

Research Article

Decision Optimization of Low-Carbon Dual-Channel Supply Chain of Auto Parts Based on Smart City Architecture

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Received 27 March 2020; Revised 24 April 2020; Accepted 5 May 2020; Published 21 May 2020

Guest Editor: Zhihan Lv

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Affected by the Internet, computer, information technology, etc., building a smart city has become a key task of socialist construction work. The smart city has always regarded green and low-carbon development as one of the goals, and the carbon emissions of the auto parts industry cannot be ignored, so we should carry out energy conservation and emission reduction. With the rapid development of the domestic auto parts industry, the number of car ownership has increased dramatically, producing more and more CO₂ and waste. Facing the pressure of resources, energy, and environment, the effective and circular operation of the auto parts supply chain under the low-carbon transformation is not only a great challenge, but also a development opportunity. Under the background of carbon emission, this paper establishes a decision-making optimization model of the low-carbon supply chain of auto parts based on carbon emission responsibility sharing and resource sharing. This paper analyzes the optimal decision-making behavior and interaction of suppliers, producers, physical retailers, online retailers, demand markets, and recyclers in the auto parts industry, constructs the economic and environmental objective functions of low-carbon supply chain management, applies variational inequality to analyze the optimal conditions of the whole low-carbon supply chain system, and finally carries out simulation calculation. The research shows that the upstream and downstream auto parts enterprises based on low-carbon competition and cooperation can effectively manage the carbon footprint of the whole supply chain through the sharing of responsibilities and resources among enterprises, so as to reduce the overall carbon emissions of the supply chain system.

1. Introduction

Smart city is a new concept and mode to promote intelligent urban planning, construction, management, and service by using the new generation of information technology such as the Internet of Things, cloud computing, big data, and spatial geographic information integration. The development of a smart city in China attaches great importance to the integration of the smart city and green low carbon [1]. With the global warming, glacier melting, and other environmental problems becoming more and more serious, the auto parts enterprises should not ignore the importance of environmental protection while pursuing economic interests. We should actively coordinate the relationship between human

beings and nature, so as to achieve sustainable development. The Kyoto protocol adopted in 1997 has set clear emission reduction targets for the countries that signed it. At the same time, it clearly takes the market mechanism as a new path to solve the problem of greenhouse gas emission reduction, which promotes the symbiotic model of carbon emission responsibility sharing and resource sharing. China's demand for establishing a carbon trading mechanism is very urgent; on the one hand, in order to achieve the dual goals of low cost and low emissions and to maintain the long-term economic vitality of enterprises, and on the other hand, to strive for the carbon pricing right and to master the initiative of resource allocation in the low-carbon economy [2]. Therefore, with the steady development of the domestic

carbon emission trading market and the rapid growth of trading volume, the research on the optimization of low-carbon supply chain decision-making based on carbon emission responsibility sharing and resource sharing is of great significance for promoting energy conservation and emission reduction and promoting the transformation of the economic development mode and upgrading of the industrial structure.

Based on the current situation of the construction of a traditional low-carbon city, Ma et al. analyzed the existing problems and the advantages of an intelligent city and then put forward the countermeasures to promote the construction of an intelligent city and the specific path to solve all kinds of problems in the construction of an intelligent low-carbon city [3]. Based on the low-carbon value chain, Yin and others made in-depth exploration on the main components of the low-carbon value chain in the automobile industry and built a three-dimensional low-carbon path system of the automobile supply chain [4]. Lee used the case study method to improve our understanding of the carbon footprint of the automobile supply chain under the management background, providing a new way for the integration of carbon emissions in the supply chain management [5]. Yang and Guitao took the minimization of carbon emissions and the maximization of enterprise profits as the dual objectives and comprehensively used the dual theory and variational inequality to obtain the equilibrium conditions. The research shows that the environmental protection performance and economic benefit of enterprises are improved when the proportion of environmental protection target weight increases [6]. Wei considered the situation of carbon trading, introduced the change of carbon emissions in different forms of research and development, and constructed a differential game model to get the optimal research and development strategy of supply chain emission reduction [7]. Wang and Han established the loss function of perishable products with the goal of reducing carbon emission and total cost and studied the supply chain optimization strategy of location path inventory combination [8]. Díaz-Trujillo et al. analyzed the carbon pricing tools of the energy sector in Mexico and found that the carbon tax and the carbon trading system are more conducive to improve economic and environmental benefits than the traditional carbon pricing policy by using the multiobjective optimization formula [9]. Efthymiou and Papatheodorou established a low-cost and low-carbon multiobjective decision-making model and verified that cost reduction and carbon emission reduction can meet the requirements at the same time [10]. Battini et al. established a two-objective model related to cost and carbon emission and analyzed the model according to the change of carbon price, which showed that the low carbon price could not stimulate the sustainable purchase behavior [11].

Zhang et al. took low carbon emissions as the goal, considered the constraints of customer demand time window and loading and unloading time, and used the hybrid particle swarm optimization algorithm to optimize the multiproduct and multiobjective supply chain [12]. Lanzirui et al. built a minimum cost model under the background of

low carbon and analyzed the influencing factors of production decisions of enterprises with high carbon emissions under the background of carbon emission quota [13]. Taleizadeh et al. used two scenarios to study the interaction between carbon emission reduction, return policies, and quality improvement efforts. The research showed that higher refund prices are beneficial to reduce carbon emissions and improve product quality and supply chain profits [14]. Noura et al. studied the impact of carbon emission sensitive demand on supply chain design decision [15]. Huang et al. proposed a new group recommendation model based on multiattention, which uses the deep neural network structure based on multiattention to achieve accurate group recommendation [16]. Purohit et al. studied the inventory lot size problem based on the constraints of carbon emission and cyclic service level. The research showed that cost, inventory, and carbon emission decrease with the increase in carbon price [17]. Saxena et al. constructed a supply chain design model that comprehensively considered carbon tax policy, economy, and carbon emission and used the improved cross entropy method to get the carbon price that can obtain the maximum environmental benefit [18].

Mauro et al. evaluated the pretreatment technology of a coal-fired power plant from two aspects of environment and technology economy and evaluated the impact of pretreatment technology on the carbon emission avoidance cost [19]. Di Filippo et al. compared and analyzed the effects of carbon pricing policy, command and control policy, and resource incentive three tools in order to solve the obstacles of market failure to take measures to reduce carbon emissions in the concrete supply chain. The research showed that the carbon pricing policy is relatively effective [20]. Aiming at the problem of grab point planning, Hu et al. proposed a grab planning method based on the Gaussian process classification of big data [21]. On calculating the carbon footprint of the grain, Roibás et al. proposed alternative transportation schemes that can reduce the carbon footprint of final products [22]. Wilson and Staffell found that the transformation of coal to natural gas can be realized through effective carbon pricing, so as to reduce carbon emissions [23]. Allevi et al. established a model including carbon emission policy, recovery, transportation, and technical factors to evaluate the effect of applying environmental policies on a multilayer closed-loop supply chain network and solved it by using the theory of variational inequality. The analysis shows that the combined application of the carbon emission tax of truck transportation and the EU emission trading system (EU-ETS) at manufacturer level is beneficial to environmental protection [24]. In order to improve the effectiveness of Internet of Things recommendation, Huang et al. proposed a multimodal representation learning-based Internet of Things recommendation model [25]. Shaw et al. used the Benders decomposition algorithm to solve the problem of the sustainable supply chain network design under the constraints of opportunities. By using an example, we found that the carbon credit price is positively correlated with the enterprise's changeable cost and negatively correlated with the variable emissions [26]. Yu et al. established a mixed integer nonlinear programming

(MINLP) model of shelf space allocation under the background of the carbon tax and discussed the influence of shelf space capacity on product allocation decision [27]. Singh et al. considered the carbon footprint in the traditional supplier selection process and proposed a framework to help reduce the carbon footprint of beef products using the combination of big data, operational research, and other technologies [28].

