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Research Article

Site Selection Optimization of Reverse Logistics Network for Waste Tires

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In order to solve the problem of reverse recycling of waste tires in Heilongjiang Province, this paper chooses the third party as the core to construct a reverse logistics network system of waste tires based on the current situation of reverse logistics of waste tires. The reverse recycling area of waste tires in Heilongjiang Province is divided into five areas (the first area is Harbin; the second area contains Qiqihar, Daqing, and Suihua; the third area contains Yichun, Hegang, Jiamusi, and Shuangyashan; Qitaihe, Jixi, and Mudanjiang form the fourth area; and the fifth area contains Daxinganling and Heihe). The analytic hierarchy process (AHP) is employed to analyze the influence factors of site selection of reverse logistics network and obtain the total weight of each evaluation factor. The weights of economic conditions, the number of waste tires, traffic conditions, development planning and policy, and geographical conditions are obtained as 0.3547, 0.2256, 0.1690, 0.1644, and 0.0863, respectively. The economic conditions and the number of waste tires with high weights are vital factors for selecting a reverse logistics network for waste tires. The linear mixed-integer programming method (LINGO) is utilized for site selection. Harbin, Qiqihar, Daqing, Mudanjiang, Jiamusi, and Suihua are chosen for the recovery center's site selection, while Daqing, Mudanjiang, and Suihua are chosen as the site selection of remanufacturing enterprise.

1. Introduction

China is not only a tire manufacturing and consumption country but also a country lacking in rubber resources. The annual consumption of rubber globally accounts for about 30% of the total rubber consumption, while the rubber products industry requires 80% of natural rubber and 30% of synthetic rubber depending on imports. The contradiction between supply and demand is very prominent [1]. Scientific recycling of waste tires and reusing and harmlessly treating them can protect the ecological environment, save rubber resources, reduce energy consumption, and develop a circular economy. As a national strategic emerging industry, the comprehensive utilization of waste tires provides significant social benefits in the circular economy development. According to the industry specification conditions for comprehensive utilization of waste tires released by the Ministry of Industry and Information Technology in 2020 [2], the total production of auto tires in China in 2019 is 650 million, and the domestic consumption is 380 million, while the market holding of motor tires reaches 1.7 billion. In recent years, waste tire production in China has grown significantly. In 2020, the amount of produced waste tires was about 350 million, and the equivalent weight exceeded 10 million tons. The disposal of waste tires has attracted much attention. Improper disposal of waste tires leads to environmental impact, safety risks, and a waste of resources. After years of development, China's waste tire comprehensive utilization industry has initially formed four business segments: used tire retreading, waste tire production of recycled rubber, waste tire production of rubber powder, and waste tire (rubber) thermal pyrolysis [1]. The industrial system of comprehensive utilization of waste tires with Chinese characteristics has been initially established, and the industrial chain of comprehensive utilization of waste tires has been formed [1]. However, due to the lack of specific logistics system management methods and effective management measures from generation, recovery, transportation, storage to

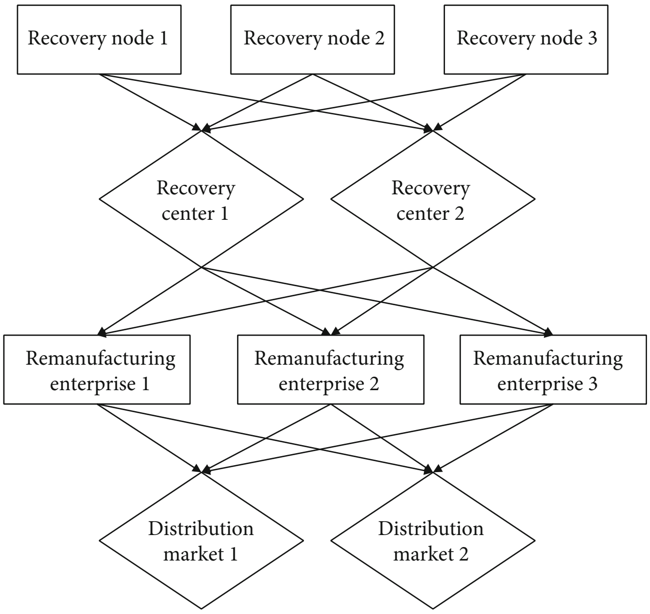

Figure 1: The reverse logistics network system of waste tires in Heilongjiang Province.

disposal, the current reverse logistics network system of waste tires in China is not standardized.

Meanwhile, few studies have been performed on the network site selection of the reverse logistics for waste tires. Various works have been performed in foreign countries on the construction and site selection of reverse logistics network systems, and high achievements have been obtained in both theory and practice [3–5]. Although the corresponding research was recently performed in China, scholars achieved specific results in this area. The existing research mainly focused on the single period and single objective levels in certain environment and multiperiod and multiobjective levels in uncertain environment. Different reverse logistics network systems and models have been studied and established to satisfy different requirements and constraints. After constructing the mathematical model, LINGO, neural network, genetic algorithm, grid algorithm, and other methods can be utilized to solve the model. Analytic hierarchy process (AHP), the center of gravity method, integer or mixed-integer programming method, Baumol-Wolfe method, antipodean method, fuzzy theory analysis, and other methods have been adopted for site selection [6–8].

