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Optimization of reverse logistics network for end-of-life vehicles: A Shanghai case study

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A B S T R A C T

With the surge in car ownership, the end-of-life vehicles recycling market has shown enormous development potential. As the reverse logistics network for recycling end-of-life vehicles suffers from high operating costs and low recycling rates, there is an urgent need to upgrade the actual recycling measures for end-of-life vehicles to an operable level. This article first uses the OGM (1, N) model to predict the number of end-of-life vehicles in the coming years. At the same time, a reverse logistics network model with the second-hand car market as the recycling centre was constructed with the goal of minimizing the total cost of the end-of-life vehicles reverse logistics network. The network model was simulated using mixed integer programming (MILP), and the optimal solution was solved through LINGO 12 programming. Through an example analysis of Shanghai, it is found that the market of end-of-life vehicles will embrace growth, and it is verified that the optimized reverse logistics network can effectively reduce the operation cost and logistics cost of recycling centres, and can effectively improve the actual recycling rate of end-of-life vehicles. Finally, the optimized site selection results are obtained, and a specific traffic distribution scheme is proposed, which is crucial for promoting cars that meet scrap standards to be recycled through formal channels and reducing logistics costs for recycling enterprises.

A R T I C L E I N F O

Keywords:
End-of-life vehicles;
Reverse logistics;
Recycling;
OGM (1, N) model;
Mixed-integer programming (MILP);
LINGO

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1. Introduction

With the continuous development of the Chinese automobile market, China became the world's largest producer and seller of automobiles in 2009. As of 2020, China's car ownership has reached 281 million units, and the end-of-life car recycling market has huge potential. According to statistics, the scrap rate of vehicles in China is about 3 %, while the scrap rate in developed countries reaches 6 % to 8 %. At the same time, the recycling and dismantling rate in China is relatively low, only 1 % to 1.5 % of the car ownership, while the recycling and dismantling rate in developed countries is 5 % to 6 %. In the face of the contradiction between the rapid growth of car ownership and the low recovery rate of end-of-life vehicles, in the context of a low-carbon and digital economy [1, 2], China's reverse logistics services led by third-party end-of-life vehicles recycling and dismantling enterprises are facing great challenges, for which the Chinese government has also formulated relevant policies and regulations [3]. For example, the Implementation Rules for the Management of End-of-Life Motor Vehicles Recycling (2020) proposed the goal of market-oriented, specialized, and intensive development of the end-of-life motor vehicle recycling and dismantling industry. However, China's end-of-life vehicles recycling companies still face some problems. Scattered resources, insufficient capital investment, sloppy business management, outdated dismantling technology and a lack of standardisation and normalisation of recycling and dismantling operations are among their main challenges. Moreover, dismantling enterprises still focus on the sale of scrap steel as their main profit target, neglecting the added value of components, and the reuse rate of components is very low. There are even some illegal and non-standard recycling enterprises, which not only disrupt the normal order of the end-of-life vehicles dismantling and recycling market, but also have a negative impact on environmental protection and resource utilization. In addition, according to the lifecycle of automotive products, the peak period of mandatory scrapping standards for automobiles has not yet been reached, and the number of end-of-life vehicles is continuously increasing at a rate of over 15 % per year. The future surge in the end-of-life vehicles market also poses greater challenges to environmental protection and resource utilization. In this regard, in-depth study of automotive reverse logistics can achieve the rational use of resources, reduce environmental pollution and enhance the economic benefits of enterprises, solve the problems faced by the industry and achieve sustainable development, which is of great significance to improve the overall level and competitiveness of China's end-of-life vehicles recycling and dismantling industry.

2. Literature review

Scholars have conducted research using different research methods in predicting the number of end-of-life vehicles and car ownership [4]. Among them, Hao *et al.* proposed a combined prediction model composed of grey model, exponential smoothing method and artificial neural network optimized by Particle swarm optimization (PSO) algorithm to solve the nonlinear characteristics and uncertainty problems of the number of end-of-life vehicles recovered, and verified the accuracy of the prediction through an example [5]. Mohammadali-Ali *et al.* considered vehicle life (EOL factor) to improve the effectiveness of end-of-life vehicles recycling when establishing a system dynamics model [6]. Zhang *et al.* used singular spectrum analysis (SSA) of univariate time series models and vector autoregressive (VAR) models of multivariate models to predict car ownership [7]. Dargay and Gately, from an economic perspective, linked car ownership with per capita income and combined it with dynamic econometric models to establish a prediction model for car ownership [8].

At present, research on the optimization of reverse logistics networks for end-of-life vehicles has achieved many results, and the objective function used in existing research is mainly the lowest total cost. Demirel and Gokcen proposed a mixed integer Linear programming model for the reverse logistics network design of used and end-of-life vehicles under the participation of different roles, which successfully reduced the cost of network transportation of end-of-life vehicles and related materials [9]. Lin *et al.* established a FLAERN mathematical model with the goal of cost minimization to solve the facility location allocation problem in the end-of-life vehicles recycling network, and proposed an algorithm based on artificial bee colony for optimization [10]. Govindan and Gholizadeh comprehensively investigated the relationship between the elastic sustainable RLs and the variable and flexible capabilities of facilities in electric vehicles, and adopted a robust optimized cross-entropy hybrid solution method to calculate the total cost of the elastic sustainable RLN with the main goal of minimizing the total cost of the RLN [11]. Seval and Ozturk developed a mathematical planning model for reverse logistics network design to manage a reverse flow network of end-of-life vehicles in the context of a manufacturer being responsible for the entire lifecycle of its products, which was used to determine the number and location of network facilities as well as the volume of material flows [12]. Amin *et al.* conducted a Case study on the key participants in North American ELVs collection for the reverse logistics path problem of recycling used vehicles, and proposed a two-stage heuristic solution to maximize the optimal distribution of dealers between internal fleets and between internal fleets and external operators [13]. Min *et al.* proposed a mixed integer nonlinear programming model and genetic algorithm aimed at solving a spatially and temporally integrated reverse logistics problem involving returned products [14]. Marin and Pelegrin analysed the Return to Plant Location Problem (RPLP) based on the heuristic and exact solution method of Lagrange decomposition [15]. Du and Evans established a double objective MIP optimization model for the reverse logistics network problem of Third-party logistics companies providing logistics services for after-sales service networks, and designed a solution consisting of discrete search method, dual Simplex algorithm method and constraint method [16].

