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RESEARCH ARTICLE

# Pricing Strategy and Social Welfare in a Supply Chain With Different Rights Structure Under Carbon Tax Policy

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**ABSTRACT** Aiming at the pricing and emission reduction decision-making problem of a two-level supply chain consisting of multiple manufacturers and multiple retailers, this paper proposes a consistent pricing mechanism based on multi-agent structure to coordinate the supply chain, and the operation of supply chain participants from competition to cooperation. The proposed algorithm is distributed and collaborative, thus eliminating the need for a central snap-ins, central price coordinators, or leaders. Firstly, a two-level supply chain social welfare model with multi-agent structure is established, and the system nodes in this model are scalable. Then, the pricing and carbon tax policies of the supply chain under different dominant rights are discussed to determine the optimal transaction price and carbon tax policies in order to maximize social welfare. The research results show that the transaction price increases with the increase of the carbon tax rate, and the social welfare decreases with the increase of the carbon tax rate, so the government should formulate the carbon tax within a reasonable range. It is also found that the overall social welfare obtained when there is no dominant node is higher than the social welfare obtained when there is dominant node. It can guide the market to optimize the allocation of resources according to production needs, so as to achieve the maximum efficient use and social welfare.

**INDEX TERMS** Multi-intelligence systems, carbon tax policy, different rights structures, pricing strategies, social welfare.

## I. INTRODUCTION

With the crisis of global warming and the vigorous development of low-carbon economy, carbon tax policy has become an effective economic means to reduce greenhouse gas emissions and has produced remarkable results. The United Kingdom, Australia, Finland, Norway, Germany and other countries have developed carbon tax policies to promote enterprises to enter low-carbon production models [1]. For example, the carbon tax in British Columbia has reduced carbon emissions by 10% since 2008, while the rest of Canada has only reduced carbon emissions by 1.1% [2]. In 2008, the United States and Colombia began to implement carbon tax regulations. In 2009, China implemented a carbon emission reduction plan and promised to achieve carbon neutrality by 2060 in 2022, providing a good environment for formal carbon tax regulations [3]. Further, studies by Lu et al. (2010) show that carbon taxes have proven to be effective policy tools for reducing emissions, with few negative effects on economic growth [4]. How does the

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government's macro policy on carbon tax policy affect the micro behavior of enterprises and consumers? This is-sue has very important practical significance for policy makers and enterprises.

At present, there are a large number of literatures on the impact of carbon tax policy on enterprise operation decision-making. For example, Chen et al. used the input-output model to study the carbon tax policy from the perspective of efficiency [5]. Chen et al. studied the joint pricing and production decisions of duopoly enterprises under the carbon tax policy [6]. Zhou studied the influence of the optimal decision of the game participants, carbon tax and consumer environmental awareness on the equilibrium decision and social welfare in the case of monopoly and competition in the retail market [7]. Yi established a Stackelberg game model to study the cost sharing contract of energy saving and emission reduction in supply chain under the conditions of government subsidies and carbon tax. The retailer decides the cost sharing contract first, and then the manufacturer deter-mines the energy saving level, carbon emission level and wholesale price in turn. Finally, retailers decide the retail price and impose a carbon tax on carbon emissions [8]. Ran studied the design of a coordination contract for low-carbon supply chain under the carbon tax policy and government subsidies. It has achieved the growth of emission reduction and the total profit of the supply chain, while improving the sustainable competitiveness and coordination of the supply chain [9]. Zhang researchers constructed an evolutionary game model to analyze the impact of carbon tax and innovation subsidy on the innovation efficiency of enterprises and the choice of manufacturers' green innovation mode. The stable conditional strategy of the manufacturer is derived [10]. In the traditional supply chain, manufacturers are in a strong position, and then stand in the perspective of maximizing their own interests to formulate a unified price. However, with the development of business, there have been many ' super retailers ' such as Suning, Wal-Mart and so on. They occupy a strong position in the supply chain, resulting in the sinking of the power structure in the supply chain. When setting a unified price, retailers have more and more voice.

When studying the pricing strategy of price consistency in the dual-channel supply chain, the author does not only consider the problem from the perspective of the manufac-turer, but also considers the supply chain with different power structures to draw a more comprehensive and realistic conclusion.

However, there is little literature on the impact of carbon tax policy on the equilibrium strategy of enterprises considering different rights structures. In reality, there is a traditional assumption that the manufacturer is dominant and the retailer follows in the supply chain [11]. However, with the rapid development of the retail industry and the trend of diversification and personalization of demand, the dominant position of traditional manufacturers is gradually being balanced and surpassed by downstream retailers. Retail giants represented by Wal-Mart, Tesco and Gome are gradually dominant in the supply chain. Therefore, when studying the pricing strategy of price consistency in the supply chain, the author does not only consider the problem from the perspective of the manufacturer, but also considers the supply chain with different power structures to draw a more comprehensive and realistic conclusion. Zhou studied the retailer-dominated pricing decision problem in a two-echelon supply chain [12]. Li and Chen discussed the impact of channel integration on price and supply chain competition between two brands [13]. Li Tao et al. found that supply chain members can get more benefits from playing a leader role under different power structures [14]. However, different from these studies, this paper takes the supply chain under the carbon tax policy with different rights structure as the research object, and discusses the pricing strategy and social welfare of the supply chain based on the carbon tax policy.

