i, \quad (i = 2, \cdots, p), \quad X \in S, \quad \varepsilon_i \geq Z_i, \quad (i = 2, \cdots, p).$$

The model solution is shown in Table 1 below.

| $\varepsilon_2$ | $\varepsilon_3$ | $\varepsilon_4$ | $\varepsilon_5$ | $Z_1$   | $Z_2$   | $Z_3$   |
|----------------|----------------|----------------|----------------|--------|--------|--------|
| $0.3Z_2 + Z_3$ | $0.6Z_3 + Z_4$ | 162240         | 104            | 589000 | 140800 | 67     |
| $0.2Z_2 + Z_3$ | $0.5Z_3 + Z_4$ | 149760         | 97.5           | 588500 | 141000 | 69     |
| $0.15Z_2 + Z_3$| $0.4Z_3 + Z_4$ | 143520         | 91             | 586520 | 142800 | 78     |
| $0.1Z_2 + Z_3$ | $0.3Z_3 + Z_4$ | 137280         | 84.5           | 586500 | 141800 | 78     |
| $0.05Z_2 + Z_3$| $0.2Z_3 + Z_4$ | 131040         | 78             | 586380 | 141800 | 77     |

It can be seen from the above results, with the increase of $\varepsilon_2$ and $\varepsilon_3$, $Z_i$ gradually decreases, but $Z_2$ and $Z_3$ increase with the decrease of $Z_i$. For example, when $Z_1$ decreasing from 589,000 to 586500, $Z_2$ increases from 140800 to 142800 and $Z_3$ from 67 to 78. This shows that objective function 1 and objective function 2, 3 are in conflict. In management practice, enterprises need to balance the operating costs of the entire logistics system according to environmental factors. But the three objections are not conflicting within a certain range. For example, when $Z_1$ was reduced from 586520 yuan to 586380 yuan, $Z_2$ decreased from 142800 to 141800 and $Z_3$ from 78 to 77. Therefore, companies can reduce operating costs, while reducing environmental costs and improving customer convenience in a reasonable range.

4. Conclusions

Reverse logistics is an important part of the circular economy, and competition in the reverse logistics industry is fierce at the same time. The reverse logistics process must consider not only costs, but also environmental factors and customer convenience. The multi-objective planning model of reverse logistics established in this paper can systematically optimize the company's operating costs, carbon dioxide emissions and customer service levels on the premise of meeting customer needs.

Acknowledgements

The paper is funded by Gaoyuan Discipline of Shanghai-Environmental Science and Engineering (Resource Recycling Science and Engineering (A30DB182602)) and Foundation of Subject of Management Science and Engineering of Shanghai Polytechnic University (XXKPY1606).

References

[1] Wang S C, Yang B and Xu B Y 2015 Remanufacturing logistics network design considering FTR Computer Integrated Manufacturing System 06 1609-1616
[2] Zhou Y S and Wang S Y 2008 Generic Model of Reverse Logistics Network Design Journal of Transportation Systems Engineering and Information Technology 03 71-78
[3] Chen Y, Yang Y B and Zhang L 2016 Reverse logistics network design of waste household Mathematics in Practice and Theory 46(17) 81-89
[4] Zohal M and Soleimani H 2016 Developing an ant colony approach for green closed-loop supply chain network design: a case study in gold industry Journal of Cleaner Production 133 314-337
[5] Zarabakhshnia N, Soleimani H, Goh M and Razavi S S 2019 A novel muti-objective model for green forward and reverse logistics network design Journal of Cleaner Production 208
1304-1316

[6] John S T, Sridharan R, Ram Kumar P N and Krishnamoorthy M 2018 Multi-period reverse logistics network design for used refrigerators Applied Mathematical Modelling 54 311-331

[7] Abdallah T, Diabat A and Simchi-Levi D 2012 Sustainable supply chain design: a closed-loop formulation and sensitivity analysis Production Planning & Control 23(2) 120-133

[8] Eskandarpour M, Masehian E, Soltani R and Khosrojerdi A 2014 A reverse logistics network for recovery systems and a robust metaheuristic solution approach International Journal of Advanced Manufacturing Technology 74(9-12) 1393-1406

[9] Hatefi S M and Jolai F 2014 Robust and reliable forward reverse logistics network design under demand uncertainty and facility disruptions Applied Mathematical Modelling 38(9-10) 2630-2647

[10] Demirel E, Demirel N and Gökçen H 2014 A mixed integer linear programming model to optimize reverse logistics activities of end-of-life vehicles in Turkey Journal of Cleaner Production 112(3) 2101-2113