Similar to the reverse logistics network optimization problem of end-of-life vehicles, facilities location [17], production Linear programming [18, 19], supply chain performance evaluation [20], production and procurement planning are also combinatorial optimization problems [21, 22], and the modelling of combinatorial optimisation problems as mixed integer programming models is widely used in the solution of these problems [23, 24]. And the global optimization software LINGO is used for rapid solution, which has achieved good results in the examples. For example, Yong and Jing used LINGO to establish a logistics network optimization design model, select a carbon emission distribution centre demand matching model, a distribution path optimization model and a multi-objective optimization model aimed at minimizing carbon emissions, and optimize the model [25]. Xiao *et al*. constructed a four level reverse logistics network model including the origin of end-of-life vehicles, the recycling centre, the remanufacturing centre and the disassembler, and used LINGO to solve the mixed integer Linear programming mathematical model established, pointing out that the location of the dismantling centre and the capability rating strategy have an important impact on the total cost of the logistics network [26, 27].

Based on this, this article first predicts the future prospects of the end-of-life vehicles market using the OGM (1, N) model based on grey theory. Further, the reverse logistics network model with the second-hand automobile market as the recovery and transit centre is constructed by fully considering the factors such as the dismantling capacity of the dismantling point, the logistics volume balance of each network node, and the Fixed cost. Select appropriate decision variables, construct a linear objective function with the minimum total cost, model the reverse network problem of end-of-life vehicles as a Mixed Integer Programming model, and then use LINGO software to obtain the optimal solution. Finally, a case study was conducted to verify the effectiveness of the model.

3. Research methodology

3.1 Prediction model for the number of end-of-life vehicles

The specific modelling process of OGM (1, N) model is as follows.

(1) Grey sequence generation

Set $X_i^{(0)} = (x_i^{(0)}(1), x_i^{(0)}(2), \dots, x_i^{(0)}(n))$ as the dependent variable sequence. Sequence $X_i^{(0)} = (x_i^{(0)}(1), x_i^{(0)}(2), \dots, x_i^{(0)}(n))$ is an independent variable sequence with high correlation with sequence $X_1^{(0)}$.

(2) Perform a cumulative generation (1-AGO) on $X_{\mathrm{i}}^{(0)}$ to obtain the sequence $X_1^{(1)}$:

$$X_i^{(1)} = \left(x_i^{(1)}(1), x_i^{(1)}(2), \dots, x_i^{(1)}(n)\right) \tag{1}$$

Among them: $x_i^{(1)}(k) = \sum_{i=1}^{k} x_i^{(0)}(i)$, $k = 1,2,\dots,n$.

(3) Generate the nearest neighbour mean sequence $Z_1^{(1)}$ from $X_1^{(1)}$:

$$Z_1^{(1)} = \left(z_1^{(1)}(2), z_1^{(1)}(3), \dots, z_1^{(1)}(m)\right) \tag{2}$$

Among them: $z_1^{(1)}(k)$=$[x_1^{(1)}(k) + x_1^{(1)}(k-1)]/2$, $k = 2,3,\dots,m$.

(4) Build OGM (1, N) model:

$$x_1^{(0)}(k) + a z_1^{(1)}(k) = \sum_{i=2}^{k} b_i x_i^{(1)}(k) + h_1(k-1) + h_2 \tag{3}$$

The $h_1(k-1)$ and h_2 in the equation are referred to as the linear correction term and grey action of the OGM (1, N) model, respectively, a is referred to as the development coefficient, $b_i {x_i}^{(1)}(k)$ is called the driving term, b_i is called the driving coefficient.

(5) Parameter Estimation of OGM (1, N) model

The Least Squares Satisfaction of Parameter Column $\hat{a} = \left[b_1, b_2, \dots, b_N, a, h_1, h_2\right]^{\mathrm{T}}$ in OGM (1, N) model:

$$\hat{a} = (B^T B)^{-1} B^T Y \tag{4}$$

Among them:

$$B = \begin{bmatrix} {x_2}^{(1)}(2) & {x_3}^{(1)}(2) & \cdots & {x_N}^{(1)}(2) & -{z_2}^{(1)}(2) & 1 & 1 \\ {x_2}^{(1)}(3) & {x_3}^{(1)}(3) & & {x_N}^{(1)}(3) & -{z_2}^{(1)}(3) & 2 & 1 \\ \vdots & \vdots & \ddots & \vdots & & & \vdots \\ {x_2}^{(1)}(m) & {x_3}^{(1)}(m) & \cdots & {x_N}^{(1)}(m) & -{z_2}^{(1)}(2) & m-1 & 1 \end{bmatrix} \tag{5}$$

$$Y = \begin{bmatrix} {x_1}^{(0)}(2) \\ {x_1}^{(0)}(3) \\ \vdots \\ {x_1}^{(0)}(m) \end{bmatrix} \tag{6}$$

So $\hat{x}_1{}^{(0)}(k) = \sum_{i=2}^{k} b_i {x_i}^{(1)}(k) - a{z_1}^{(1)}(k) + h_2 + h_1(k-1)$ is the differential model of OGM (1, N).

$$\hat{x}_1{}^{(0)}(k) = \sum_{t=1}^{k-1}\left[u_1 \sum_{i=2}^{N} u_2^{t-1} b_i x_i^{(1)}(k-t+1)\right] + u_2^{k-1}\hat{x}_1{}^{(1)}(1) + \sum_{j=0}^{k-2} u_2^{j}\left[(k-j)u_3 + u_4\right. \tag{7}$$

In the Eq. 7, $k = 2,3,\dots$.

$$u_1 = \frac{1}{1+0.5a}, u_2 = \frac{1-0.5a}{1+0.5a}, u_3 = \frac{h_1}{1+0.5a}, u_4 = \frac{h_2-h_1}{1+0.5a}$$

(6) Obtaining predicted values

The following is the cumulative reduction formula of OGM (1, N) model:

$$\hat{x}_1^{(0)}(k) = \hat{x}_1^{(1)}(k) - \hat{x}_1^{(1)}(k-1), k = 2,3,\dots,m \tag{8}$$

3.2 Construction of reverse logistics network model for end-of-life vehicles

This article constructs a reverse logistics network model with the second-hand car market as the recycling centre, based on the two key issues of reverse logistics network design and low recycling rate in the optimization of recycling end-of-life vehicles, with the goal of minimizing the total cost of the reverse logistics network for end-of-life vehicles. At the same time, constraints such as the conservation of logistics volume between network nodes, limitations on the processing capacity of recycling centres, limitations on the dismantling capacity of dismantling centres, and the number of established logistics network recycling centres are set to ensure overall coordination among relevant organizations and fully complete recycling tasks.