With the continuous diversification of the market, the supply chain is not only composed of a single manufacturer and a single retailer. There can be multiple manufacturers and multiple retailers in the supply chain, and price competition between manufacturers and retailers will be carried out to obtain more profits. Advanced supply chain models emphasize the dynamic combination between manufacturers and retailers to win market share with the most cost-effective and best services. Savaskan constructed a pricing decision model of closed-loop supply chain composed of a single manufacturer and a number of competitive retailers by using the method of game theory [15]. Ferguson analyzed the competition between new products and remanufactured products produced by monopoly manufacturers and the external remanufacturing competition [16]. Shi studied the influ-ence of the company's organizational structure on the direct sales or indirect sales of these new products and remanufactured products [17]. Ullah et al. studied the optimal remanufacturing strategy and reusable packaging capability of the closed-loop supply chain model of a single retailer and multiple retailers [18]. In [19], the Nash game method is used to study the optimal price and order quantity decision problem of the three-tier supply chain. Sasan studied the four-tier supply chain structure of multi-supplier, multi-manufacturer, multi-dealer and multi-retailer, and used the Comparative Particle Swarm Optimization method to design the operation strategy aiming at the minimum operating cost and maximum operating reliability of the supply chain [20]. Giria studied a monopoly manufacturer, a third-party logistics service provider (TPLSP) and multiple independent retailers, and designed relevant contract parameters to coordinate the decentralized supply chain strategy [21]. Considering the carbon tax policy, Xu studied a two-stage supply chain consisting of one manufacturer and two retailers, and established six game models [22].

However, the centralized scheduling method used in the existing research can usually achieve good overall performance, but almost complete information must be shared. However, due to the distributed nature of the real supply chain, this is difficult or even impractical. In the actual supply chain system, the relationship between demand and supply has the characteristics of typical complex networks. Using complex network theory to study the supply chain system can reveal the inherent evolutionary dynamics of the supply chain system and better realize the operation of the supply chain system. Each distributed entity can be identified as an ' agent ' and considered as a node as shown in Figure 1. Therefore, such a supply chain system can be modeled as a multi-agent system. The study of multi-agent-based supply chain systems can be traced back to the mid-1980s, when the academic community attempted to initiate new methods based on distributed computing technology for planning and scheduling supply chain systems [22], [24]. Dynamic optimization of material and inventory management [25]; In [26] and [27], the goal is to establish a coordination mechanism to support supply chain members to coordinate their distributed decision-making process. The main task of [28] is to design the stability analysis and control based on multi-agent, so that the supply chain system can meet certain specified performance. However, most of the existing multi-agent supply chain models are static and do not apply to supply chain systems with dynamic attributes. In this paper, a distributed supply chain demand and supply management mechanism for maximizing social welfare is given by using multi-agent control theory. The main contributions are as follows:

i) Compared with other literature models and design methods, this paper introduces the multi-agent consensus theory into the supply chain pricing strategy. Through the establishment of the common objective function of social welfare maximization, a multi-agent network relationship model between manufacturers and retailers is constructed.

ii) Reveal the impact of different power structure differences on members' decision-making behavior and system operation efficiency. It is generally believed that the members who take the lead in making decisions have more power than other members, so the party with priority decision-making power is the power dominant, which affects the decision-making behavior of non-dominant members to achieve the best operating efficiency of the supply chain.

iii) Discuss the impact of carbon tax policy on the consistency agreement and the decision model, and give the relationship model for reference in price setting. We carefully analyzed the different operating modes under these settings and provided some suggestions for managers to choose the most appropriate strategy in practice.

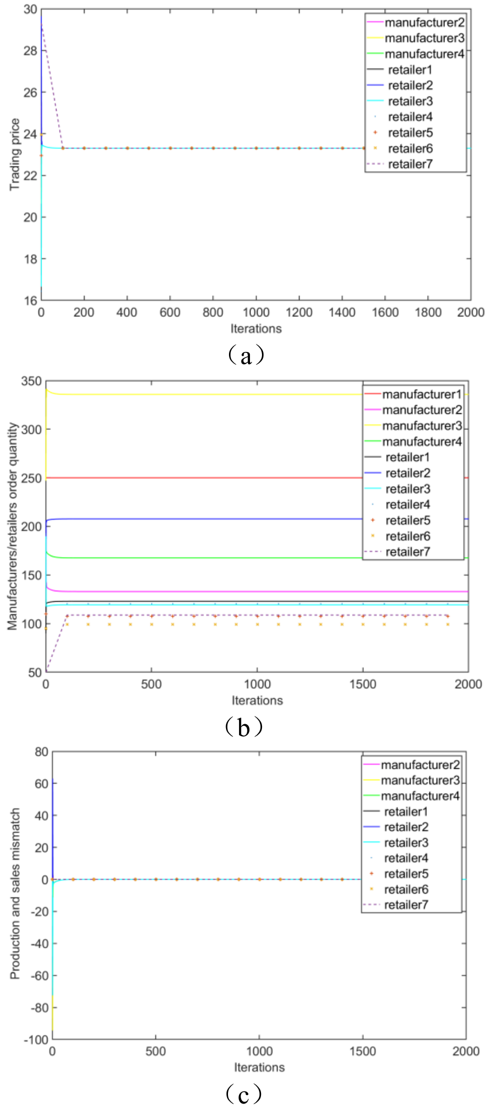

**FIGURE 1.** **The manufacturer is dominant: (a) Trading price; (b) Manufacturers/retailers order quantity; (c) Production and sales mismatch.**