Given the existing research at home and abroad, it can be found that the construction and site selection of a waste tire reverse logistics network system can be complex and should be studied further. With improving the living standards, car ownership in Heilongjiang Province and the number of waste tires gradually increase. However, the research on reverse logistics of waste tires in Heilongjiang Province is still in its infancy, and there is no perfect reverse logistics system of waste tires. In recent years, the Government of Heilongjiang Province has encouraged the development of green circular economy systems. As the primary source of recycled rubber, the reverse recycling of waste tires has been concerned by the government. The effective reuse of waste tires is the key field to achieve the goal of "carbon peak and carbon neutralization." With the concept of sustainable development and circular economy becoming more and more popular, people pay more and more attention to the activities of reverse logistics. The establishment of waste tire reverse logistics system can effectively recycle and reuse waste tire rubber, which not only saves a lot of rubber resources, but also effectively controls the harm to the environment. The recycling of waste tires, as an effective way of recycling and harmless disposal of these "solid wastes," is of great significance for the development of circular economy, saving rubber resources, reducing energy consumption, protecting the ecological environment, reducing and gradually eliminating "black pollution," and promoting the green and sustainable development of the rubber industry, and achieving my country's "carbon peak" and "carbon neutrality."

2. Construction of the Reverse Logistics Network System of Waste Tires in Heilongjiang Province

Waste tire reverse logistics refers to a series of activities that meet the development requirements of circular economy, recycle the tires that cannot meet the actual use requirements and scrap tires, classify, treat, disassemble and remanufacture the recycled waste tires, and maximize the potential value of waste tires. Agricultural vehicles, private cars, public vehicles, trucks, and engineering vehicles are the primary sources of waste tires in Heilongjiang Province. Most existing waste tire recycling in Heilongjiang Province are agricultural machinery sales points, vehicle maintenance shops, large passenger transport companies, and waste (renewable resources) recycling centers. Most existing reprocessing enterprises are small waste tire processing plants or remanufacturing enterprises, including other renewable resources reprocessing. The existing reverse logistics recycling mode of waste tires in Heilongjiang Province includes recycling waste tires by mobile recycling personnel, agricultural machinery sales points, vehicle maintenance shops, large passenger transportation companies, and waste (renewable resources) recycling centers. The recycling of waste tires will be sold according to the requirements of the waste tire remanufacturing enterprises. Since waste tires' existing reverse logistics system is not mature and perfect, it cannot guarantee a high waste tire recovery rate. The site selection of remanufacturing enterprises is not reasonable and normative, and most of them are located in densely populated areas, which will cause significant cost consumption.

According to the development goals of "China tire recycling industry" fourteenth five-year development plan, by 2025, laws and regulations, policies, standards, technologies, suitable information statistical service system, and a standardized waste tire recycling system should be established to achieve the comprehensive utilization of waste tires in China [1]. Therefore, in combination with the actual geographical environment and the current economic development situation in Heilongjiang Province, the reverse logistics network system of waste tires in Heilongjiang Province is established based on the recycling mode with the third party as the core (see Figure 1). Under the reverse logistics network mode of waste tires with the third party as the core, the waste tires are recycled by the third-party enterprise, and the manufacturer does not directly participate and has a high recycling level and professional level. This mode can reduce the operation risk and management cost borne by the manufacturer. Figure 1 shows that the reverse logistics network system of waste tires in Heilongjiang Province consists of four levels: recovery node, recovery center, remanufacturing enterprise, and distribution market. The first level is the recovery node established by consumers as the main body. The addition of the recovery node ensures the maximum recovery of waste tires and improves their recovery rate. The second level is the recycling center, which collects the waste tires recovered by each recycling node for primary classification and processing. The third level is the remanufacturing enterprise, which aims to process and reproduce recycled tires. The fourth level is the distribution market, which gathers all kinds of remanufactured products to realize trading, recycling, and achieving economic benefits.

3. Analysis of Factors Affecting the Site Selection of Reverse Logistics Network

AHP is employed to analyze factors influencing the site selection of the reverse logistics network in Heilongjiang Province. According to the administrative planning of Heilongjiang Province, the reverse recycling area of waste tires is divided into five areas. The first area is Harbin; the second area contains Qiqihar, Daqing, and Suihua; the third area contains Yichun, Hegang, Jiamusi, and Shuangyashan; the fourth area includes Qitaihe, Jixi, and Mudanjiang; and the fifth area includes Daxinganling and Heihe. Traffic conditions, geographical conditions, economic conditions, the number of waste tires, and development planning and policy are selected as the evaluation factors.

3.1. Analytic Hierarchy Process (AHP).

The AHP steps are as follows: (1) determining the aims; (2) determining the hierarchy according to the goal; (3) constructing the comparative judgment matrix to determine the priority relationship; and (4) testing the hierarchy order and consistency [9, 10].