Parameter settings

To convert the reverse logistics in the recycling process of end-of-life vehicles into a specific mathematical model, some parameters need to be annotated and explained. The parameter symbols and definitions used in this study are shown in Table 1.

Table 1 Definition of parameter symbols

Category	Symbol	Definition
Set	$KHQ(i)$	Customer area address set ($i = 1,2,3,\dots,n, \forall i \in K$)
	$HSZX(j)$	Recycling centre addresses set ($j = 1,2,3,\dots,m, \forall j \in HSZX$)
	$CJZX(z)$	Dismantling centre address set ($z = 1,2,3,\dots,p, \forall z \in CJZX$)
	$AZ(w)$	Address of remanufacturing centre or landfill site set ($w = 1,2,\dots,t, \forall w \in AZ$)
	$U(i,j)$	Relevant indicator set from customer area i to recycling centre j ($i = 1,2,3,\dots,n, j = 1,2,3,\dots,m, \forall i \in K，\forall j \in HSZX$)
	$T(j,z)$	Relevant indicator set from recovery centre j to dismantling centre z($j = 1,2,3,\dots,m, z = 1,2,3,\dots,p, \forall j \in HSZX，\forall z \in CJZX$)
	$R(z,w)$	Relevant indicator set from dismantling centre z to remanufacturing centre or landfill plant w ($z = 1,2,3,\dots,p, w = 1,2,\dots,t, \forall z \in CJZX, \forall w \in AZ$)
Parameter	$CH1(j)$	Fixed investment cost of recycling centre j
	$CH2(j)$	Operating costs amortized per vehicle recovered by the recycling centre j
	$CC(z)$	The dismantling cost of dismantling a single end-of-life vehicles
	$LKH(i,j)$	Distance from recycling centre i to dismantling centre j
	$QK(i)$	Total number of end-of-life vehicles in customer area i
	$N(j)$	Maximum recycling capacity of recycling centre j
	$E(z)$	Maximum dismantling capacity of dismantling centre z
	$M(z)$	Recycling quantity of dismantling centre
	$V1$	Unit freight from customer area to recycling centre (RMB/vehicle · kilometre)
	$V2$	Unit shipping cost from recycling centre to dismantling centre (RMB/vehicle · kilometre)
	A	Unit transportation from dismantling centre to component remanufacturing centre (RMB/vehicle · kilometre)
	B	Unit transportation from dismantling centre to steel enterprise (RMB/vehicle · kilometre)
	C	Unit transportation from dismantling centre to landfill site (RMB/vehicle · kilometre)
Decision variables	$Y(j)$	If a new recycling centre is set up at h, take 1; otherwise, take 0
	$QKH(i,j)$	The number of end-of-life motor vehicles transported from customer area i to recycling centre j
	$QHC(j,z)$	The number of end-of-life motor vehicles from recycling centre j to dismantling centre z
	$QCA(z,w)$	The number of vehicles transporting motor vehicle waste from the dismantling centre j to the waste landfill w
	$QCZ(z,w)$	The number of automotive engines transported from dismantling centre j to remanufacturing centre w
	$QCG(j)$	The number of end-of-life vehicles and scrap metal transported from the dismantling centre to the steel plant

Model specification

- This article studies the logistics network of a single product and cycle, where the weight of a single vehicle represents the overall quality.
- The transportation distance between each logistics node is known, and the transportation cost per unit distance is known, and the transportation cost is positively correlated with the transportation distance.
- Material and component losses during transportation are not taken into account, including the scrap disposal rate during dismantling.
- The alternative solutions for the construction or expansion of facilities in the automotive reverse logistics network are known, including their alternative locations and number, location selection near the second-hand car market in a certain area, and setting their recycling capacity in advance.
- The transportation from the recycling centre to the dismantling centre will be estimated based on transporting multiple end-of-life vehicles at once.
- Ignoring the uncertainty of time and the dynamism of the supply chain, the cost of inventory backlog is included in the unit operating cost.
- The third-party logistics company can reach cooperation with them, and the cooperation status will not change in a short time.

Objective function

The objective function of establishing a model with the lowest total cost of reverse logistics network for end-of-life vehicles:

$$min\,TC = TC1 + TC2 + TC3 + TC4 + TC5 + TC6 + TC7 + TC8 \tag{9}$$

- Fixed investment cost of network recycling transit centres ($TC1$)

$TC1$ is the sum of the products of $CH1(j)$ and $Y(j)$:

$$TC1 = \sum_{j=1}^{n} CH1(j)\,Y(j) \tag{10}$$

- Operating costs of network recycling transit centres ($TC2$)

$TC2$ is the sum of the products of $QKH(i,j)$ and $CH2\,(j)$:

$$TC2 = \sum_{i=1}^{m}\sum_{j=1}^{n} QKH(i,j)\,CH2(j) \tag{11}$$

- The total dismantling cost of the dismantling company ($TC3$)

$TC3$ is the sum of the products of $QHC(j,z)$ and $CC\,(z)$:

$$TC3 = \sum_{j=1}^{n}\sum_{z=1}^{p} QHC(j,z)\,CC(z) \tag{12}$$

- The total logistics cost of network transportation

The calculation of the total transportation cost is based on the sum of the products of the distance between each network node, the freight cost per kilometre, and the quantity of recycling between network nodes.