## II. PRELIMINARIES

### A. NETWORK MODEL

The communication network considered in this paper, in which each multi-intelligence node can pass information to each other, corresponds to a graph-theoretic representation of the network as $G^1.G^1 = (V^1, E^1, A^1)$ represents its communication structure, where $V^1$ represents the set of MAS agents studied in this chapter, $v_i^1$ represents the $i$ th node, and $E^1$ is the set of edges between nodes in the MAS. The set of neighboring nodes of the node $i$ is represented using $N_i^1 = \{j | (i, j) \in E\}$, where the number of neighboring nodes $j$ is represented using the symbol $\left|N_i^1\right|$ and $E^1 \in V^1 \times V^1$. $A^1$ is an adjacency matrix of order $n \times n$ representing the connection weight relationships between nodes, whose elements $a_{ij}$ expressions can be defined as follows [29].

$$a_{ij} = \begin{cases} \frac{1}{\max\limits_{i \in V} |N_i^1|+1}, & j \in N_i \\ 0, & others \\ 1 - \sum\limits_{j \in N_i} \frac{1}{\max\limits_{i \in V} |N_i^1|+1}, & i = j \end{cases} \tag{1}$$

### B. BASIC MODELS

In this study, the two-level supply chain of a single product composed of manufacturers and retailers is taken as the research object, including m manufacturers and n retailers. In addition, in the model of this paper, the carbon emissions generated by manufacturers in the process of producing products will have negative externalities on society. Therefore, the government's goal is to maximize social welfare by setting the optimal carbon tax rate to balance the self-interest of supply chain members and negative externalities. It is emphasized here that the external diseconomy caused by the manufacturer's unit car-bon emissions to society is measured by the unit price of carbon dioxide. The government's goal is to formulate a carbon cost charge ratio that maximizes social welfare, which can be understood as a carbon tax rate. Referring to the definition of social welfare by Park et al. M, the meaning of social welfare in this paper is the sum of the profits of manufacturers and retailers plus the government's carbon tax revenue minus the external diseconomy caused by the manufacturer's carbon emissions to society. The external diseconomy caused by the manufacturer's carbon emissions to the society is measured by the cost of carbon emissions, that is, the product of the unit carbon price and the total carbon emissions in the manufacturer's production; therefore, social welfare can be expressed as the sum of the profits of manufacturers and retailers minus the external diseconomy caused by manufacturers' carbon emissions to society.

According to the needs of the paper, the following assumptions are made for the model of this paper, and the controversial assumptions are explained and explained in detail: 1) Due to the different carbon taxes levied by different energy sources, this paper assumes that in the two-stage supply chain of manufacturer-retailer, the government 's carbon tax policy is mainly aimed at the carbon emissions generated by the manufacturer's production process. 2) The government 's tax rate on manufacturers ' carbon emissions per unit remains unchanged, and the carbon tax paid by manufacturers is proportional to the total carbon emissions of manufacturers. 3) Carbon emissions are only generated in the production process of the manufacturer, and the carbon emissions generated by the manufacturer's unit product are $e_0$. 4) Manufacturers produce under the carbon tax policy. The government levies a carbon tax on enterprises based on carbon emissions. The carbon tax rate is $p_0$.

1) Retailer model

It is assumed that the desired demand $D$ is influenced by the retailer's retail price $\tilde{p}$, which takes the form of

$$D = a - \gamma \tilde{p} \tag{2}$$

where $a$ is the base market volume; $\gamma$ is the price sensitivity factor, reflecting the impact of price on demand. For each retailer, there is a range of adjustability within a supply cycle to maximize its profitability. For example, when a retailer sets different prices at different times, consumers will adjust their purchase period and the quantity they buy. The retailer's demand is thus adjusted according to the consumer's response to the retail price.

For the retailer cell, then the welfare function of the retailer $sw_{i,R}(D_i, p)$ is defined as

$$sw_{i,R}(D_i, p) = U_i(D_i) - p \cdot D_i \tag{3}$$

where $U_i(D_i)$ is the utility function for cell $i$, which represents the satisfaction of the first $i$ load cell with the current demand $D_i$, usually satisfying the following three properties:

Property 1: The utility function is a non-decreasing function.

Property 2: The derivative of the utility function decreases as the demand increases.

Property 3: The satisfaction level is zero when no goods are available, and is constant when the quantity of goods is greater than a certain level.

This leads to the following utility function for the retailer:

$$U_i(D_i) = \begin{cases} \beta_i D_i + \alpha_i D_i^2, D_i \le \frac{\beta_i}{2\alpha_i} \\ \frac{\beta_i^2}{4\alpha_i}, D_i > \frac{\beta_i}{2\alpha_i} \end{cases} \tag{4}$$

2) Manufacturer's model

$C_i(Q_i)$ represents the production cost of the $i$th manufacturer and can be described as a quadratic function of production output, i.e. the cost function can be expressed as

$$C_i(Q_i) = a_i Q_i^2 + b_i Q_i + c_i \tag{5}$$

where $a_i > 0$, $b_i$, $c_i$ is the cost parameter for the $i$ manufacturer's unit.

This paper defines that the welfare function of the manufacturer's unit $sw_{i,M}(Q_i, p)$ can be expressed as

$$sw_{i,M}(Q_i, p) = p \cdot Q_i - C_i(Q_i) - ep_0 Q_i \tag{6}$$

## III. OPTIMAL STRATEGY

In this section, under a given carbon tax policy, the paper takes multiple manufacturers and multiple retailers as a multi-agent system to analyze the optimal decisions under different rights structures. Based on the distributed consensus algorithm, the transaction prices of manufacturers and retailers under different dominant conditions are solved, and the optimal operation decisions are made with the maximum social welfare of the entire supply chain.