(1) The eigenvectors $\bar{w} = (\overline{w_1}, \overline{w_2}, \cdots, \overline{w_n})^T$ are obtained by normalizing and summing the judged columns as

$$\overline{w_i} = \sum_{j=1}^{n} \frac{a_{ij}}{\sum a_{ij}}, \tag{1}$$

where a_{ij} stands for the ratio of the importance of element i to element j.

(2) The eigenvectors are normalized to obtain the elements of the weight vector $w = (w_1, w_2, \cdots, w_n)^T$ as

$$w_i = \frac{\overline{w_i}}{\sum \overline{w_i}}. \tag{2}$$

(3) The maximum eigenvalue is calculated as

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(Aw)_i}{n w_i}, \tag{3}$$

where $(Aw)_i$ represents the ith element of the vector Aw

(4) The consistency test index CI and the consistency ratio index CR are calculated as

$$\begin{aligned} \mathrm{CI} &= \frac{\lambda_{\max} - n}{n - 1}, \\ \mathrm{CR} &= \frac{\mathrm{CI}}{\mathrm{RI}}. \end{aligned} \tag{4}$$

If $\mathrm{CR} < 0.1$, the consistency of the judgment matrix is acceptable; otherwise, the matrix should be modified.

(5) Hierarchical total sorting and consistency test are performed.

(a) The criterion-level and subcriteria-level weight vectors are obtained according to the single order sorting as

$w^{(k-1)} = (w_1{}^{(k-1)}, w_2{}^{(k-1)}, \cdots, w_n{}^{(k-1)})^T$; $w_j{}^k = (w_{1j}{}^{(k)}, w_{2j}{}^{(k)}, \cdots, w_{nj}{}^{(k)})^T$.

Accordingly, the total weights of the subcriterion layer to criterion layer can be calculated as

$$w_i^{(k)} = \sum_{j=1}^{m} P_{ij}^{(k)} w_i^{(k)}. \tag{5}$$

(b) Calculate the $\mathrm{CI}^{(k-1)}$ and $\mathrm{RI}^{(k-1)}$of the subcriteria level, and then, perform the consistency check of the criterion level:

$$\begin{aligned} \mathrm{CI}^{(k)} &= \left(\mathrm{CI}_1{}^{(k)}, \mathrm{CI}_2{}^{(k)}, \cdots, \mathrm{CI}_\mathrm{m}{}^{(k)}\right) w^{(k-1)}, \\ \mathrm{RI}^{(k)} &= \left(\mathrm{RI}_1{}^{(k)}, \mathrm{RI}_2{}^{(k)}, \cdots, \mathrm{RI}_m{}^{(k)}\right) w^{(k-1)}, \\ \mathrm{CR}^{(k)} &= \frac{\mathrm{CI}^{(k)}}{\mathrm{RI}^{(k)}}, \end{aligned} \tag{6}$$

where $\mathrm{CR}^{(k)} < 0.1$ is considered that the overall consistency of the judgment matrix meets the requirements.

(6) Analyze the sorting result and make the corresponding decision.

3.2. Constructing a Hierarchical Structure Model. Figure 2 shows the hierarchical structural model of site selection of the reverse logistics network for waste tires, in which the target layer (A) is the analysis of the reverse logistics network site selection. The middle layer (B) includes the first, second, third, fourth, and fifth areas. The bottom layer (C) consists of five evaluation factors: traffic conditions, geographical conditions, economic conditions, the number of waste tires, and development plans and policies [11].

3.3. Construction of Judgment Matrices. The judgment matrix of the first layer (denoted by A) describes the judgment matrix relative to the highest level.

$$A = \begin{bmatrix} 1 & 1 & 3 & 4 & 6 \\ 1 & 1 & 2 & 3 & 4 \\ 1/3 & 1/2 & 1 & 1 & 3 \\ 1/4 & 1/3 & 1 & 1 & 2 \\ 1/6 & 1/4 & 1/3 & 1/2 & 1 \end{bmatrix}. \tag{7}$$

The five secondary judgment matrices relative to the middle layer, denoted by B_i (i=1,2,3,4,5), are given in the following.

Comparison results of the influencing factor indices in the first area:

$$B_1 = \begin{bmatrix} 1 & 3 & 1/3 & 2 & 1 \\ 1/3 & 1 & 1/5 & 1/3 & 1/3 \\ 3 & 5 & 1 & 2 & 1 \\ 1/2 & 3 & 1/2 & 1 & 1/4 \\ 1 & 3 & 1 & 4 & 1 \end{bmatrix}. \tag{8}$$

Comparison results of the influencing factor indices in the second area:

$$B_2 = \begin{bmatrix} 1 & 3 & 1/3 & 1/2 & 2 \\ 1/3 & 1 & 1/2 & 1/3 & 1/2 \\ 3 & 2 & 1 & 2 & 4 \\ 2 & 3 & 1/2 & 1 & 3 \\ 1/2 & 2 & 1/4 & 1/3 & 1 \end{bmatrix}. \tag{9}$$