The total transportation cost includes the shipping cost from the recycling centre to the dismantling centre ($TC4$):

$$TC4 = \sum_{i=1}^{m}\sum_{j=1}^{n} LKH(i,j)\,QKH(i,j)\,V1 \tag{13}$$

The total cost of shipping between the recycling centre and the dismantling centre ($TC5$):

$$TC5 = \sum_{j=1}^{n}\sum_{z=1}^{p} LHC(j,z)\,QHC(j,z)\,V2 \tag{14}$$

Freight cost from dismantling centre to remanufacturing company ($TC6$), garbage factory ($TC7$), steel factory ($TC8$) are shown as follows:

$$TC6 = \sum_{z=1}^{p}\sum_{w=1}^{t} LCA(z,w)\,QKH(z,w)\,A \tag{15}$$

$$TC7 = \sum_{z=1}^{p}\sum_{w=1}^{t} LCZ(z,w)\,QKH(z,w)\,F \tag{16}$$

$$TC8 = \sum_{z=1}^{p} LCG(j)\,QCG(j)\,G \tag{17}$$

Restraint condition

Based on the current situation of the reverse logistics network for end-of-life vehicles, this study establishes constraints from aspects such as the conservation of logistics volume between network nodes, limitations on the processing capacity of recycling centres, limitations on the dismantling capacity of dismantling centres, the number of established in the logistics network recycling centres, and integer constraints.

(1) Constraints on conservation of logistics volume

Based on the principle of material flow conservation between various nodes in the logistics network, the following constraint conditions for material flow conservation are established.

Balance of total material flow of end-of-life vehicles:

$$\begin{gathered}\sum_{i=1}^{m} QK(i) = \sum_{i=1}^{m}\sum_{j=1}^{n} QKH(i,j) = \sum_{j=1}^{n}\sum_{z=1}^{p} QHC(j,z) = \\ = \sum_{z=1}^{p}\sum_{w=1}^{t} QCA(z,w) = \sum_{z=1}^{p}\sum_{w=1}^{t} QCA(z,w) = \sum_{Z=1}^{p} QCG(z)\end{gathered} \tag{18}$$

Conservation of material flow at node i in each customer area:

$$QK(i) = \sum_{j=1}^{n} QKH(i,j) \qquad (i = 1,2,3,\dots,n) \tag{19}$$

Conservation of material flow at various network recycling and transfer centre nodes:

$$\sum_{i=1}^{n} QKH(i,j) = \sum_{z=1}^{p} QHC(j,z)\,(j = 1,2,3,\dots,m) \tag{20}$$

Conservation of material flow at nodes from steel mills, garbage dumps, remanufacturing companies to dismantling enterprises:

$$\sum_{j=1}^{m} QHC(j,z) = \sum_{w=1}^{t} QCA(z,w)\,(z = 1,2,3,\dots,p) \tag{21}$$

$$\sum_{j=1}^{m} QHC(j,z) = \sum_{w=1}^{t} QCA(z,w)\,(z = 1,2,3,\dots,p) \tag{22}$$

$$\sum_{j=1}^{m} QHC(j,z) = QCG(j) \qquad (z = 1,2,3,\dots,p) \tag{23}$$

(2) Limitations on processing capacity of recycling centres

According to the recycling capacity limit of the recycling centre, the 0-1 variable $Y(j)$ of the recycling centre meets the minimum and maximum processing quantity limits. The value of $Y(j)$ is determined by the conservation constraint of the recycling centre's processing capacity, thereby determining the location:

$$\sum_{i=1}^{n} QKH(i,j) \leq N(j)\,Y(j) \quad (j = 1,2,3,\dots,m) \tag{24}$$

$$\sum_{z=1}^{p} QHC(j,z) \leq N(j)\,Y(j) \quad (j = 1,2,3,\dots,m) \tag{25}$$

$$\sum_{i=1}^{n} QKH(i,j) \geq P(j)\,Y(j) \quad (j = 1,2,3,\dots,m) \tag{26}$$

$$\sum_{z=1}^{p} QHC(j,z) \geq N(j)\,Y(j) \quad (j = 1,2,3,\dots,m) \tag{27}$$

$$\sum_{j=1}^{m} QHC(j,z) \leq M(z) \qquad (z = 1,2,3,\dots,p) \tag{28}$$

(3) Limitations on the dismantling capacity of the dismantling centre

Establish constraint conditions based on the dismantling capacity limitations of each dismantling centre to meet the law of conservation of logistics volume between each node:

$$\sum_{j=1}^{m} QHC(j,z) \geq E(z) \quad (z = 1,2,3,\dots,p) \tag{29}$$

$$\sum_{w=1}^{t} QCA(z,w) \geq E(z) \quad (z = 1,2,3,\dots,p) \tag{30}$$

$$\sum_{w=1}^{t} QCA(z,w) \leq M(z) \quad (z = 1,2,3,\dots,p) \tag{31}$$

$$\sum_{w=1}^{t} QCZ(z,w) \geq E(z) \quad (z = 1,2,3,\dots,p) \tag{32}$$

$$\sum_{w=1}^{t} QCZ(z,w) \leq M(z) \quad (z = 1,2,3,\dots,p) \tag{33}$$

(4) Limitation on the number of newly established recycling points:

$$\sum_{j=1}^{3} Y(j) = 3 \tag{34}$$

$$3 \leq \sum_{j=4}^{\mathrm{n}} Y(j) \leq 5 \tag{35}$$

(5) Integer constraint:

$$Y(j) \in \{0,\ 1\} \quad (j = 1,2,3,\dots,n) \tag{36}$$

4. Results of the study

4.1 Example description and data source

This article takes Shanghai, the fifth largest city in China in terms of car ownership, as a research example to analyse and verify the effectiveness of the model. Select participants closely related to the reverse logistics of end-of-life vehicles for on-site research and interviews, and obtain the required data from government official websites and relevant literature.

(1) According to Google Maps data, Fig. 1 shows the distribution of end-of-life vehicle network nodes in Shanghai.

Fig. 1 Distribution of scrap vehicle network nodes in Shanghai

(2) Distances between nodes were computed using Google Maps, with the following specifics: the distance between the customer area and the recycling centre; the distance between the recycling centre and the dismantling enterprise; the distance between the dismantling enterprise and the landfill plant; the distance between the dismantling centre and Shanghai Baosteel Group Corporation; and the distance between the dismantling enterprise and the remanufacturing company. Here, only the distance data between the 16 customer areas and the selected recycling centres for end-of-life vehicles in Shanghai are shown in Table 2.