To sum up, the current research related to the carbon footprint and the low-carbon supply chain focuses on the optimization of the supply chain system of carbon emission, while the research on carbon emission responsibility sharing and resource sharing is less. Therefore, in the context of carbon emission, this paper establishes a low-carbon supply chain decision-making optimization model based on carbon emission responsibility sharing and resource sharing. This model takes economy and environment as the goal and uses variational inequality to analyze the optimal conditions of the whole low-carbon supply chain system by coordinating and transforming the two interactive goal equilibrium problems. On the basis of proving the existence of the solution of the variational inequality of the supply chain system, this paper analyzes the change rule of the profit and carbon emission under the carbon trading with various parameters (such as recycling coefficient and remanufacturing coefficient of waste products) by numerical simulation and verifies the rationality and effectiveness of the model. It can be seen from the results that through the competition and cooperation of upstream and downstream auto parts enterprises for low carbon, the carbon footprint of the whole supply chain can be effectively managed, so as to achieve the purpose of reducing the overall carbon emissions of the supply chain system.

The innovations of this paper are as follows: (1) from the perspective of research, in addition to considering carbon emission constraints, carbon emission responsibility sharing and resource sharing are also considered. (2) In the research method, the variational inequality is used to optimize the whole low-carbon supply chain system. (3) As for the research results, this paper draws the conclusion through simulation: through the competition and cooperation of upstream and downstream auto parts enterprises for low carbon, the carbon footprint of the whole supply chain can be effectively managed, so as to achieve the purpose of reducing the overall carbon emissions of the supply chain system.

2. Problem Description and Symbol Definition

The low-carbon supply chain network of auto parts is composed of suppliers, producers, physical retailers, online retailers, demand markets, and recyclers. The basic structure is shown in Figure 1. The solid line in Figure 1 represents the forward logistics, and the dotted line represents the reverse logistics. Auto parts raw material suppliers provide raw materials for manufacturers. The products of manufacturers are sold to the demand market through physical retailers and online retailers, and the products are recycled by recyclers

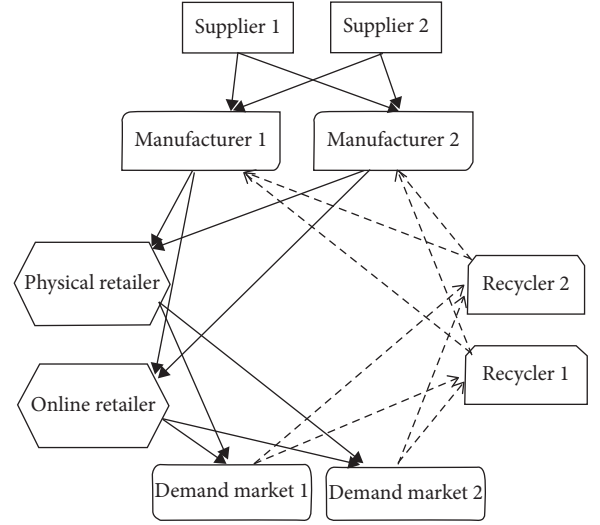


FIGURE 1: Network structure of the low-carbon supply chain.

after use. The definition of variables and function setting is shown in Tables 1 and 2, respectively.

3. The Establishment of Network Equilibrium Optimization Model for Supply Chain of Auto Parts

3.1. The Establishment of Network Equilibrium Model under the Economic Goal of Low-Carbon Supply Chain

3.1.1. Network Equilibrium Model of Suppliers. If Q_{sm} is the supply quantity from the supplier to the manufacturer, ρ_{sm} is the price of the material from the supplier to the manufacturer, and the profit of the supplier is the profit of the material supplied to the manufacturer minus the purchase cost of the supplier, then minus the transaction variable cost with the manufacturer, the objective function of the supplier s is

$$\max \sum_{m=1}^M \rho_{sm} Q_{sm} - \left(\sum_{m=1}^M f_s(Q_{sm}) + \sum_{m=1}^M c_{sm}(Q_{sm}) \right). \quad (1)$$

The optimal conditions of all suppliers are equivalent to the following variational inequalities, and the solution $Q_{sm} \geq 0$ satisfies

$$\sum_{s=1}^S \sum_{m=1}^M \left[\frac{\partial f_s(Q_{sm})}{\partial Q_{sm}} + \frac{\partial c_{sm}(Q_{sm})}{\partial Q_{sm}} - \rho_{sm} \right] \times (Q_{sm} - Q_{sm}^*) \geq 0, \quad \forall Q_{sm} \geq 0. \quad (2)$$

The variational inequality (2) shows that the transaction price of auto parts suppliers is equal to the sum of the marginal purchase cost and the marginal transaction cost for any supply greater than zero in the equilibrium state.

3.1.2. Network Equilibrium Model of Manufacturers. If Q_{mr} is the product quantity provided by the manufacturer to the

TABLE 1: Decision variables and parameters.