### A. DESCRIPTION OF THE PROBLEM OF MANUFA-CTURER-LED SUPPLY CHAIN (MS SUPPLY CHAIN)

Considering the selfishness of each participant, the goal of each manufacturer or retailer is to maximize their own interests, which may lead to coordination failure. The maximization of social welfare can not only maximize the total welfare of the whole society, but also ensure the maximization of individual profits. Therefore, efficiency and fairness should be taken into account. In the MS supply chain, a dominant manufacturer 1, $1 \in M$ is selected as the dominant player in the supply chain and first determines the product quantity $Q_1$, with other manufacturers and retailers as followers. Here, we take the maximization of social welfare as the objective function to achieve coordinated operation among participants. Therefore, the objective function of supply chain management can be expressed as:

$$\left( s\pi_{1,M}(Q_1,p) + \sum_{\substack{i=2\\ i\in M}}^{m} sw_{i,M}(Q_i,p) + \sum_{\substack{i=1\\ i\in R}}^{n} sw_{i,R}(D_i,p) \right) \tag{7}$$

$$s.t. Q_1 + \sum_{\substack{i=2\\ i\in M}}^{m} Q_i = \sum_{\substack{i=1\\ i\in R}}^{n} D_i \tag{8}$$

$$0 \le Q_i \le Q_{i,\max} \tag{9a}$$

$$0 \le D_i \le D_{i,\max} \tag{9b}$$

where $M$ is the set of manufacturer units and $R$ is the set of retailer units, $m$ is the number of manufacturer units and $n$ is the number of manufacturer units. $Q_i$ represents the quantity produced by the manufacturer and $D_i$ represents the quantity demanded by the $i$ retailer; $p$ is the transaction price.

The social welfare maximization problem is subject to the constraints of production and demand balance, as well as the production capacity of each manufacturer and the sales capacity of retailers. Where (8) describes the balance between order quantity and production quantity, (9a) and (9b) characterize the local production capacity and sales capacity constraints of each production unit and retail unit.

By substituting $sw_{i,M}(Q_i, p)$ and $sw_{i,R}(D_i, p)$ for the manufacturer and the retailer units from (4) and (6) into (7) and presenting the optimization as a minimization problem, we can write (7) as (10), shown at the bottom of the page. The optimization problem represented by the problem (10) is a convex optimization problem with affine constraints. Therefore, the Karush-Kuhn-Tucker (KKT) condition is used to ensure global optimality [30].

### B. OPTIMAL PRICING STRATEGIES FOR SUPPLY CHAIN MEMBERS

In order to solve the problem (10) in a distributed manner, the typical Lagrangian method is used to decouple it. Then, a new variable is introduced to represent the imbalance between production and sales volume, which is important for the convergence of global production and sales mismatch. Considering the directed communication network, consensus-based iterative rules are proposed to ensure the convergence of consensus incremental cost (incremental utility). At the same time, iterative rules based on proportional consensus are used to ensure the convergence of production and sales mismatch. The detailed description can be found in the consensus supply chain management algorithm.

In problem (10), the objective function is the sum of local functions, and constraints (9a) and (9b) are local, and constraint (8) is a global coupling constraint. Here, if constraint (8) is decoupled, problem (10) can be decoupled into multiple sub-optimization problems. The constrained objective

$$\begin{aligned}
&\underset{Q_i,D_i,p}{Min} - \left( s\pi_{1,M}(Q_1,p) + \sum_{\substack{i=2\\ i\in M}}^{m} sw_{i,M}(Q_i,p) + \sum_{\substack{i=1\\ i\in R}}^{n} sw_{i,R}(D_i,p) \right)\\
&= \underset{Q_i,D_i,p}{Min} \left( \begin{gathered} C_1(Q_1) + ep_0Q_1 - p\cdot Q_1 + \\ \sum_{\substack{i=2\\ i\in M}}^{m} \left( C_i(Q_i) + \sum_{i\in M} ep_0 Q_i - p\cdot Q_i \right) + \sum_{\substack{i=1\\ i\in R}}^{n} (p\cdot D_i - U_i(D_i)) \end{gathered} \right)\\
&= \underset{Q_i,D_i,p}{Min} \left( C_1(Q_1) + ep_0Q_1 + \sum_{\substack{i=2\\ i\in M}}^{m} C_i(Q_i) + \sum_{\substack{i=2\\ i\in M}}^{m} ep_0Q_i - \sum_{\substack{i=1\\ i\in R}}^{n} U_i(D_i) \right)
\end{aligned} \tag{10}$$

function (8) and Lagrangian function can be written as

$$L = \sum_{\substack{i=2\\ i\in M}}^{m} C_i(Q_i) + \sum_{\substack{i=2\\ i\in M}}^{m} ep_0 Q_i - \sum_{\substack{i=1\\ i\in R}}^{n} U_i(D_i) + \lambda\Big(Q_1 + \sum_{\substack{i=2\\ i\in M}}^{m} Q_i - \sum_{\substack{i=1\\ i\in R}}^{n} D_i\Big) \tag{11}$$

According to KKT conditions, where $\lambda \geq 0$ is the Lagrangian multiplier. By the formula (11), the original optimization decoupling problem (10) can be decomposed into $N$ suboptimization problems with local constraints with given $\lambda$. As the inequality constraints are local, it is not necessary to add them to the augmented cost function, because they can be regarded as the boundary of the domain of the problem.

$$\lambda_i = \begin{cases} C_i'(Q_i) - ep_0, i \in M \\ U_i'(D_i), i \in R \end{cases} \tag{12}$$

The optimization of the problem (10) is solved if all nodes satisfy the local constraint and all $\lambda_i, \quad \forall i \in V, \quad V = M \cup R$ achieve consensus. That is $\lambda_i = \lambda^* > 0, \forall i \in V$. When the variables $\lambda_i, \quad \forall i \in V$ converge, the global supply and demand balance needs to be guaranteed. Hence, consensus theory could be used to solve problem (10) in a distributed way.