Table 2 Distance between customer area and recycling centre

Distance (km)	Wuning Road Service Branch	Boyuan Road Service Branch	Hulan Road Service Branch	Shanghai Used Car Trade Market	Shanghai Port second-hand car trading market	Shanghai Xinzhuang Old Motor Vehicle Trading Market	Shanghai Pudong Used Motor Vehicle Trading Market	Shanghai Chongming Old Motor Vehicle Trading Market	Shanghai Bailian United Used Motor Vehicle Trading Market
Pudong New Area	23	45	23	54	17	29	13	90	18
Huangpu District	9.4	31	17	45	22	23	20	103	11
Xuhui District	25	8	23	36	48	16	21	109	18
Changning District	3.3	18	20	33	31	19	23	104	13
Jing'an District	5.4	26	17	40	30	20	21	102	11
Putuo District	3.7	19	16	26	30	22	31	103	10
Hongkou District	11	34	15	38	16	28	19	90	8.9
Yangpu District	16	35	22	43	16	29	17	89	16
Minhang District	19	23	33	36	46	5.7	21	115	27
Baoshan District	24	38	10	51	22	43	37	98	19
Jiading District	32	17	26	20	43	32	53	117	24
Jinshan District	70	67	86	73	102	54	71	168	77
Songjiang District	40	38	54	44	67	21	41	137	48
Qingpu District	38	36	55	25	62	28	52	143	50
Fengxian District	43	48	57	62	67	31	42	139	51
Chongming District	101	118	98	125	81	120	95	2	93

(3) The recycling of end-of-life vehicles is generally carried out through the recycling and dismantling company's doorstep transportation or by customers driving the vehicles that are about to be end-of-life to the recycling company. Based on actual research, this study believes that the transportation unit fuel consumption during vehicle recycling is 0.2 liters/kilometre, and the freight cost between each node is shown in Table 3.

Table 3 Freight costs between nodes

	V1	V2	A	B	C
Freight cost (RMB/kilometre · vehicle)	2.8	0.8	0.16	0.4	0.9

4.2 Prediction results of end-of-life vehicles in Shanghai

The grey correlation analysis was carried out on the relevant indicators selected for the prediction of the number of 16 end-of-life vehicles from 2011 to 2018. Finally, with 0.83 as the threshold, Gross regional product, per capita gross product, total social consumer goods, disposable income of residents, and car ownership were taken as the main factors of the grey correlation prediction. The final prediction indicates that the number of cars scrapped in Shanghai from 2019 to 2021 is 110,853, 130,054, and 140,509, respectively, as calculated using MATLAB.

4.3 Analysis of the results of the reverse logistics network model for end-of-life vehicles in Shanghai

Effectively reducing the cost of reverse logistics network

Referring to the reverse logistics network data of end-of-life vehicles in Shanghai, a mixed integer programming (MILP) simulation network model was used to simulate the operation, and LINGO 12 programming was used to solve the optimal solution. Integrate resources between various nodes to find the optimal traffic allocation result. And select a location for the recycling centre. The solution report is displayed as follows:

Global optimal solution found.
Objective value: 0.1302113E + 09
Objective bound: 0.1302113E + 09
Infeasibilities: 0.000000
Extended solver steps: 0
Total solver iterations: 149

The current program has a total of 283 variables, with 149 iterations. The optimal value of the objective function min $TC = 0.1302113E + 09$, which means the logistics cost is 130429.9 million RMB.

Recovery centre cost: $TC1 + TC2 = 183800 + 811424 = 995224$
Logistics freight cost: $TC4 + TC5 + TC6 + TC7 + TC8 = 2160869 + 658096.4 + 639380.5 +$
$+ 1389350 + 822120.8 = 5669816.7$

At present, there are about 50 recycling points in the existing reverse logistics network for end-of-life vehicles, and the average operating cost of each recycling point is about 300000 RMB. The total operating cost exceeds the sum of logistics freight cost and the operating cost of the recycling centre.

Choosing the second-hand car market as the recycling and transfer centre and establishing a reverse logistics network system for end-of-life vehicles can effectively reduce the logistics and operational costs of reverse logistics for end-of-life vehicles. Allowing profits to end-of-life vehicles dismantling companies increases the profit margin of the dismantling centre, causing a large number of end-of-life vehicles flowing into informal channels such as the underground black market to flow into formal channels for scrapping.

Effectively improving the recycling rate of reverse logistics networks

Table 4 Scrap vehicle recycling data from 2015 to 2016

Time	Car ownership (10000 units)	Theoretical scrap volume (10000 units)	Actual cancellation volume (10000 units)	Actual recycling volume (10000 units)
2015	332.35	13.2	8.5	4.01
2016	359.48	14.37	9.7	4.2

The theoretical scrap quantity is generally 4 % of the total inventory, taking the historical data in Table 8 for 2016 as an example:

$$\text{Actual scrap rate} = \frac{\text{Actual cancellation volume}}{\text{Theoretical scrap volume}} \cdot 100\ \% = \frac{9.7}{14.37} \cdot 100\ \% = 67.5\ \%$$

$$\text{Actual recovery rate} = \frac{\text{Actual recycling volume}}{\text{Actual cancellation volume}} \cdot 100\ \% = \frac{4.2}{9.7} \cdot 100\ \% = 43.2\ \%$$

According to industry calculations, generally 40 % enter formal dismantling channels, 30 % are illegally dismantled and dismantled, and 30 % are re launched through second-hand modifications. Half of the 46700 end-of-life vehicles that have not been deregistered can be recovered and deregistered through inspection of the second-hand car market.

$$\text{Actual scrap rate} = \frac{\text{Actual cancellation volume}}{\text{Theoretical scrap volume}} \cdot 100\ \% = \frac{12.04}{14.37} \cdot 100\ \% = 83.8\ \%$$

$$\text{Actual recovery rate} = \frac{\text{Actual recycling volume}}{\text{Actual cancellation volume}} \cdot 100\ \% = \frac{6.535}{12.035} \cdot 100\ \% = 54.3\ \%$$

Using data from 2016, it is expected that the actual scrap rate will increase from 67.5 % to 83.8 %, and the actual recovery rate will increase from 43.2 % to 54.3 %.