Variable or parameter	Definition of variable or parameter
s	Auto parts supplier, $s \in \{1, 2, \dots, S\}$
m	Auto parts manufacturer, $m \in \{1, 2, \dots, M\}$
r	Physical retailer and online retailer of auto parts, $r \in \{r1, r2\}$
	Physical retailer $r_1 \in \{1, 2, \dots, R\}$; online retailer $r_2 \in \{1, 2, \dots, R\}$
d	Auto parts market, $d \in \{1, 2, \dots, D\}$
n	Auto parts recycler, $n \in \{1, 2, \dots, N\}$
$Q_{sm}, Q_{mr}, Q_{rd}, Q_{dn}, Q_{mn}$	The trading volume of auto parts supplier s and manufacturer m , auto parts manufacturer m and physical retailer r , auto parts physical retailer and online retailer r and demand market d , auto parts demand market d and recycler n , auto parts recycler n and manufacturer m
$\rho_{sm}, \rho_{mr}, \rho_{rd}, \rho_{dn}, \rho_{mn}, \rho_d$	Transaction price or sales price of auto parts supplier, manufacturer, physical retailer, online retailer, demand market, and recycler
f_s, f_{ms}, f_{mn}	Purchasing cost function of auto parts suppliers, production cost function of new materials used by manufacturers, and production cost function of old materials used
$c_{sm}, c_{ms}, c_{mr}, c_{nr}, c_r, c_{rm}, c_{rd}, c_{dr}, c_{dn}, c_n, c_{nd}, c_{nm}$	Transaction cost function of auto parts suppliers and manufacturers; transaction cost function of auto parts manufacturers and suppliers, physical retailers and online retailers, recyclers; storage cost function of auto parts physical retailers and online retailers, transaction cost function of physical retailers, online retailers and producers, transaction cost function of demand market; transaction cost function of auto parts demand market, physical retailers, online retailers and recyclers; auto parts recycling cost function of acquisition, transportation and storage, recycler and demand market, and transaction cost function of producer
v_{im}, v_r, v_{in}	Production, sales, and recovery of auto parts and components unit energy use cost of each process input
u_{om}, u_{or}, u_{on}	Production, sales, and recovery of auto parts unit carbon emission cost of each process output end
CC_j^+, CC_j^-	The amount of carbon emissions purchased and sold by a node auto parts enterprise j is calculated in tons of carbon dioxide equivalent (tCO_2e), $j \in M \cup R \cup N$
A^c, V^{cc}	Unit purchase and sale price of carbon trading
$CF_{im}, CF_{ir}, CF_{in}$	Weight coefficient of energy use at input nodes of production, sales, and recovery processes of auto parts
$EF_{om}, EF_{or}, EF_{on}$	Carbon emission coefficient of output nodes of production, sales, and recovery processes of auto parts
ϕ_{sm}, ϕ_{mn}	Availability factor of raw materials from auto parts suppliers or reprocessed products from recyclers
$D_d(\rho_d)$	Demand function of auto parts market d
θ	Conversion and reuse coefficient of recycled auto parts
χ	Disposal cost of unit scrapped auto parts
CO_i^{in}, CO_o^{out}	Characteristic coefficient of energy consumption and carbon emission converted into carbon dioxide equivalent
$L^{cop}, L^{cos}, L^{CO_2e}$	The maximum amount of carbon emission that can be purchased or sold and the amount of carbon emission distribution

TABLE 2: Function settings.

Cost	Cost function
Purchase cost of auto parts supplier	$f_1(Q_{sm}) = (\sum_{m=1}^2 Q_{1m})^2 + a(\sum_{m=1}^2 Q_{1m})(\sum_{m=1}^2 Q_{2m}) + b\sum_{m=1}^2 Q_{2m}$
Transaction costs between auto parts suppliers and manufacturers	$f_2(Q_{sm}) = c(\sum_{m=1}^2 Q_{2m})^2 + (\sum_{m=1}^2 Q_{1m})(\sum_{m=1}^2 Q_{2m}) + \sum_{m=1}^2 Q_{1m}$
Production cost of new materials used by auto parts manufacturers	$c_{sm}(Q_{sm}) = aQ_{sm}^2 + eQ_{sm}$, where $s = 1, 2; m = 1, 2$
Production cost of old materials used by auto parts manufacturers	$f_{1s}(Q_{sm}, \varphi_{sm}) = (\varphi_{sm} \sum_{s=1}^2 Q_{s1})^2 + b(\varphi_{sm} \sum_{s=1}^2 Q_{s1})(\varphi_{sm} \sum_{s=1}^2 Q_{s2}) + f$
Transaction costs between auto parts manufacturers and suppliers	$f_{2s}(Q_{sm}, \varphi_{sm}) = (\varphi_{sm} \sum_{s=1}^2 Q_{s2})^2 + (\varphi_{sm} \sum_{s=1}^2 Q_{s1})(\varphi_{sm} \sum_{s=1}^2 Q_{s2}) + g$
Transaction costs of auto parts manufacturers, physical retailers, and online retailers	$f_{1n}(Q_{nm}, \varphi_{nm}) = a(\varphi_{nm} \sum_{n=1}^2 Q_{n1})^2 + b(\varphi_{nm} \sum_{n=1}^2 Q_{n1}) + b$
Transaction costs of auto parts manufacturers and recyclers	$f_{2n}(Q_{nm}, \varphi_{nm}) = (\varphi_{nm} \sum_{n=1}^2 Q_{n2})^2 + b(\varphi_{nm} \sum_{n=1}^2 Q_{n2}) + h$
Storage cost of auto parts physical retailer and online retailer	$c_{ms}(Q_{sm}) = aQ_{sm}^2 + kQ_{sm}$, where $m = 1, 2; s = 1, 2$
Transaction cost of auto parts physical retailer, online retailer, and manufacturer	$c_{nr}(Q_{nr}) = aQ_{nr}^2 + kQ_{nr}$, where $m = 1, 2; r = 1, 2$
Transaction cost of auto parts physical retailer, online retailer, and demand market	$c_{nm}(Q_{nm}) = aQ_{nm}^2 + kQ_{nm}$, where $m = 1, 2; n = 1, 2$
Auto parts demand function	$c_1(Q_{m1}) = a(\sum_{m=1}^2 Q_{m1})^2 + k,$ $c_2(Q_{m2}) = a(\sum_{m=1}^2 Q_{m2})^2 + f$
Auto parts demand market and retailer's transaction cost	$c_{rm}(Q_{rm}) = aQ_{rm}^2 + lQ_{rm}$, where $r = 1, 2; m = 1, 2$
Auto parts demand market and transaction cost of recycler	$c_{rd}(Q_{rd}) = aQ_{rd}^2 + kQ_{rd}$, where $r = 1, 2; d = 1, 2$
Storage cost of auto parts recycler	$D_1(\rho_d) = -b\rho_1 - o\rho_2 + p$ $D_2(\rho_d) = -o\rho_1 - b\rho_2 + p$
Transaction cost between auto parts recycler and demand market	$c_{dr}(Q_{rd}) = Q_{rd} + f$, where $d = 1, 2; r = 1, 2$
Transaction cost between auto parts recycler and manufacturer	$c_{dn}(Q_{dn}) = Q_{dn} + h$, where $d = 1, 2; n = 1, 2$
Conversion and reuse coefficient of recycled auto parts	$c_1(Q_{d1}) = a(\sum_{d=1}^2 Q_{d1})^2 + h,$ $c_2(Q_{d2}) = a(\sum_{d=1}^2 Q_{d2})^2 + b$
Availability factor of reprocessed products of auto parts recycler	$c_{n,d}(Q_{dn}) = qQ_{dn}^2 + Q_{dn}$, where $n = 1, 2; d = 1, 2$ $c_{nm}(Q_{nm}) = aQ_{nm}^2 + Q_{nm}$, where $n = 1, 2; m = 1, 2$ $\theta = cr_k - t$ $\varphi_{sm} = \alpha\mu - u$

physical retailer and the online retailer, ρ_{mr} is the product price of the manufacturer, the cost of the manufacturer includes the production cost, the cost paid to the supplier and the recycler, the transaction cost with the supplier, the physical retailer, the online retailer, and the recycler, and the

cost of energy and carbon emission consumed in the production shall also be considered, then assuming that the unit energy cost consumed in the production process is v_i and the unit carbon emission cost is u_o , the objective function of producer m is

$$\begin{aligned}
 \max \quad & \sum_{r=1}^R \rho_{mr} Q_{mr} - \left(\sum_{s=1}^S f_{ms}(Q_{sm}, \varphi_{sm}) + \sum_{n=1}^N f_{mn}(Q_{nm}, \varphi_{nm}) \right. \\
 & + \sum_{s=1}^S \rho_{sm} Q_{sm} + \sum_{n=1}^N \rho_{nm} Q_{nm} + \sum_{s=1}^S c_{ms}(Q_{sm}) + \sum_{r=1}^R c_{mr}(Q_{mr}) \\
 & \left. + \sum_{n=1}^N c_{mn}(Q_{nm}) + \sum_{r=1}^R v_{im} CF_{im} Q_{mr} + \sum_{r=1}^R u_{om} EF_{om} Q_{mr} \right) \\
 \text{s.t.} \quad & \sum_{r=1}^R Q_{mr} \leq \varphi_{sm} \sum_{s=1}^S Q_{sm} + \varphi_{nm} \sum_{n=1}^N Q_{nm}.
 \end{aligned} \tag{3}$$