Note 1: The technical result of equation (12) is consistent with the fundamental welfare theorem of microeconomics. Furthermore, the structure of the IWC algorithm given allows this market to operate in a fully distributed manner for a multiagent-based supply chain system, the control object of each agent is twofold: one is to control the production, and the other adjusts the price of the product to achieve consensus.

#### 1) DISTRIBUTED ALGORITHM

In the MS supply chain, a dominant manufacturer $1, 1 \in M$ is selected as the dominant player in the supply chain and first determines the product transaction price $\lambda_i$, with other manufacturers and retailers as followers, to obtain the following distributed algorithm based on

$$\lambda_i(k+1) = \sum_{j\in V} a_{ij}\lambda_j(k) + \eta\xi_i(k), i \in V \tag{13}$$

where $a_{ij}$ is determined by equation (1) and the iteration step size $\eta$ is a constant.

The iterative formula for updating the commodity aggregates is derived from the consistency variable formula (12) as follows.

$$Q_i(k+1) = \underset{Q_i^m \leq Q_i(k) \leq Q_i^M}{\arg\min} \; [C_i(Q_i(k)) - ep_0 Q_i(k) - \lambda_i(k+1)Q_i(k)], \quad i \in M \tag{14}$$

$$D_i(k+1) = \underset{D_i^m \leq D_i(k) \leq D_i^M}{\arg\min} \; [\lambda_i(k+1)D_i(k) - U_i(D_i(k))], i \in R \tag{15}$$

Equation (15) $\xi_i$ is the degree of production and sales mismatch, representing the deviation change of production and sales, and its value can also reflect the error change of consistency variable. The iterative formula is as follows: summing up and analyzing the results of the above calculations, Theorem 1 is obtained.

*Theorem 1:* If the graph is connected, and there exists a sufficiently small constant $\sigma$ such that $0 < \eta < \sigma$, when the manufacturer is the dominant node, then the proposed consistency algorithm is stable and there exists an optimal pricing and optimal productions volume i.e. that is, the following equation holds.

$$\begin{aligned} &\lim_{k\to\infty} \lambda_i(k) = \lambda^* = \lambda_1, \forall i \in V \\ &\lim_{k\to\infty} Q_i(k) = Q_i^*, \forall i \in M \\ &\lim_{k\to\infty} D_i(k) = D_i^*, \forall i \in R \end{aligned} \tag{16}$$

where $k$ is the number of iterations, $\lambda^*$ is a constant, $Q_i^*$ is the final converged production number for the $i$ node, and $D_i^*$ is the final converged order number for the $i$ node.

See appendix for proof.

### C. RETAILER-LED SUPPLY CHAIN (RS SUPPLY CHAIN) MODEL

Since this paper is designed based on the idea of multi-agent network, the supply chain members (manufacturers and retailers) all appear as network nodes, so when the design is dominated by retailers, only a key retailer is dominated, that is, the product transaction price is determined by the dominant retailer. Retailers and manufacturers at other nodes are followers, and the design method is similar to the manufacturer-led process. In the RS supply chain, Without loss of generality, a dominant retailer $1, 1 \in R$ is selected as the dominant player in the supply chain and first determines the product quantity $D_1$, with other retailers and manufacturers as followers. Here, we take the maximization of social welfare as the objective function to achieve coordinated operation among participants. Therefore, the objective function of supply chain management can be expressed as (17), shown at the bottom of the next page.

Note 2: We can interpret the locally dual variable $\lambda_i$ as the local price of the commodity, that is, updating the unit price in real time according to the price of the neighbor's product and the imbalance of local supply and demand. Local commodity prices are incremental benefits for both supply and demand sides, and once these incremental benefits are equal to each other, the supply-demand imbalance becomes zero and the global optimal level of social welfare is reached. Therefore, we call this algorithm the IWC algorithm. In this structure, price regulators have no access to individual utility/cost functional ion parameters and individual manufacturer/retailer units have no access to information provided by neighbors. Therefore, the privacy of information in distributed units is guaranteed.

## IV. SIMULATION OF ALGORITHMS

Due to the large number of model parameters, it is very difficult to analyze and compare directly. Therefore, the numerical analysis method is used to discuss and draw according to the results of the example, so as to visually observe the decision-making effect under different circumstances, and verify the rationality of the model constructed in this paper. This part will use Mathematica software to simulate the elements.

As mentioned above, in this section, we assume that there are seven retailers and four suppliers. Firstly, the example verifies the influence of carbon tax rate on the optimal decision and the pricing decision of the enterprise. Then we focus on the social welfare of supply chains with different rights structures under these carbon tax policies. The parameter selection for manufacturers and retailers are shown in Table 1.