Comparison results of the influencing factor indices in the third area:

$$B_3 = \begin{bmatrix} 1 & 2 & 1/3 & 1/2 & 2 \\ 1/2 & 1 & 1/2 & 1/3 & 3 \\ 3 & 2 & 1 & 2 & 3 \\ 2 & 3 & 1/2 & 1 & 4 \\ 1/2 & 1/3 & 1/3 & 1/4 & 1 \end{bmatrix}. \tag{10}$$

Comparison results of the influencing factor indices in the fourth area:

$$B_4 = \begin{bmatrix} 1 & 2 & 1/5 & 1/3 & 2 \\ 1/2 & 1 & 1/3 & 1/5 & 1 \\ 5 & 3 & 1 & 2 & 3 \\ 3 & 5 & 1/2 & 1 & 3 \\ 1/2 & 1 & 1/3 & 1/3 & 1 \end{bmatrix}. \tag{11}$$

Comparison results of the influencing factor indices in the fifth area:

$$B_5 = \begin{bmatrix} 1 & 1/3 & 1/3 & 1/5 & 2 \\ 3 & 1 & 1/2 & 1/3 & 1 \\ 3 & 2 & 1 & 1 & 3 \\ 5 & 3 & 1 & 1 & 5 \\ 1/2 & 1 & 1/3 & 1/5 & 1 \end{bmatrix}. \tag{12}$$

3.4. Calculation of the Weight of Each Evaluation Factor. The

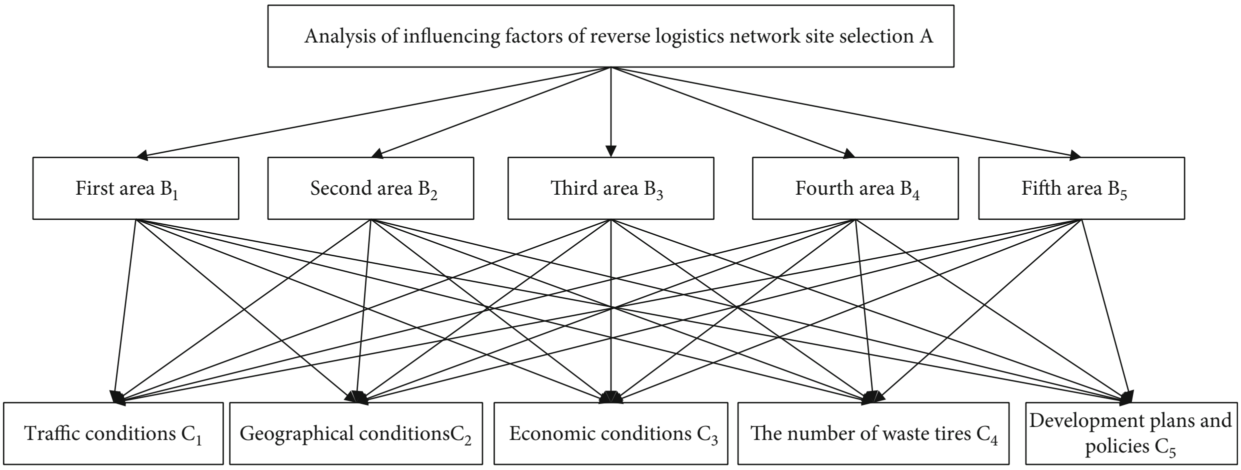

Figure 2: Hierarchical structural model.

Yaahp software is employed to calculate each matrix's weight coefficients and maximum eigenvalues [12, 13].

The weight coefficient can be calculated through the judgment matrix A. Among all areas, the first area has the highest weight (0.3806), followed by the second area (0.3055), the third area (0.1409), the fourth area (0.1131), and the fifth area with the lowest weight (0.0599).

The judgment matrix B_1 that corresponds to each influencing factor index of the first area can calculate the weight coefficient. The weight of economic conditions is the highest (0.3371), followed by development planning and policies (0.2806), traffic conditions (0.1961), the number of waste tires (0.1222), and geographical conditions (0.0640).

The judgment matrix B_2 that corresponds to each influencing factor index of the second area is employed to obtain the weight coefficient. The weight of economic conditions is the highest (0.3728), followed by the number of waste tires (0.2668), traffic conditions (0.1719), development planning and policies (0.1046), and geographical conditions (0.0839).

The judgment matrix B_3 that corresponds to each influencing factor index of the third area is employed to calculate the weight coefficient. The weight of economic conditions is the highest (0.3533), followed by the number of waste tires (0.2836), traffic conditions (0.1591), geographical conditions (0.1307), and development planning and policies (0.1046).

The judgment matrix B_4 that corresponds to each influencing factor index of the fourth area is adopted to determine the weight coefficient. The weight of economic conditions is the highest (0.3994), followed by the number of waste tires (0.3027), traffic conditions (0.1247), development planning and policies (0.0911), and geographical conditions (0.0822).

The judgment matrix B_5 that corresponds to all influencing factor indices of the fifth area is utilized to determine the weight coefficient. The weight of the number of waste tires is the highest (0.3908), followed by economic conditions (0.2938), geographical conditions (0.1435), traffic conditions (0.0884), and development planning and policies (0.0835).