The optimal conditions of all producers are equivalent to the following corresponding variational inequalities:

$$\begin{aligned}
 & \sum_{m=1}^M \sum_{r=1}^R \left(\frac{\partial c_{mr}(Q_{mr})}{\partial Q_{mr}} + v_{im} CF_{im} + u_{om} EF_{om} + \zeta_{1m} - \rho_{mr} \right) \times (Q_{mr} - Q_{mr}^*) + (Q_{sm} - Q_{sm}^*) \\
 & \times \sum_{m=1}^M \sum_{s=1}^S \left(\frac{\partial f_{ms}(Q_{sm}, \varphi_{sm})}{\partial Q_{sm}} + \frac{\partial c_{ms}(Q_{sm})}{\partial Q_{sm}} + \rho_{sm} - \varphi_{sm} \zeta_{1m} \right) + \sum_{m=1}^M \sum_{n=1}^N \left(\frac{\partial f_{mn}(Q_{nm}, \varphi_{nm})}{\partial Q_{nm}} + \frac{\partial c_{mn}(Q_{nm})}{\partial Q_{nm}} + \rho_{nm} - \varphi_{nm} \zeta_{1m} \right) \\
 & \times (Q_{nm} - Q_{nm}^*) + \sum_{m=1}^M \left(\varphi_{sm} \sum_{s=1}^S Q_{sm} + \varphi_{nm} \sum_{n=1}^N Q_{nm} - \sum_{r=1}^R Q_{mr} \right) \times (\zeta_{1m} - \zeta_{1m}^*) \geq 0, \\
 & \forall Q_{mr} \geq 0, Q_{sm} \geq 0, Q_{nm} \geq 0, \zeta_{1m} \geq 0,
 \end{aligned} \tag{4}$$

where ζ_{1m} in is the Lagrange coefficient to ensure the constraint condition of the objective function is established, which represents the minimum supply cost of the producer, that is, the cost that the producer is willing to bear at most for the unit product. The economic interpretation of variational inequality (4) is as follows.

The first one indicates that in equilibrium, for any trading volume greater than zero, the sum of the marginal transaction cost of the manufacturer and the retailer, the marginal energy use cost of the production input, the marginal carbon emission cost of the production output, and its minimum supply cost is equal to the transaction price of the auto parts manufacturer.

The second item indicates that in the equilibrium state, for any trading volume greater than zero, the marginal production cost of new materials, the marginal transaction cost of suppliers and producers, and the sum of the transaction price of suppliers is equal to the product of the availability coefficient and the minimum supply cost of suppliers' raw materials, and the third item is similar.

The fourth item indicates that in the equilibrium state, for any trading volume greater than zero, the sum of the trading volume of the auto parts manufacturer and the retailer is equal to the product of the trading volume of the supplier and the manufacturer and their availability coefficient of raw materials plus the product of the trading

volume of the recycler and the manufacturer and their availability coefficient of reprocessed products.

3.1.3. Network Equilibrium Model of Physical Retailer and Online Retailer. Suppose Q_{rd} is the physical retailer's and the online retailer's sales volume, ρ_{rd} is the physical retailer's and the online retailer's sales price, the unit energy

consumption cost is v_i , and the unit carbon emission cost is u_o . When the physical retailer's and the online retailer's cost is storage cost, payment to the manufacturer cost, and the transaction cost with the manufacturer and the demand market, plus energy consumption and the carbon emission cost in sales operation, then the objective function of the physical retailer and the online retailer r is

$$\begin{aligned} \max \quad & \sum_{d=1}^D \rho_{rd} Q_{rd} - \left(\sum_{m=1}^M c_r(Q_{mr}) + \sum_{m=1}^M \rho_{mr} Q_{mr} + \sum_{m=1}^M c_{rm}(Q_{mr}) + \sum_{d=1}^D c_{rd}(Q_{rd}) + \sum_{d=1}^D v_{ir} CF_{ir} Q_{rd} + \sum_{d=1}^D u_{or} EF_{or} Q_{rd} \right) \\ \text{s.t.} \quad & \sum_{d=1}^D Q_{rd} \leq \sum_{m=1}^M Q_{mr}. \end{aligned} \quad (5)$$

The optimal conditions of all physical retailers and online retailers are equivalent to the following variational inequalities:

$$\begin{aligned} & \sum_{r=1}^R \sum_{d=1}^D \left(\frac{\partial c_{rd}(Q_{rd})}{\partial Q_{rd}} + v_{ir} CF_{ir} + u_{or} EF_{or} + \zeta_{2r} - \rho_{rd} \right) \times (Q_{rd} - Q_{rd}^*) + \sum_{r=1}^R \sum_{m=1}^M \left(\frac{\partial c_r(Q_{mr})}{\partial Q_{mr}} + \frac{\partial c_{rm}(Q_{mr})}{\partial Q_{mr}} + \rho_{mr} - \zeta_{2r} \right) \\ & \times (Q_{mr} - Q_{mr}^*) + \sum_{r=1}^R \left(\sum_{m=1}^M Q_{mr} - \sum_{d=1}^D Q_{rd} \right) \times (\zeta_{2r} - \zeta_{2r}^*) \geq 0, \\ & \forall Q_{rd} \geq 0, Q_{mr} \geq 0, \zeta_{2r} \geq 0, \end{aligned} \quad (6)$$

where the “*” sign indicates that the variable is in equilibrium, corresponding to the optimal solution of variational inequality (6). Among them, the Lagrange coefficient ζ_{2r} ensures that the constraint condition of the objective function holds, which means the physical retailer's and the online retailer's minimum supply cost, that is, the highest cost that the physical retailer and the online retailer are willing to pay when selling each unit of product. The variational inequality (6) shows the following.

The first one indicates that in equilibrium, for any trading volume greater than zero, the sum of the marginal transaction cost, the input energy use cost, the output unit carbon emission cost, and the minimum supply cost of the retailer is equal to the transaction price of the auto parts retailer.

The second indicates that in equilibrium, for any supply greater than zero, the sum of the retailer's marginal storage cost, the retailer's marginal transaction cost, and the manufacturer's transaction price is equal to the minimum supply cost of the auto parts retailer.