Optimization of site selection for network recycling centres

According to the results of $Y(j)$, the following six second-hand car trading markets will be designated as the recycling transfer points for the reverse logistics network of end-of-life vehicles in Shanghai in the future, as shown in Table 5.

Table 5 Location of network recycling centres using the used car market as a transit point

Wuning Road Service Branch	2907 Zhongshan North Road, Putuo District, Shanghai
Boyuan Road Service Branch	Certification Hall, Floor 1, No. 969, Boyuan Road, Jiangqiao Town, Jiading District, Shanghai
Hulan Road Service Branch	Room 108, Building 4, No. 525 Hulan Road, Baoshan District, Shanghai
Shanghai Xinzhuang Old Motor Vehicle Trading Market	3318 Gudai Road, Shanghai
Shanghai Pudong Used Motor Vehicle Trading Market	1441 Yuqiao Road, Pudong New Area, Shanghai
Shanghai Bailian United Used Motor Vehicle Trading Market	3550 Gonghexin Road, Jing'an District, Shanghai

Optimized allocation of network resources

Based on the above site selection optimization results, the following resource optimization allocation suggestions are proposed to effectively reduce the total operating cost of the entire reverse logistics network for end-of-life vehicles.

(1) The flow distribution between the customer area and the recycling area is shown in Table 6.

Table 6 Flow Distribution of customer area – Recycling area (Unit: Vehicles)

Distance (km)	Wuning Road Service Branch	Boyuan Road Service Branch	Hulan Road Service Branch	Shanghai Used Car Trade Market	Shanghai Port second-hand car trading market	Shanghai Xinzhuang Old Motor Vehicle Trading Market	Shanghai Pudong Used Motor Vehicle Trading Market	Shanghai Chongming Old Motor Vehicle Trading Market	Shanghai Bailian United Used Motor Vehicle Trading Market
Pudong New Area	0	0	0	0	0	0	0	0	1236
Huangpu District	0	0	0	0	0	1110	7608	0	0
Xuhui District	0	5341	0	0	0	0	0	0	0
Changning District	694	1150	0	0	0	3043	0	0	0
Jing'an District	0	1586	3968	0	0	0	0	0	2218
Putuo District	6306	0	0	0	0	0	0	0	0
Hongkou District	0	0	0	0	0	0	0	0	9154

Table 6 (Continuation)

Yangpu District	0	0	0	0	0	0	0	0	5830
Minhang District	0	0	0	0	0	1850	0	0	0
Baoshan District	0	0	2032	0	0	0	0	0	0
Jiading District	0	923	0	0	0	0	0	0	0
Jinshan District	0	0	0	0	0	370	0	0	0
Songjiang district	0	0	0	0	0	785	0	0	0
Qingpu District	0	0	0	0	0	490	0	0	0
Fengxian District	0	0	0	0	0	452	0	0	0
Chongming District	0	0	0	0	0	0	156	0	0

(2) To reduce costs, the following flow distribution plan is proposed for the recycling centre to the dismantling centre, as shown in Table 7.

Table 7 Flow distribution of recycling centre – Dismantling centre (Unit: Vehicles)

Distance (km)	Xinguang Renewable Resources (Shanghai) Co., Ltd	Oulubao (Baosteel) Dismantling Co., Ltd	Shanghai Huadong Dismantling Co., Ltd	Shanghai Huajian Dismantling Co., Ltd	Shanghai Motor Vehicle Recycling Service Centre	Shanghai Xinzhuang Dismantling Co., Ltd	Shanghai Jiaoyun Bus Dismantling Co., Ltd
Wuning Road Service Branch	0	0	0	0	0	0	7000
Boyuan Road Service Branch	8000	0	0	0	0	0	1000
Hulan Road Service Branch	0	6000	0	0	0	0	0
Shanghai Used Car Trade Market	0	0	0	0	0	0	0
Shanghai Port second-hand car trading Market	0	0	0	0	0	0	0
Shanghai Xinzhuang Old Motor Vehicle Trading Market	0	0	0	0	0	8000	0
Shanghai Pudong Used Motor Vehicle Trading Market	0	9000	0	0	0	0	0
Shanghai Chongming Old Motor Vehicle Trading Market	0	0	0	0	0	0	0
Shanghai Bailian United Used Motor Vehicle Trading Market	0	5000	3000	2500	2800	1902	2000

(3) The article proposes that Xinguang Renewable Resources (Shanghai) Co., Ltd. will transport the dismantled waste to Chongming Garbage Dump. Within the upper limit of the treatment capacity of the Laogang Garbage Dump, the dismantling company will try its best to transport the waste to the Laogang Garbage Dump for treatment, as shown in Table 8.

Table 8 Flow distribution of dismantling centre – Landfill plant (Unit: Vehicles)

Distance (km)	Xinguang Renewable Resources (Shanghai) Co., Ltd	Oulubao (Baosteel) Dismantling Co., Ltd	Shanghai Huadong Dismantling Co., Ltd	Shanghai Huajian Dismantling Co., Ltd	Shanghai Motor Vehicle Recycling Service Centre	Shanghai Xinzhuang Dismantling Co., Ltd	Shanghai Jiaoyun Bus Dismantling Co., Ltd
Chongming Garbage Landfill Plant	8000	0	0	0	0	0	0
Laogang Solid Waste Comprehensive Utilization Base	0	20000	3000	2500	2800	9902	10000

(4) The flow distribution between the dismantling centre and the steel plant is shown in Table 9.

Table 9 Flow distribution of dismantling centre – Steel plant (Unit: Vehicle)

Distance (kilometre)	Xinguang Renewable Resources (Shanghai) Co., Ltd	Oulubao (Baosteel) Dismantling Co., Ltd	Shanghai Huadong Dismantling Co., Ltd	Shanghai Huajian Dismantling Co., Ltd	Shanghai Motor Vehicle Recycling Service Centre	Shanghai Xinzhuang Dismantling Co., Ltd	Shanghai Jiaoyun Bus Dismantling Co., Ltd
Shanghai Baosteel Group Corporation	8000	20000	3000	2500	2800	9902	10000

(5) The article puts forward the opinion that Oulubao (Baosteel) Vehicle Dismantling Co., Ltd. and Shanghai Jiaoyun Bus Dismantling Co., Ltd. will transport the five major assemblies of the recovered vehicles to SAIC Motor, and other dismantling companies in Shanghai will transport the five major assemblies of the recovered vehicles to Shanghai Fumei Auto Automatic Transmission Technical Service Co., Ltd, as shown in Table 10.