Table 1: Maximum eigenvalues of each matrix.

	A	B_1	B_2	B_3	B_4	B_5
$\lambda_{\max}$	5.0562	5.2614	5.2858	5.2591	5.2285	5.2511

Table 2: Consistency indices (RI).

n	1	2	3	4	5	6	7
RI	0	0	0.58	0.90	1.12	1.24	1.32

Table 3: The number of waste tires in Heilongjiang Province.

City	Number of waste tires ($\times 10^4$)	Recovery amount of waste tires ($\times 10^4$)	Recovery amount of waste tires (tons)
Harbin	800	160	13300
Qiqihar	180	36	3000
Daqing	210	42	3500
Mudanjiang	200	40	3330
Jiamusi	140	28	2330
Suihua	150	30	2500
Jixi	60	12	1000
Shuangyashan	40	8	660
Yichuan	50	10	830
Qitaihe	30	6	500
Hegang	28	5.6	470
Daxinganling	50	10	830
Heihe	45	9	750

The maximum eigenvalue for each matrix ($\lambda_{\max}$) is presented in Table 1, and the corresponding consistency indices (RI) are given in Table 2.

Table 4: Distance between recovery nodes (km).

City	A	B	C	D	E	F	G	H	I	J	K	L	M
A	0	—	—	—	—	—	—	—	—	—	—	—	—
B	305.2	0	—	—	—	—	—	—	—	—	—	—	—
C	153.1	159	0	—	—	—	—	—	—	—	—	—	—
D	334.6	649.5	494.4	0	—	—	—	—	—	—	—	—	—
E	384.8	670.1	517.8	339.6	0	—	—	—	—	—	—	—	—
F	151.1	403.2	248.2	452.9	470.1	0	—	—	—	—	—	—	—
G	487.4	775.6	620.5	172.8	206.6	572.8	0	—	—	—	—	—	—
H	457.7	746.2	591.1	415.8	85.3	543.4	280.6	0	—	—	—	—	—
I	323.3	475.5	456.8	661.6	204.5	212.6	407.1	285.4	0	—	—	—	—
G	430.5	719	564	225.4	150.6	516.3	90.2	225.4	352.5	0	—	—	—
K	443.2	625.2	582.1	404.7	66.8	362.4	269.5	147.7	152	213.8	0	—	—
L	706.3	430.7	559.7	1050.9	776.4	578.3	1173.7	857.2	573.9	1118	723.6	0	—
M	573.4	493	622	384.8	681.8	483.7	1028.6	762.6	479.3	972.9	629	337.9	0

According to Equations (2)–(5), the consistency ratio index (CR) for each matrix can be calculated as

$$\begin{aligned} &\mathrm{CR}^{(A)} = 0.0125 < 0.1\,; \\ &\mathrm{CR}^{(B_1)} = 0.0584 < 0.1\,; \\ &\mathrm{CR}^{(B_2)} = 0.0638 < 0.1\,; \\ &\mathrm{CR}^{(B_3)} = 0.0578 < 0.1\,; \\ &\mathrm{CR}^{(B_4)} = 0.0510 < 0.1\,; \\ &CR^{(B_5)} = 0.0560 < 0.1. \end{aligned} \tag{13}$$

It can be concluded from the above values that all the areas passed the consistency test and all the judgment matrices meet the requirements. The weights of traffic conditions, geographical conditions, economic conditions, the number of waste tires, and development planning and policy are 0.1690, 0.0863, 0.3547, 0.2256, and 0.1164, respectively. Among them, economic conditions and the number of waste tires have the highest weights. Thus, these two factors are vital in selecting the reverse logistics network site for waste tires. The area's economic conditions directly affect the development level of the automobile industry, infrastructure, and logistics. Choosing areas with better economic conditions as the site selection of each facility can ensure the continuity of the reverse logistics system of waste tires and enhance the system's practical use value. Choosing an area with many waste tires as the site selection of each facility point can help the facility point to give full play to its functions and reduce transportation costs.

4. Construction of the Reverse Logistics Network Model of Waste Tires

4.1. Model Assumption. This paper employs the linear mixed-integer programming method (LINGO) for mathematical modeling and obtains each facility's optimal location, quantity, and flow rate under the objective of an ideal state and minimum cost. Before establishing the model, the following assumptions should be considered: (1) The capacity of the recovery node is infinite and can work stably and continuously; (2) the investment cost, unit operating cost, and transportation cost of each facility are fixed values and are not related to the period; (3) each recycling node can recycle all the waste tires in the corresponding area, while the waste tires are not overstocked; (4) all the facilities and the work among them in the reverse logistics network system of waste tires are in ideal mode; that is, waste tires are fully utilized without any loss; and (5) the reverse logistics network system of waste tires can operate effectively for a long time [14].