The third indicates that in equilibrium, for any supply greater than zero, the sum of the transaction volume of auto parts manufacturers and physical retailers and online retailers is equal to that of retailers and the demand market.

3.1.4. Network Equilibrium Model of Demand Market. The variables that the demand market needs to decide include two parts. In positive logistics, the demand market meets the following conditions:

$$\rho_{rd} + c_{dr}(Q_{rd}) \begin{cases} = \rho_d, & Q_{rd} > 0, \\ \geq \rho_d, & Q_{rd} = 0. \end{cases} \quad (7)$$

The demand market has the following supply-demand balance relationship:

$$D_d(\rho_d) \begin{cases} = \sum_{r=1}^R Q_{rd}, & \rho_d > 0, \\ \geq \sum_{r=1}^R Q_{rd}, & \rho_d = 0. \end{cases} \quad (8)$$

The economic explanation is as follows: formula (7) indicates that if the sum of the physical retailer's and the online retailer's selling price and the transaction cost of the demand market is equal to the demand price, then there is a transaction between the physical retailer, the online retailer, and the demand market; otherwise, the transaction volume between the two is zero; formula (8) indicates that if the demand of the demand market is exactly equal to the quantity of products purchased from the physical retailer and the online retailer, then the equilibrium price is positive; if the two are not equal, then the equilibrium demand price is zero.

In reverse logistics, the demand market D determines whether to sell to the recycler according to the recycling price of waste products. This relationship can be expressed as follows:

$$c_{dn}(Q_{dn}) \begin{cases} = \rho_{dn}, & Q_{dn} > 0, \\ \geq \rho_{dn}, & Q_{dn} = 0, \end{cases} \quad (9)$$

$$\text{s.t.} \quad \sum_{n=1}^N Q_{dn} \leq \sum_{r=1}^R Q_{rd}. \quad (10)$$

Equation (10) indicates that the total amount recovered by the recycler from the demand market D does not exceed the total amount of products in the demand market. By synthesizing the behavior and constraints of the demand market in forward logistics and reverse logistics, the optimal conditions of all demand markets can be obtained, which are equivalent to the following variational inequalities, and the solution $(Q_{dn}, Q_{rd}, \rho_d, \zeta_{3d}) \geq 0$ satisfies

$$\begin{aligned} & \sum_{d=1}^D \sum_{r=1}^R [\rho_{rd} + c_{dr}(Q_{rd} - \rho_d - \zeta_{3d})] \times (Q_{rd} - Q_{rd}^*) + \sum_{d=1}^D \sum_{n=1}^N (c_{dn}(Q_{dn}) - \rho_{dn} + \zeta_{3d}) \times (Q_{dn} - Q_{dn}^*) \\ & + \sum_{d=1}^D \left(\sum_{r=1}^R Q_{rd} - D_d(\rho_d) \right) \times (\rho_d - \rho_d^*) + \sum_{d=1}^D \left(\sum_{r=1}^R Q_{rd} - \sum_{n=1}^N Q_{dn} \right) \times (\zeta_{3d} - \zeta_{3d}^*) \geq 0. \end{aligned} \quad (11)$$

3.1.5. Network Equilibrium Model of Recycler. It is assumed that the quantity of waste products sold by the recycler to the manufacturer is Q_{nm} and the selling price is ρ_{nm} . Q_{dn} is the total quantity of recycled waste products. The profit of the recycler is the profit obtained from the sale of reusable products to the manufacturer minus the cost of acquisition, transportation, and storage of the recycler, the cost of

recycling paid to the demand market, and the transaction cost with the demand market and the manufacturer, plus a part of the recycled waste products that need to be scrapped. The total amount of scrapping is $(1 - \theta) \sum_{d=1}^D Q_{dn}$, the cost is $\chi(1 - \theta) \sum_{d=1}^D Q_{dn}$, and the energy consumption and carbon emission in the recycling process cost, the objective function of recovery quotient n , is

$$\begin{aligned} \max \quad & \sum_{m=1}^M \rho_{nm} Q_{nm} - \left(\sum_{d=1}^D c_n(Q_{dn}) + \sum_{d=1}^D \rho_{dn} Q_{dn} + \sum_{m=1}^M c_{nm}(Q_{nm}) + \sum_{d=1}^D c_{nd}(Q_{nd}) + \chi(1 - \theta) \sum_{d=1}^D Q_{dn} + \sum_{d=1}^D v_{in} CF_{in} Q_{dn} + \sum_{d=1}^D u_{on} EF_{on} Q_{dn} \right) \\ \text{s.t.} \quad & \sum_{m=1}^M Q_{nm} \leq \theta \sum_{d=1}^D Q_{dn}. \end{aligned} \quad (12)$$

The optimal conditions of all recovery quotients are equivalent to the following variational inequalities:

$$\begin{aligned} & \sum_{n=1}^N \sum_{m=1}^M \left(\frac{\partial c_{nm}(Q_{nm})}{\partial Q_{nm}} + \zeta_{4n} - \rho_{nm} \right) \times (Q_{nm} - Q_{nm}^*) + \sum_{n=1}^N \sum_{d=1}^D \left(\frac{\partial c_n(Q_{dn})}{\partial Q_{dn}} + \frac{\partial c_{nd}(Q_{dn})}{\partial Q_{dn}} + \rho_{dn} + v_{in} CF_{in} + u_{on} EF_{on} + \chi((1 - \theta) - \theta \zeta_{4n}) \right) \\ & \times (Q_{dn} - Q_{dn}^*) + \sum_{n=1}^N \left(\theta \sum_{d=1}^D Q_{dn} - \sum_{m=1}^M Q_{nm} \right) \times (\zeta_{4n} - \zeta_{4n}^*) \geq 0, \forall Q_{nm} \geq 0, Q_{dn} \geq 0, \zeta_{4n} \geq 0, \end{aligned} \quad (13)$$

where ζ_{4n} is the Lagrangian coefficient to ensure the constraint condition of the objective function is established, which represents the minimum recovery cost of the recycler, that is, the cost that the recycler is willing to bear at most for the unit product recovery. The economic explanation of variational inequality (13) is as follows.

The first item indicates that in equilibrium, for any supply greater than zero, the marginal transaction price of the auto parts recycler is equal to the sum of the marginal transaction cost of the recycler and the manufacturer and the minimum recovery cost of the recycler.

The second item indicates that in the equilibrium state, for any supply greater than zero, the sum of the marginal storage cost of the recycler, the marginal transaction cost of the recycler and the demand market, the transaction price of the demand market, the energy use cost of the input end, the carbon emission cost of the output end, and the disposal cost of the unit scrap product is equal to the minimum recovery cost of the auto parts recycler.

The third item indicates that under the equilibrium state, for any supply greater than zero, the transaction volume of

the auto parts demand market and the recycler is equal to that of the recycler and the manufacturer.