Table 10 Flow distribution of dismantling centre – Remanufacturing company (Unit: Vehicle)

Distance (km)	Xinguang Renewable Resources (Shanghai) Co., Ltd	Oulubao (Baosteel) Dismantling Co., Ltd	Shanghai Huadong Dismantling Co., Ltd	Shanghai Huajian Dismantling Co., Ltd	Shanghai Motor Vehicle Recycling Service Centre	Shanghai Xinzhuang Dismantling Co., Ltd	Shanghai Jiaoyun Bus Dismantling Co., Ltd
Shanghai Xingfu Rebede Powertrain Co., Ltd. (SAIC Motor)	0	20000	0	0	0	0	10000
Shanghai Fumei Auto Automatic Transmission Technical Service Co., Ltd. (authorized by Dongfeng Peugeot-Citroën and Great Wall Motor)	8000	0	3000	2500	2800	9902	0

5. Discussion

In terms of theoretical contributions, this study mainly analyses and predicts the prospects of Shanghai's automobile market first, then breaks the tradition that most scrap automobile dismantling companies in Shanghai set up recycling centres only to collect materials rather than serve as transfer points, and establishes a tripartite logistics network system with the second-hand car trading market as the recycling centre to realize the optimal layout of full coverage of recycling points and distribution systems. The most efficient implementation of transport.

At the same time, this study also has great practical significance to the society. First of all, the automobile manufacturing industry consumes a lot of resources, and its development speed is accelerating, and the demand for resources is also increasing. Research on the reverse logistics network of end-of-life vehicles is conducive to improving the utilization rate of resources, promoting the development of circular economy [28], and promoting the recycling of raw materials such as steel, rubber, non-ferrous metals and the five assemblies of automobiles. In addition, the exhaust gas emitted by end-of-life vehicles on the road will be three times that of ordinary cars, and the unreasonable disposal of end-of-life vehicles will cause serious potential environmental pollution problems. This study focuses on the control of reverse logistics of automobiles, which is helpful to reduce environmental pollution and reduce the harm to the environment caused by the use of end-of-life vehicles. At the enterprise level, in the recycling process, more than 95 % of the raw materials of an old automobile can be reused. Realizing the recycling of end-of-life vehicles parts and five assemblies is conducive to reducing the production cost of enterprises, improving the utilization rate of raw materials in the automotive manufacturing field, reducing the cost of raw materials, and creating profits for the forward logistics process of automobiles.

6. Conclusion

This study proposes a logistics network location planning and flow allocation proposal with the second-hand car market as the recycling centre. Based on the historical number of end-of-life vehicles in Shanghai, the future quantity is predicted and used as input data for the model to simulate network operation. The grey prediction results show that the recycling volume of end-of-life vehicles in Shanghai will reach 140000 in 2021, and the prospects for the end-of-life vehicles recycling industry are very optimistic. To solve the optimization problem of reverse logistics network for end-of-life vehicles, this study used LINGO 12 software for model solving. The obtained resource optimization allocation plan effectively improves the actual recovery rate and reduces the operational and logistics costs of the logistics network.

The reverse logistics network of end-of-life vehicles is a complex and uncertain system. However, the research object of this paper is only the reverse logistics network of end-of-life vehicles with single-variety, single-cycle, recycling manufacturing and utilization, which is complex and multi-product in reality. The detailed study of multi-product situation is more suitable for practical problems. The construction of mixed integer model considering environmental protection, economy, resource utilization and other benefits can provide a comprehensive framework for scrap vehicle reverse logistics network. The follow-up research will also focus on the dynamic prediction of the amount of recycling, which will be based on the changes of many factors such as market demand, technological development, policies and regulations, in order to realize the dynamic real-time allocation of resources and adapt to the changing environment and market demand, so as to achieve the innovation breakthrough of reverse logistics network.

References

[1] Iruthayaraj, D.L., Arockiam, R.R.P., Subbaian, J. (2023). Real-time indoor environment quality monitoring for vehicle cabin, *Environmental Engineering and Management Journal,* Vol 22, No. 11, 1801-1811, doi: 10.30638/eemj.2023.156.

[2] Qi, Y., Niu, Y., Zhou, Z. (2023). Digital economy empowering the development level of Chinese manufacturing industry, *Economic Computation and Economic Cybernetics Studies and Research,* Vol. 57 No. 4, 243-258, doi: 10.24818/18423264/57.4.23.15.

[3] Wang, L., Chen, X.Y., Zhang, H. (2021). Joint distribution models in fast-moving consumer goods wholesale enterprise: Comparative analysis and a case study, *Advances in Production Engineering & Management*, Vol. 16, No. 2, 212-222, doi: 10.14743/apem2021.2.395.

[4] Simic, V. (2013). End-of-life vehicle recycling - A review of the state-of-the-art, *Tehnički Vjesnik – Technical Gazette,* Vol. 20, No. 2, 371-380.

[5] Hao, H., Zhang, Q., Wang, Z., Zhang, J. (2018). Forecasting the number of end-of-life vehicles using a hybrid model based on grey model and artificial neural network, *Journal of Cleaner Production,* Vol. 202, 684-696, doi: 10.1016/j.jclepro.2018.08.176.

[6] Mohamad-Ali, N., Ghazilla, R.A.R., Abdul-Rashid, S.H., Sakundarini, N., Ahmad-Yazid, A., Stephenie, L. (2017). Development of an end-of-life vehicle recovery model using system dynamics and future research needs, *IOP Conference Series: Materials Science and Engineering,* Vol. 210 No. 1, Article No. 012075, doi: 10.1088/1757-899X/210/1/012075.