4.2. Model Construction. The reverse logistics network of waste tires contains many factors influencing the site selection. Considering all of these factors makes the model highly complex and challenging to solve. Thus, this paper only considers fixed cost, transportation cost, and treatment cost [15]. The model's relevant parameters and decision variables are defined as follows:

4.2.1. Symbol Definition. a_i represents the ith recovery node, and A stands for the collection of all recovery nodes; b_j represents the jth recovery center, and B stands for the collection of all recovery centers; and $c_k$represents the kth remanufacturing enterprise, and C stands for the collection of all remanufacturing enterprise.

4.2.2. Parameters. $D_{ABa_i}^{b_j}$ represents the transportation distance from the ith recovery node to the jth recovery center. $D_{BCb_j}^{c_k}$ represents the transportation distance from the ith recovery center to the jth remanufacturing enterprise.

E, F, G represent the costs. The unit transportation cost from the ith recovery node to the jth recovery center is represented by $E_{ABa_i}^{b_j}$. $E_{BCb_j}^{c_k}$ describes the unit transportation cost from the jth recovery center to the kth remanufacturing enterprise. F_{Aa_i} stands for the fixed cost of the ith recovery node. F_{Bb_j} represents the fixed cost of the jth recovery center. The fixed cost of the kth remanufacturing enterprise is denoted by F_{Cc_k}. G_{Aa_i} describes the unit operating cost of the ith recovery node. G_{Bb_j} represents the unit operating cost of the jth recovery center. G_{Cc_k} stands for the unit operating cost of the kth remanufacturing enterprise.

H_{Aa_i} represents the maximum inventory of waste tires at the ith recovery node (infinite inventory is assumed in this paper). H_{Bb_j} describes the maximum disposal capacity of waste tires in the jth recovery center. The maximum disposal capacity of waste tires in the kth remanufacturing enterprise is denoted by H_{Cc_k}. P_{Aai} stands for the recovery amount of waste tire of the ith recovery node.

4.2.3. Decision Variable. $P_{ABa_i}^{b_j}$ represents the transportation volume from the ith recovery node to the jth recovery center. $P_{BCb_j}^{c_k}$ stands for the transportation volume from the j th recovery center to the kth remanufacturing enterprise.

If a_i is selected as the recovery node, Y_{Aa_i} is 1; otherwise, it is 0. If b_j is selected as the recovery center, Y_{Bb_j} is 1; otherwise, it is 0. If c_k is equal to the remanufacturing enterprise, Y_{Cc_k} is 1; otherwise, it is 0, $Y_{Aa_i}, Y_{Bb_j}, Y_{Cc_k} \in Y$.

The objective function is constructed as:

$$\begin{aligned}\operatorname{Min} Z = {} & \sum_{a_i}\left(F_{Aa_i}Y_{Aa_i}\right) + \sum_{b_j}\left(F_{Bb_j}Y_{Bb_j}\right) + \sum_{c_k}\left(F_{Cc_k}Y_{Cc_k}\right) \\ & + \sum_{a_i}\sum_{b_j}\left(D_{ABa_i}^{b_j}E_{ABa_i}^{b_j}P_{ABa_i}^{b_j}\right) + \sum_{b_j}\sum_{c_k}\left(D_{ABa_i}^{b_j}E_{BCb_j}^{c_k}P_{BCb_j}^{c_k}\right) \\ & + \sum_{a_i}\left(G_{Aa_i}P_{Aai}Y_{Aa_i}\right) + \sum_{b_j}\left(G_{Bb_j}P_{ABa_i}^{b_j}Y_{Bb_j}\right) \\ & + \sum_{c_k}\left(G_{Cc_k}P_{BCb_j}^{c_k}Y_{Cc_k}\right),\end{aligned} \tag{14}$$

where Z represents the total cost of the reverse logistics network of waste tires. $\sum_{a_i}(F_{Aa_i}Y_{Aa_i})$ describes the fixed cost of recovery nodes; $\sum_{b_j}(F_{Bb_j}Y_{Bb_j})$ stands for the fixed cost of recovery centers; the fixed cost of remanufacturing enterprise is represented by $\sum_{c_k}(F_{Cc_k}Y_{Cc_k})$; $\sum_{a_i}\sum_{b_j}(D_{ABa_i}^{b_j}E_{ABa_i}^{b_j} P_{ABa_i}^{b_j})$ denotes the transportation cost of the recovery node to the recovery center; $\sum_{b_j}\sum_{c_k}(D_{ABa_i}^{b_j}E_{BCb_j}^{c_k}P_{BCb_j}^{c_k})$ describes the transportation cost from the recovery center to the remanufacturing enterprise; and $\sum_{a_i}(G_{Aa_i}P_{Aai}Y_{Aa_i})$, $\sum_{b_j}(G_{Bb_j} P_{ABa_i}^{b_j}Y_{Bb_j})$, and $\sum_{c_k}(G_{Cc_k}P_{BCb_j}^{c_k}Y_{Cc_k})$ stand for the operating costs of recovery nodes, the recovery center, and the remanufacturing enterprise, respectively.