**TABLE 1.** **Parameters of the manufacturers and retailers.**

Retailer parameters

| Node | $\alpha_i$ | $\beta_i$ | $D_{i\,min}$ | $D_{i\,max}$ |
|---|---|---|---|---|
| 1 | 0.043 | 33.8 | 0 | 350 |
| 2 | 0.049 | 43.66 | 0 | 300 |
| 3 | 0.047 | 34.52 | 0 | 220 |
| 4 | 0.048 | 34.87 | 0 | 220 |
| 5 | 0.075 | 39.45 | 0 | 240 |
| 6 | 0.075 | 38.4 | 0 | 235 |
| 7 | 0.051 | 34.4 | 0 | 190 |

Manufacturer parameters

| Node | $a_i$ | $b_i$ | $Q_{i\,min}$ | $Q_{i\,max}$ |
|---|---|---|---|---|
| 1 | 0.018 | 12.47 | 0 | 400 |
| 2 | 0.017 | 18.78 | 0 | 300 |
| 3 | 0.015 | 13.23 | 0 | 500 |
| 4 | 0.014 | 18.61 | 0 | 350 |

### A. IMPACT OF CARBON TAX RATE ON OPTIMAL DECISION MAKING

In this section, we first analyze the impact of carbon tax rates on the transaction prices of manufacturers and retailers in the supply chain under different rights structures. Under the same carbon tax rate, when the manufacturer is dominant, the convergence value of the consensus variable selection is 23.3. From Figure 1(a), it can be seen that the incremental costs of other retailers and manufacturers as followers are consistent. Figure 1(b) can be seen that the output meets the upper and lower bound constraints and supply and demand balance conditions. Figure 1(c) verifies that the supply and demand mismatch level converges to 0, that is, the supply chain is stable and the algorithm is feasible.

When the retailer is dominant, the convergence value of the consensus variable is 23.5. From Figure 2(a), it can be seen that the incremental cost of other retailers and manufacturers as followers is consistent. Figure 2(b) can be seen that the output satisfies the upper and lower bound constraints and the supply and demand balance conditions. Figure 2(c) verifies that the supply and demand mismatch level converges to 0.

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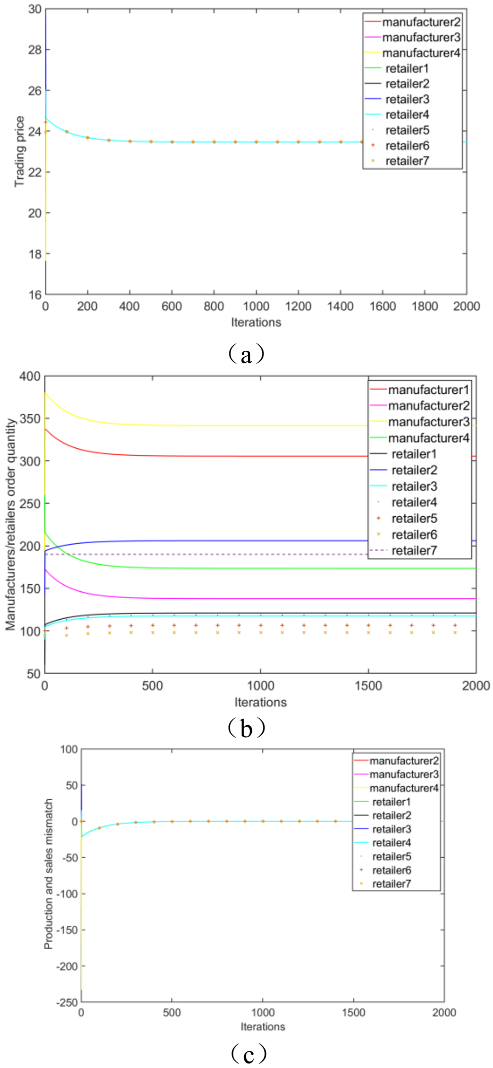
$$\begin{aligned}
&\underset{Q_i,D_i,p}{Min} -\left(\sum_{\substack{i=1\\ i\in M}}^{m} sw_{i,M}(Q_i,p)+sw_{1,R}(D_1,p)+\sum_{\substack{i=2\\ i\in R}}^{n} sw_{i,R}(D_i,p)\right)\\
&=\underset{Q_i,D_i,p}{Min}\left(\begin{array}{l}\displaystyle\sum_{\substack{i=1\\ i\in M}}^{m}\left(C_i(Q_i)+\sum_{i\in M} ep_0Q_i-p\cdot Q_i\right)\\ \displaystyle -U_1(D_1)+p\cdot D_1+\sum_{\substack{i=2\\ i\in R}}^{n}\left(p\cdot D_i-U_i(D_i)\right)\end{array}\right)\\
&=\underset{Q_i,D_i,p}{Min}\left(\sum_{\substack{i=1\\ i\in M}}^{m} C_i(Q_i)+\sum_{\substack{i=1\\ i\in M}}^{m} ep_0Q_i-U_1(D_1)-\sum_{\substack{i=2\\ i\in R}}^{n} U_i(D_i)\right)
\end{aligned}\tag{17}$$



(a)

(b)

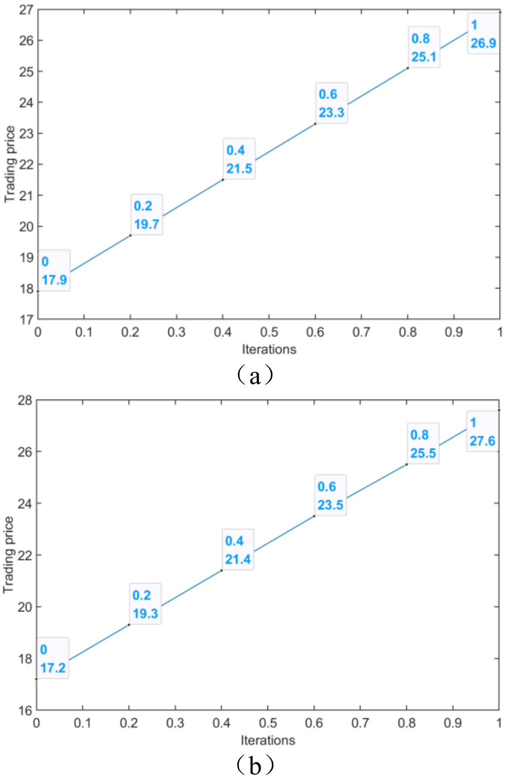
(c)

**FIGURE 2.** The retailer is dominant: (a) Trading price; (b) Manufac-turers/retailers order quantity; (c) Production and sales mismatch.