3.1.6. Network Equilibrium Model with Carbon Trading as Objective Function. In the supply chain, when the carbon emission limit of A_{CC} node enterprise j is not enough, it can buy the carbon emission limit CC_j^- sold by other enterprises at a price through the carbon trading market; on the contrary, when the carbon emission limit of the enterprise with good energy conservation and emission reduction is redundant, it can sell the carbon emission limit of the enterprise CC_j^+ needed at V^{CC} price. Carbon emissions are calculated in terms of carbon dioxide equivalent per ton (CO_2e). Then, the objective function of the trading profit of a node enterprise j is

$$\text{Max } V^{CC}CC_j^+ - A^{CC}CC_j^-, \quad (14)$$

where $j \in M \cup R \cup N$.

The constraint is that the energy consumption and the carbon footprint of each node enterprise in the supply chain network are within the limit, that is,

$$\begin{aligned} CO_o^{\text{out}} \sum_{r=1}^R EF_{om} Q_{mr} + CO_i^{\text{in}} \sum_{r=1}^R CF_{im} Q_{mr} + CC_m^+ - CC_m^- &\leq L_m^{\text{CO}_2e}, \\ CO_o^{\text{out}} \sum_{d=1}^D EF_{or} Q_{rd} + CO_i^{\text{in}} \sum_{d=1}^D CF_{ir} Q_{rd} + CC_r^+ - CC_r^- &\leq L_r^{\text{CO}_2e}, \\ CO_o^{\text{out}} \sum_{d=1}^D EF_{on} Q_{dn} + CO_i^{\text{in}} \sum_{d=1}^D CF_{in} Q_{dn} + CC_n^+ - CC_n^- &\leq L_n^{\text{CO}_2e}, \\ CC_m^+ &\leq L_m^{\text{COS}}, \\ CC_m^- &\leq L_m^{\text{COP}}, \\ CC_r^+ &\leq L_r^{\text{COS}}, \\ CC_r^- &\leq L_r^{\text{COP}}, \\ CC_n^+ &\leq L_n^{\text{COS}}, \\ CC_n^- &\leq L_n^{\text{COP}}. \end{aligned} \quad (15)$$

The solution of the objective function with constraints on the carbon footprint of the whole low-carbon supply chain is equivalent to the solution of the corresponding

variational inequality below, which satisfies the following conditions:

$$\begin{aligned}
& (CC_m^+, CC_m^-, CC_r^+, CC_r^-, CC_n^+, CC_n^-, Q_{mr}, Q_{rd}, Q_{dn}, \zeta_{5m}, \xi_{5r}, \tau_{5n}, \alpha_{5m}, \alpha'_{5m}, \beta_{5r}, \beta'_{5r}, \gamma_{5n}, \gamma'_{5n}) \geq 0 \\
& \sum_{m=1}^M (\zeta_{5m} + \alpha_{5m} - V^{cc}) \times (CC_m^+ - CC_m^{+*}) + \sum_{m=1}^M (A^{cc} - \zeta_{5m} + \alpha'_{5m}) \times (CC_m^- - CC_m^{-*}) \\
& + \sum_{r=1}^R (\xi_{5r} + \beta_{5r} - V^{cc}) \times (CC_r^+ - CC_r^{+*}) + \sum_{r=1}^R (A^{cc} - \xi_{5r} + \beta'_{5r}) \times (CC_r^- - CC_r^{-*}) \\
& + \sum_{n=1}^N (\tau_{5n} + \gamma_{5n} - V^{cc}) \times (CC_n^+ - CC_n^{+*}) + \sum_{n=1}^N (A^{cc} - \tau_{5n} + \gamma'_{5n}) \times (CC_n^- - CC_n^{-*}) \\
& + \sum_{m=1}^M \sum_{r=1}^R (CO_o^{\text{out}} EF_{om} + CO_i^{\text{in}} CF_{im}) \zeta_{5m} \times (Q_{mr} - Q_{mr}^*) \\
& + \sum_{r=1}^R \sum_{d=1}^D (CO_o^{\text{out}} EF_{or} + CO_i^{\text{in}} CF_{ir}) \xi_{5r} \times (Q_{rd} - Q_{rd}^*) \\
& + \sum_{n=1}^N \sum_{d=1}^D (CO_o^{\text{out}} EF_{on} + CO_i^{\text{in}} CF_{in}) \tau_{5n} \times (Q_{dn} - Q_{dn}^*) \\
& + \sum_{m=1}^M \left[L_m^{\text{CO}_2^e} - CO_o^{\text{out}} \sum_{r=1}^R EF_{om} Q_{mr} - CO_i^{\text{in}} \sum_{r=1}^R CF_{im} Q_{mr} - CC_m^+ + CC_m^- \right] \times (\zeta_{5m} - \zeta_{5m}^*) \\
& + \sum_{r=1}^R \left[L_r^{\text{CO}_2^e} - CO_o^{\text{out}} \sum_{d=1}^D EF_{or} Q_{rd} - CO_i^{\text{in}} \sum_{d=1}^D CF_{ir} Q_{rd} - CC_r^+ + CC_r^- \right] \times (\xi_{5r} - \xi_{5r}^*) \\
& + \sum_{n=1}^N \left[L_n^{\text{CO}_2^e} - CO_o^{\text{out}} \sum_{d=1}^D EF_{on} Q_{dn} - CO_i^{\text{in}} \sum_{d=1}^D CF_{in} Q_{dn} - CC_n^+ + CC_n^- \right] \times (\tau_{5n} - \tau_{5n}^*) \\
& + \sum_{m=1}^M (L_m^{\text{COS}} - CC_m^+) \times (\alpha_{5m} - \alpha_{5m}^*) + \sum_{m=1}^M (L_m^{\text{COP}} - CC_m^-) \times (\alpha'_{5m} - \alpha_{5m}^{'*}) \\
& + \sum_{r=1}^R (L_r^{\text{COS}} - CC_r^+) \times (\beta_{5r} - \beta_{5r}^*) + \sum_{r=1}^R (L_r^{\text{COP}} - CC_r^-) \times (\beta'_{5r} - \beta_{5r}^{'*}) \\
& + \sum_{n=1}^N (L_n^{\text{COS}} - CC_n^+) \times (\gamma_{5n} - \gamma_{5n}^*) + \sum_{n=1}^N (L_n^{\text{COP}} - CC_n^-) \times (\gamma'_{5n} - \gamma_{5n}^{'*}) \geq 0,
\end{aligned} \tag{16}$$

where $\zeta_{5m}, \xi_{5r}, \tau_{5n}, \alpha_{5m}, \alpha'_{5m}, \beta_{5r}, \beta'_{5r}, \gamma_{5n}, \gamma'_{5n}$ is the Lagrange coefficient to ensure the constraint conditions of the objective function is established.