4.3. The Constraints. The mathematical model should meet constraints to ensure the applicability of the construction system [16].

$$\left\{\begin{array}{l}\sum\limits_{a_i}P_{Aa_i} = \sum\limits_{a_i}\sum\limits_{b_j}P_{ABa_i}^{b_j} \\ \sum\limits_{a_i}\sum\limits_{b_j}P_{ABa_i}^{b_j} = \sum\limits_{b_j}\sum\limits_{c_k}P_{BCb_j}^{c_k} \\ P_{Aa_i} \le H_{Aa_i}Y_{Aa_i} \\ \sum\limits_{a_i}P_{ABa_i}^{b_j} \le H_{Bb_j}Y_{Bb_j} \\ \sum\limits_{b_j}P_{BCb_j}^{c_k} \le H_{Cc_k}Y_{Cc_k} \\ P_{Aa_i} \le P_{Aa_i}Y_{Aa_i} \\ \sum\limits_{a_i}P_{ABa_i}^{b_j} \le \sum\limits_{a_i}P_{ABa_i}^{b_j}Y_{Bb_j} \\ \sum\limits_{b_j}P_{BCb_j}^{c_k} \le \sum\limits_{b_j}P_{BCb_j}^{c_k}Y_{Cc_k} \\ a_i \in A \\ b_j \in B \\ c_k \in C \\ i \in N^* \\ j \in N^* \\ k \in N^* \\ Y \in 1, 0\end{array}\right., \tag{15}$$

where $\sum_{a_i}P_{Aa_i} = \sum_{a_i}\sum_{b_j}P_{ABa_i}^{b_j}$ indicates that the shipment amount should be equal to the recovery node's recovery amount. $\sum_{a_i}\sum_{b_j}P_{ABa_i}^{b_j} = \sum_{b_j}\sum_{c_k}P_{BCb_j}^{c_k}$ reflects that the shipment amount should be equal to the recovery center's recovery amount. $P_{Aa_i} \le H_{Aa_i}Y_{Aa_i}$ indicates that the recovery amount should be less than or equal to the maximum inventory amount of each recovery node. $\sum_{a_i}P_{ABa_i}^{b_j} \le H_{Bb_j}Y_{Bb_j}$ reflects that the recovery amount should be less than or equal to the maximum inventory amount of each recovery center. $\sum_{b_j}P_{BCb_j}^{c_k} \le H_{Cc_k}Y_{Cc_k}$ indicates that the recovery amount of each remanufacturing enterprise should be less than or equal to the maximum processing capacity $P_{Aa_i} \le P_{Aa_i}Y_{Aa_i}$, $\sum_{a_i}P_{ABa_i}^{b_j} \le \sum_{a_i}P_{ABa_i}^{b_j}Y_{Bb_j}$, and $\sum_{b_j}P_{BCb_j}^{c_k} \le \sum_{b_j}P_{BCb_j}^{c_k} Y_{Cc_k}$ indicate that the transportation will occur if and only if each facility point is selected.

4.4. The Number of Waste Tires at Each Recycling Node. According to the 2020 Statistical Yearbook of Heilongjiang Province and each city, the number of tires in each city in Heilongjiang Province is integrated, as presented in Table 3.

Since the distance calculated by the distance formula between two points cannot represent the actual

Table 5: Site selection decision of recovery center.

City	Harbin	Qiqihar	Daqing	Mudanjiang	Jiamusi	Suihua	Jixi	Shuangyashna	Yichuan	Qitaihe	Hegang	Daxinganling	Heihe
Selected or not	1	1	1	1	1	1	0	0	0	0	0	0	0

Table 6: Site selection decision of remanufacturing enterprise.

City	Harbin	Qiqihar	Daqing	Mudanjiang	Jiamusi	Suihua	Jixi	Shuangyashna	Yichuan	Qitaihe	Hegang	Daxinganling	Heihe
Selected or not	0	0	1	1	0	1	0	0	0	0	0	0	0

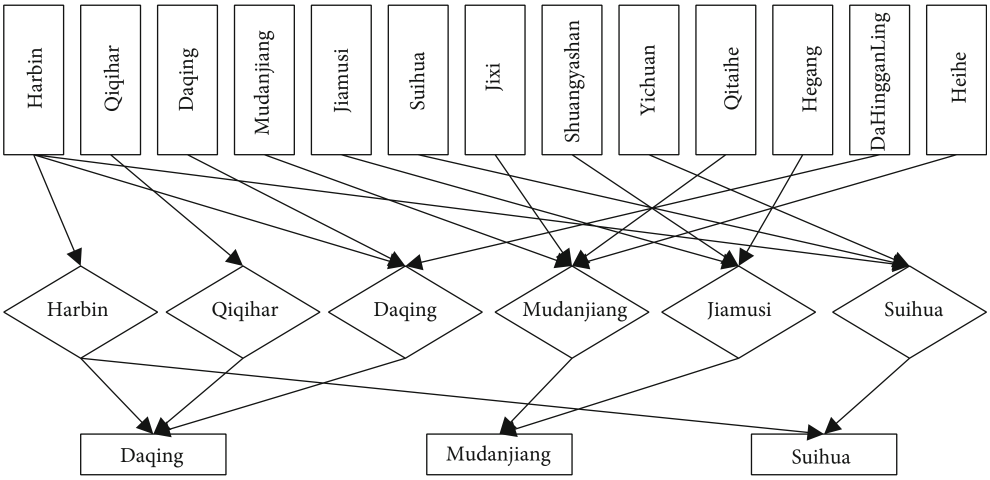

Figure 3: Reverse logistics network diagram of waste tires in Heilongjiang Province.