In addition, the range of effective tax rates for carbon taxes is explored. Figure 3(a) and 3(b) show that the transaction price for manufacturers and retailers increases as the carbon tax increases. Therefore, it is best for the government not to impose excessive carbon taxes on manufacturers, as excessive carbon taxes will lead to higher transaction prices.

## B. DEMAND AND SOCIAL WELFARE

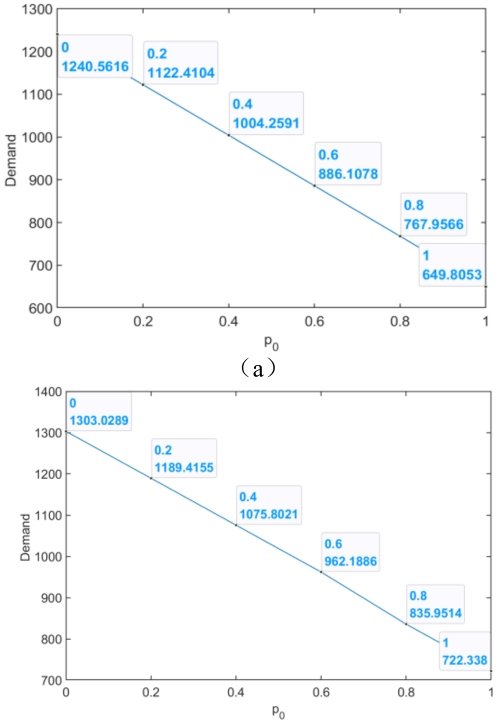
Figure 4(a) and 4(b) show that the market demand for the product decreases as carbon tax increases, so it would be better for the government not to impose an excessive carbon tax on manufacturers, and excessive carbon taxes excessively inhibit market demand for products.



(a)

(b)

**FIGURE 3.** Trading price: (a) the manufacturer is dominant; (b) the retailer is dominant.

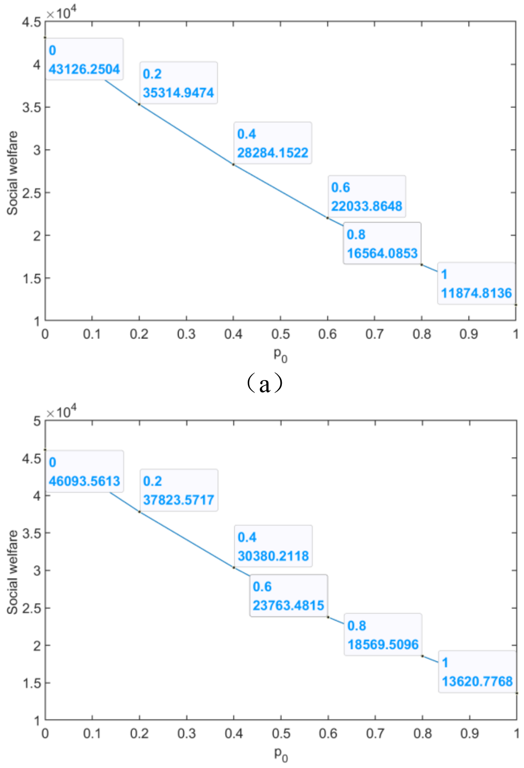


(a)

(b)

**FIGURE 4.** Demand: (a) the manufacturer is dominant; (b) the retailer is dominant.

Analyze the improvement of social welfare by the implementation of the optimal carbon tax policy. Figure 5(a) shows that under a manufacturer dominant approach, the dominant manufacturer is the most profitable, the overall welfare of the manufacturers and the retailers decreases as the carbon tax increases. Figure 5(b) shows that under a retailer dominant



（a）

（b）

**FIGURE 5.** **Social welfare: (a) the manufacturer is dominant; (b) the retailer is dominant.**

**TABLE 2.** **The social welfare under different structures.**

| | Dominant node structure | | No dominant node structure | |
|---|---|---|---|---|
| | The manufacturer node 1 | The retailer node 7 | The manufacturer node 1 | The retailer node 7 |
| The node welfare | 1381 | 3918 | 1350 | 1889 |
| The total welfare | 22033 | 23763 | 24784 | 24784 |

approach, the dominant manufacturer is the most profitable, the overall welfare of the manufacturers and the retailers decreases as the carbon tax increases.

### C. A COMPARISON OF DOMINANT NODE AND NO DOMINANT NODE

The social welfare under different structural forms of dominant nodes and no dominant node is analyzed. As shown in Table 2, where node 1 is the dominant manufacturer unit and node 7 is the dominant retailer unit, when there is a dominant node, the dominant node gains more profits than no dominant node structure. But the overall social welfare is less than under no dominant node structure. This indicates that when there is a dominant node, the dominant node plays a dominant role and only pursues its own profit maximization at the expense of the profits of other nodes, so the overall social welfare is low. However, when there is no dominant node, the market is in a free competition structure, and each node has equal rights and pursues common goals to maximize, so the overall social welfare obtained is higher than that obtained when there is a dominant node. Therefore, the market gains the most in the free market and can achieve a mutually beneficial and win-win situation.