[7] Zhang, Y., Zhong, M., Geng, N., Jiang, Y. (2017). Forecasting electric vehicles sales with univariate and multivariate time series models: The case of China, *Plos One,* Vol. 12, No. 5, 1-15, doi: 10.1371/journal.pone.0176729.

[8] Dargay, J., Gately, D. (1999). Income's effect on car and vehicle ownership, worldwide: 1960-2015, *Transportation research, Part A: Policy and Practice,* Vol. 33, No. 2, 101-138, doi: 10.1016/S0965-8564(98)00026-3.

[9] Demirel, E., Demirel, N., Gökçen, H. (2016). A mixed integer linear programming model to optimize reverse logistics activities of end-of-life vehicles in Turkey, *Journal of Cleaner Production,* Vol. 112, Part 3, 2101-2113, doi: 10.1016/j.jclepro.2014.10.079.

[10] Lin, Y., Jia, H., Yang, Y., Tian, G., Tao, F., Ling, L. (2018). An improved artificial bee colony for facility location allocation problem of end-of-life vehicles recovery network, *Journal of Cleaner Production,* Vol. 205, 134-144, doi: 10.1016/j.jclepro.2018.09.086.

[11] Govindan, K., Gholizadeh, H. (2021). Robust network design for sustainable-resilient reverse logistics network using big data: A case study of end-of-life vehicles, *Transportation Research Part E: Logistics and Transportation Review,* Vol. 149, Article No. 102279, doi: 10.1016/j.tre.2021.102279.

[12] Ene, S., Öztürk, N. (2015), Network modeling for reverse flows of end-of-life vehicles, *Waste Management,* Vol. 38 284-296, doi: 10.1016/j.wasman.2015.01.007.

[13] Chaabane, A., Montecinos, J., Ouhimmou, M., Khabou, A. (2021). Vehicle routing problem for reverse logistics of End-of-Life Vehicles (ELVs), *Waste Management*, Vol. 120, 209-220, doi: 10.1016/j.wasman.2020.11.008.

[14] Min, H., Ko, C.S., Ko, H.J. (2006). The spatial and temporal consolidation of returned products in a closed-loop supply chain network, *Computers & Industrial Engineering,* Vol. 51, No. 2, 309-320, doi: 10.1016/j.cie.2006.02.010.

[15] Marin, A., Pelegrin, B. (1998). The return plant location problem: Modelling and resolution, *European Journal of Operational Research,* Vol. 104, No. 2, 375-392, doi: 10.1016/S0377-2217(97)00192-6.

[16] Du, F., Evans, G.W. (2008). A bi-objective reverse logistics network analysis for post-sale service, *Computers & Operations Research,* Vol. 35, No. 8, 2617-2634, doi: 10.1016/j.cor.2006.12.020.

[17] Kheirabadi, M., Naderi, B., Arshadikhamseh, A., Roshanaei, V. (2019). A mixed-integer program and a Lagrangian-based decomposition algorithm for the supply chain network design with quantity discount and transportation modes, *Expert Systems with Applications,* Vol. 137, 504-516, doi: 10.1016/j.eswa.2019.07.004.

[18] Steinrücke, M. (2015). Integrated production, distribution and scheduling in the aluminium industry: A continuous-time MILP model and decomposition method, *International Journal of Production Research,* Vol. 53, No. 19, 5912-5930, doi: 10.1080/00207543.2015.1023401.

[19] Tan, Y., Takakuwa, S. (2011). Use of simulation in a factory for business continuity planning, *International Journal of Simulation Modelling,* Vol. 10, No. 1, 17-26, doi: 10.2507/IJSIMM10(1)2.172.

[20] Li, Y., Abtahi, A.-R., Seyedan, M. (2019). Supply chain performance evaluation using fuzzy network data envelopment analysis: A case study in automotive industry, *Annals of Operations Research,* Vol. 275, No. 2, 461-484, doi: 10.1007/s10479-018-3027-4.

[21] Guzmán, E., Poler, R., Andres, B. (2023). A matheuristic approach combining genetic algorithm and mixed integer linear programming model for production and distribution planning in the supply chain, *Advances in Production Engineering and Management,* Vol. 18, No. 1, 19-31, doi: 10.14743/apem2023.1.454.

[22] Ding, F., Liu, S., Li, X. (2022). Pareto optimality of centralized procurement based on genetic algorithm, *Tehnički Vjesnik – Technical Gazette,* Vol. 29, No. 6, 2058-2066, doi: 10.17559/TV-20220723180901.

[23] Jünger, M., Liebling, T.M., Naddef, D., Nemhauser, G.L., Pulleyblank, W.R., Reinelt, G., Rinaldi, G., Wolsey, L.A. (2010). *50 Years of integer programming 1958-2008,* Springer, Berlin, Germany, doi: 10.1007/978-3-540-68279-0.

[24] Niu, X.Y., Liu, S.F., Huang, Q.L. (2022). End-of-line delivery vehicle routing optimization based on large-scale neighbourhood search algorithms considering customer-consumer delivery location preferences, *Advances in Production Engineering & Management*, Vol. 17, No. 4, 439-454, doi: 10.14743/apem2022.4.447.

[25] Ye, Y., Wang, J. (2017). Study of logistics network optimization model considering carbon emissions*, International Journal of System Assurance Engineering and Management,* Vol. 8, Suppl. 2, 1102-1108, doi: 10.1007/s13198-017-0576-x.

[26] Xiao, Z., Sun, J., Shu, W., Wang, T. (2019). Location-allocation problem of reverse logistics for end-of-life vehicles based on the measurement of carbon emissions, *Computers & Industrial Engineering,* Vol. 127, 169-181, doi: 10.1016/j.cie.2018.12.012.

[27] Ocampo, L.A., Himang, C.M., Kumar, A., Brezocnik, M. (2019). A novel multiple criteria decision-making approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy AHP for mapping collection and distribution centers in reverse logistics, *Advances in Production Engineering & Management,* Vol. 14, No. 3, 297-322, doi: 10.14743/apem2019.3.329.

[28] Cheng, Y., Xu, J. (2021). Model of environmental management science based on circular economy theory*, Ecological Chemistry and Engineering S,* Vol. 28, No. 4, 513-524, doi: 10.2478/eces-2021-0034.