Table 7: Transport flow between facilities points (tons).

Proposed facilities	site	The area to be recovered and the amount of transportation
recovery center	Harbin	Harbin (6800)
	Qiqihar	Qiqihar (3000), DaHingganLing (560)
	Daqing	Harbin (3030), Daqing (3500), DaHingganLing (270)
	Mudanjiang	Mudanjiang (3330), Jixi (1000), Qitaihe (500), Heihe (750)
	Jiamusi	Jiamusi (2330), Shuangyashan (660), Hegang (470)
	Suihua	Harbin (3470), Suihua (2500), Yichuan (830)
Remanufacturing enterprise	Daqing	Harbin (1600), Qiqihar (3560), Daqing (6800)
	Mudanjiang	Mudanjiang (5580), Jiamusi (3460)
	Suihua	Harbin (5200), Suihua (6800)

transportation distance of goods, the distance query tool is utilized to query the distance between two cities considering the comprehensive judgment of aviation, waterway, highway, and railway data (Harbin, Qiqihar, Daqing, Mudanjiang, Jiamusi, Suihua, Jixi, Shuangyashan, Yichun, Qitaihe, Hegang, Daxinganling, and Heihe are denoted by A, B, C, D, E, F, G, H, I, J, K, L, and M, respectively). Consider that the service life of the reverse logistics network system of waste tires is long at each facility point. Thus, it can be drawn from market research and relevant literature that the construction specifications of each facility point have the same initial construction. Besides, the construction sites of each facility point are all industrial lands, and the construction cost gap is ignored. In this paper, each facility point's annual fixed cost and unit operating cost is assumed to be the same. The annual fixed cost of the recovery center is 1 million yuan, the operating cost is 120 yuan/ton, and the disposal amount is 6,800 tons. The annual fixed cost of remanufacturing enterprises is 15 million yuan, the operating cost is 300 yuan/ton, and the disposal amount is 12,000 tons. Based on the consulting China's Internet of materials and market research, the average freight per kilometer for a waste tire is 1.8 yuan/ton from the recovery node to the recovery center and 1.5 yuan/ton from the recovery center to the remanufacturing enterprise.

4.5. Model Solution. Since the proposed model involves a large amount of data and requires a large amount of calculation, highly targeted software is required to solve it. As a kind of simulation software with strong optimization capability, LINGO can be utilized to solve linear and nonlinear programming problems. LINGO can simulate and solve the location model. After iterative calculations, the optimal value (lowest cost) is obtained as 73 million yuan. Table 5 and Table 6 show the site selections for each facility point.

The site selections of the recovery center include Harbin, Qiqihar, Daqing, Mudanjiang, Jiamusi, and Suihua. In contrast, the site selections of remanufacturing enterprises include Daqing, Mudanjiang, and Suihua. Figure 3 shows the reverse logistics network diagram of waste tires in Heilongjiang Province obtained from the LINGO solution results. Based on the traffic distribution results, the transport traffic distribution among each facility point is sorted out, as presented in Table 7.

5. Conclusion

This paper mainly studies the site selection of the reverse logistics network system for waste tires in Heilongjiang Province. The main conclusions of this paper are given as follows:

(1) The reverse logistics network system of waste tires is constructed with the third party as the core by analyzing the reverse logistics of waste tires in Heilongjiang Province. This system comprises four parts: recovery node, recovery center, remanufacturing enterprise, and distribution market.

(2) The AHP is employed to analyze the influence factors of site selection of reverse logistics network for waste tires in Heilongjiang Province. Economic conditions, the number of waste tires, traffic conditions, development planning and policy, and geographical conditions were selected as the evaluation factors, and their corresponding weights were obtained as 0.3547, 0.2256, 0.1690, 0.1644, and 0.0863, respectively. The above results provide a reference for site selection of the reverse logistics network for waste tires in Heilongjiang Province.

(3) The linear mixed-integer programming method is utilized to select the reverse logistics network site for waste tires in Heilongjiang Province. Finally, the recovery center locations were Harbin, Qiqihar, Daqing, Mudanjiang, Jiamusi, and Suihua. Moreover, Daqing, Mudanjiang, and Suihua were chosen as the remanufacturing enterprise sites.

The established reverse logistics network system is suitable for a variety of recyclable goods. Due to the strong applicability and flexibility of the site selection model, it can be applied to various logistics systems. The solution method employed in the site selection model can be applied to numerous models. Because it is difficult to collect data, some data are replaced in the process of site selection, and the site selection may not be very accurate. In the future, the research on site selection methods will be further strengthened, the relevant data collection will be more comprehensive and complete, and the site selection of this study will be more practical and authentic.

Data Availability

No data were used to support this study.

Conflicts of Interest

There is no potential conflict of interest in this study

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