3.2. The Establishment of Network Equilibrium Model under the Environment Goal of Low-Carbon Supply Chain. Based on the carbon footprint management, the environmental objective function of the low-carbon supply chain is minimum carbon emission. Taking the carbon dioxide equivalent per ton tCO₂e as the calculation unit, the environmental objective function of the whole low-carbon supply chain network is

$$\min \quad CO_i^{\text{in}} C_i + CO_o^{\text{out}} E_o. \tag{17}$$

The total input energy consumption and output carbon emissions are as follows:

$$\begin{aligned}
C_i &= \sum_{m=1}^M \sum_{r=1}^R CF_{im} Q_{mr} + \sum_{r=1}^R \sum_{d=1}^D CF_{ir} Q_{rd} + \sum_{n=1}^N \sum_{d=1}^D CF_{in} Q_{dn}, \\
E_o &= \sum_{m=1}^M \sum_{r=1}^R EF_{om} Q_{mr} + \sum_{r=1}^R \sum_{d=1}^D EF_{or} Q_{rd} + \sum_{n=1}^N \sum_{d=1}^D EF_{on} Q_{dn}.
\end{aligned} \tag{18}$$

The optimal conditions of the above programming problems are equivalent to the following variational inequalities, and the solution $(Q_{mr}, Q_{rd}, Q_{dn}) \geq 0$ satisfies the following requirements:

$$\begin{aligned}
& \sum_{m=1}^M \sum_{r=1}^R (CO_o^{\text{out}} EF_{om} + CO_i^{\text{in}} CF_{im}) \times (Q_{mr} - Q_{mr}^*) \\
& + \sum_{r=1}^R \sum_{d=1}^D (CO_o^{\text{out}} EF_{or} + CO_i^{\text{in}} CF_{ir}) \times (Q_{rd} - Q_{rd}^*) \\
& + \sum_{n=1}^N \sum_{d=1}^D (CO_o^{\text{out}} EF_{on} + CO_i^{\text{in}} CF_{in}) \times (Q_{dn} - Q_{dn}^*) \geq 0.
\end{aligned} \tag{19}$$

3.3. The Network Equilibrium Model of the Whole Low-Carbon Supply Chain. The quantity of purchase and recycled products in the demand market must be equal to the quantity received by the reprocessing recycler. The price and the carbon trading volume between the upstream and downstream networks of the supply chain must meet the sum of the equivalent variational inequalities of each equilibrium condition. When the low-carbon supply chain network finally reaches the equilibrium state, its decision variables must meet the optimal conditions of suppliers, producers, physical retailers, online retailers, demand markets, and recyclers, as well as the optimal conditions of carbon trading and carbon footprint environmental objective function.

4. Simulation and Result Analysis

In this section, the above models are simulated to discuss the change rule of trading profit and carbon emission with exogenous variables (recycling coefficient, remanufacturing coefficient of waste products, etc.). It is assumed that the supply chain network model of auto parts is a closed-loop supply chain composed of two suppliers, two producers, one physical retailer, online retailer, two demand markets, and two recyclers. For the purpose of simulation calculation, the parameters used in the model and the settings of the functions involved in the model are shown in Table 3. There are many parameters involved in the model. It mainly analyzes the recycling coefficient r_k and the remanufacturing coefficient μ of the network members and observes the changes of the total profits of carbon trading and the total carbon emissions of the supply chain.

4.1. The Influence of Recycling Coefficient on Carbon Emission and Total Profit of Supply Chain. Under the different recycling coefficient r_k , the total carbon emission and the total profit of carbon trading and selling in the supply chain show an interval change trend, as shown in Figures 2 and 3, respectively. In order to facilitate the analysis of the impact of the change of the recycling coefficient on the carbon emissions and total profits of the supply chain, this paper considers the following.

It can be seen from Figure 2 that with the increase in the recycle coefficient r_k , the total amount of carbon emissions increases continuously and the range is large. This is because the larger the r_k is in the process of recycling waste products,

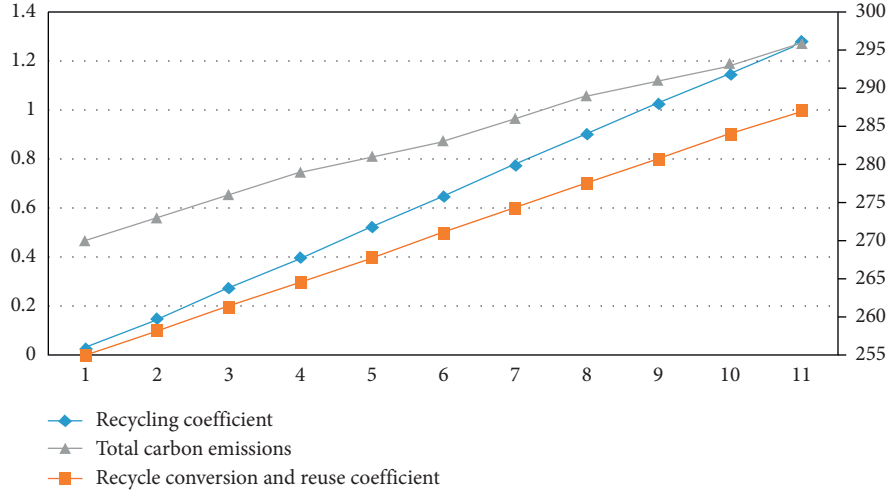
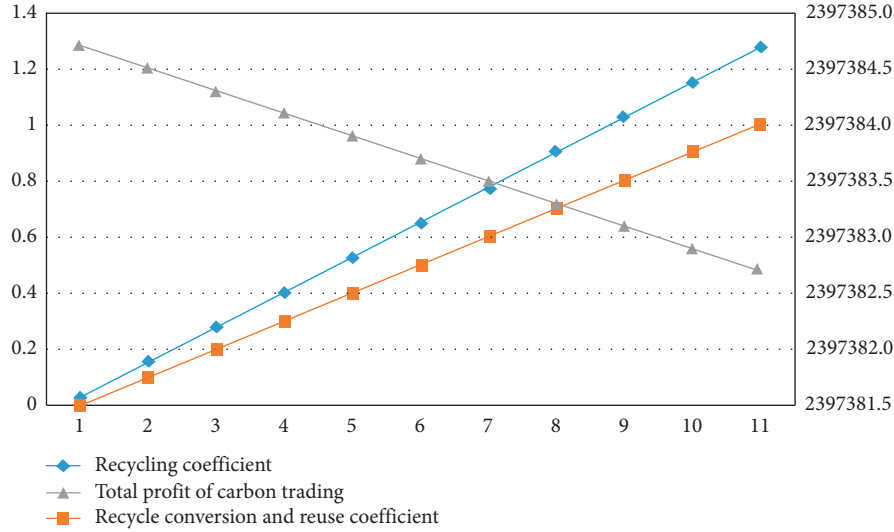
TABLE 3: Parameter setting.

Parameter	Value
v_{im}	200/t
v_{ir}	200/t
v_{in}	200/t
A^{cc}	2500/t
V^{cc}	2500/t
a	0.5
g	4
p	1000
u_{om}	200/t
u_{or}	200/t
u_{on}	200/t
φ_{sm}	0.9
φ_{nm}	0.8
b	2
h	1
q	0.4
CF_{im}	6
CF_{ir}	3
CF_{in}	8
CO_i^{in}	0.015
CO_o^{out}	0.015
c	0.8
k	3
t	0.02
EF_{om}	12
EF_{or}	6
EF_{on}	15
χ	2
λ	10^{-2}
e	3.5
l	2.5
u	0.03
L^{COS}	$8 \times 10^5/t$
L^{COP}	$8 \times 10^5/t$
L^{CO_2e}	$8 \times 10^5/t$
ε	10^{-3}
θ	0.8
f	5
o	1.5

the more the waste products will be recycled from the demand market, the more the waste products will be disposed, and the more the carbon emissions will be.

It can be seen from Figure 3 that with the increase in the recycling coefficient r_k , recycling conversion and reuse coefficient θ shows an upward trend, while the trading profit of carbon trading shows a downward trend. It shows that the increase of recycled products recycling leads to the increase of recycled products conversion and reuse, which increases the carbon emissions of supply chain members, while the carbon emission quota allocated by most members of the supply chain is not enough to make up for the increased carbon emissions and reduced carbon trading, thus reducing the trading profits of carbon trading.

4.2. Influence of Remanufacturing Coefficient of Waste Products on Carbon Emission and Total Profit of Supply Chain. With different remanufacturing coefficient μ of waste products, the total amount of carbon emissions in the

FIGURE 2: Change of total carbon emission with r_k .FIGURE 3: Change of total profit of carbon trading with r_k .

supply chain and the total profit of carbon trading show an interval trend, as shown in Figures 4 and 5, respectively. In order to analyze the influence of the remanufacturing coefficient of waste products on carbon emission and total profit of the supply chain, this paper considers the following.

As can be seen from Figure 4, the carbon emissions in the supply chain increase with the increase in μ , but the range is not very large. This is due to the increase of recycled materials and the corresponding increase of production, thus the carbon emissions increase. Recyclers have a great impact on carbon emissions. By properly increasing the remanufacturing coefficient of waste products, carbon emissions and trading profits can be optimized at the same time.

As can be seen from Figure 5, with the increase in the remanufacturing coefficient μ of waste products, the availability coefficient of reprocessed products of recyclers is also slowly increasing and the trading profit of carbon trading decreases accordingly. This is because with the manufacturing of waste products, recyclers can process more products, and the carbon emission quota allocated by producers is not enough to make up for the increased carbon emissions, which reduces the carbon trading and thus reduces the profits of carbon trading. In order to improve the profit of carbon trading in the supply chain, manufacturers need to make a reasonable ordering plan in order to balance the carbon emissions and the profit of carbon trading.

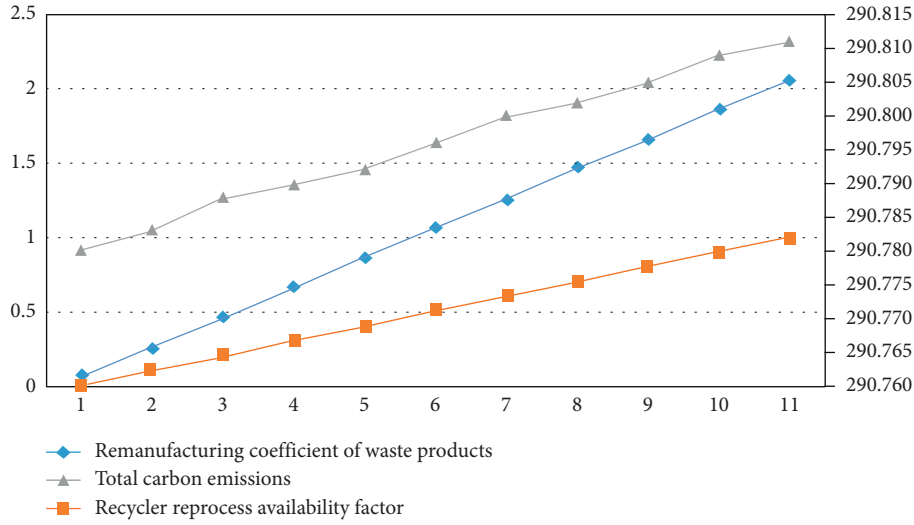


FIGURE 4: Change of total carbon emission with the remanufacturing coefficient μ of waste products.

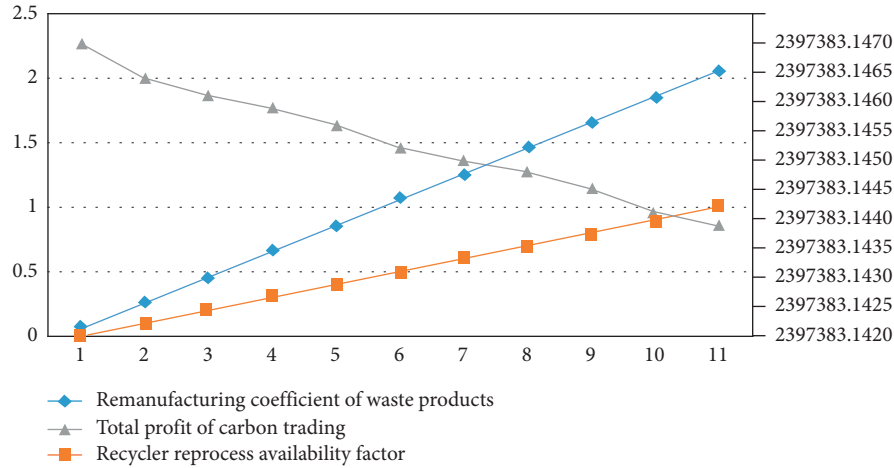


FIGURE 5: Change of total profit of carbon trading with the remanufacturing coefficient μ of waste products.

5. Conclusion

The top-level design of a smart city should focus on green in strategy, aiming to build a green smart city. Smart cities plan and build around energy conservation, emission reduction, and environmental optimization and regard sustainable development as the starting point and destination. As an important strategic industry in the construction of smart cities, the auto parts industry should also take responsibility for low-carbon emission reduction. In this paper, by considering the optimal decision-making behavior of suppliers, producers, physical retailers, online retailers, demand markets, and recyclers, as well as the situation of carbon trading and carbon emissions, the equilibrium conditions of each node in the low-carbon supply chain of auto parts are analyzed by using variational inequality, and the network equilibrium optimization model of the low-carbon supply chain is established. Using the simulation analysis method, through analyzing the relationship between carbon emissions and trading profits with the recovery coefficient of

recycled products and the remanufacturing coefficient of waste products, we can get that carbon emissions directly affect the trading profits of carbon trading; recyclers have a great impact on carbon emissions. Properly increasing the recovery coefficient of recycled products and the remanufacturing coefficient of waste products can make carbon emissions and profits of carbon trading reach the optimal level at the same time. In order to improve the profits of carbon trading in the supply chain, manufacturers need to make reasonable ordering plans to balance carbon emissions and profits of carbon trading. It further shows that in order to achieve the network equilibrium of the low-carbon supply chain of auto parts, the coordination and cooperation of supply chain members is needed. Through recycling, process improvement, and other measures, the carbon emissions of the supply chain network can be reduced, and the excess carbon emissions can be sold in the carbon trading market. The profits can offset the cost investment in emission reduction and finally achieve the purpose of low-carbon supply chain management.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form a part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The funding was sponsored by the National Social Science Fund of China (Grant no. 18CGL015).

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