## V. CONCLUSION

Under the premise of considering carbon tax, this paper takes a two-echelon supply chain of manufacturer-retailer as the research object, and focuses on the supply chain structure of multiple manufacturers and retailers, constructs a multi-agent network structure model, and compares the optimal operation decision of multi-agent consistency under the two structural market settings of manufacturer-led and retailer-led, as well as the impact of carbon tax rate on equilibrium supply chain transaction price and social welfare. Through numerical example analysis, some specific management suggestions are obtained. The results show that when the carbon tax rate is the same, under different rights structures, the following nodes can achieve the same price as the dominant nodes and get the best production quantity. When the carbon tax rate changes, the manufacturer-led transaction price increases with the increase of the carbon tax rate, and the production volume and social welfare decrease with the increase of the carbon tax rate; the manufacturer-led transaction price increases with the increase of the carbon tax rate, and the production volume and social welfare decrease with the increase of the carbon tax rate; The research of this paper has very important practical significance and reference value for how to reduce the loss of social welfare and the optimal decision-making of government and enterprises under the background of carbon tax policy. In terms of reducing the loss of social welfare, the government can consider imposing a carbon tax on manufacturers at the optimal carbon tax rate, and the determination of the optimal carbon tax rate is necessary for the different rights structure characteristics of the market in certain industries. In addition, according to international standards and national conditions, the government can announce the appropriate carbon price in advance to adjust the optimal carbon tax rate. For manufacturing enterprises, because the optimal carbon tax rate formulated by the government is positively related to carbon emissions per unit product, enterprises can seek technological innovation, economies of scale and other methods to reduce carbon emissions per unit product. Lower carbon emissions per unit can increase product demand and thus increase profits.

In addition, there are still some limitations in this study, which can be used as a direction for further attention in the future. Firstly, in order to simplify the problem, the two-echelon supply chain system constructed in this paper is relatively simple, so it can be further studied in a multi-echelon complex supply chain system closer to reality. Secondly, the paper model assumes that the market demand is deterministic demand and the member information in the supply chain is symmetrical, but the random demand and information asymmetry are closer to reality. Therefore, it is increasingly important to incorporate randomness and information asymmetry into the consideration of pricing strategies.

## APPENDIX A

In order to analyze the convergence of the above algorithm, the following lemma is introduced.

*Lemma 1:* If the matrix $\tilde{A}$ can be written as a chunked lower triangular matrix, i.e. there are

$$\tilde{A} = \begin{pmatrix} \tilde{A}_1 & 0 \\ \tilde{A}_2 & \tilde{A}_3 \end{pmatrix}$$

where $\tilde{A}$ with the set of eigenvalues $\lambda\left(\tilde{A}\right)$, $\tilde{A}_1$ and $\tilde{A}_3$ with the set of eigenvalues $\lambda\left(\tilde{A}_1\right)$ and $\lambda\left(\tilde{A}_3\right)$ respectively, then there exists

$$\lambda\left(\tilde{A}\right) = \lambda\left(\tilde{A}_1\right) \cup \lambda\left(\tilde{A}_3\right)$$

Proof of Theorem 1. With $m+1$ manufacturer nodes and $n$ retailer nodes, one of the manufacturer nodes is selected as the dominant node of the communication network in the network topology, and the rest of the manufacturer and retailer nodes are the follower nodes, in order to facilitate the subsequent proof process, the above consistency algorithm is written in the form of a matrix. According to formula (12)-(17):

$$\lambda_i\left(k+1\right) = A_M \lambda_i\left(k\right) + \eta_M \xi_i\left(k\right) \tag{A1}$$

$$\xi_i(k+1) = C_M(I - A_M)\lambda_i(k) + (A_M - \eta C_M)\xi_i(k) \tag{A2}$$

Retailer node $i, \quad i \in R$ :

$$\lambda_i\left(k+1\right) = A_R \lambda_i\left(k\right) + \eta_R \xi_i\left(k\right) \tag{A3}$$

$$\xi_i(k+1) = C_R(I - A_R)\lambda_i(k) + (A_R - \eta_R C_i)\xi_i(k) \tag{A4}$$

where $A_M, A_R$ are the corresponding coefficient matrices,

$$C_i = \begin{cases} diag\left[\frac{1}{2a_1}, \frac{1}{2a_2}, \cdots, \frac{1}{2a_m}\right], i \in M \\ diag\left[\frac{1}{2\alpha_1}, \frac{1}{2\alpha_2}, \cdots, \frac{1}{2\alpha_n}\right], i \in R \end{cases}$$

The whole system can then be represented as shown in the equation at the bottom of the page.

According to system (A6), its system matrix $A$ can be obtained as

$$A = \begin{bmatrix} A_M & 0 & \eta_M & 0 \\ 0 & A_R & 0 & \eta_R \\ C_M\left(I - A_M\right) & 0 & A_M - \eta_M C_M & 0 \\ 0 & C_R\left(I - A_R\right) & 0 & A_R - \eta_R C_R \end{bmatrix}$$

For the purpose of the proof, the system matrix A is chunked into two parts.

$$A = A_0 + H = \begin{bmatrix} A_M & 0 & 0 & 0 \\ 0 & A_R & 0 & 0 \\ C_M\left(I - A_M\right) & 0 & A_M & 0 \\ 0 & C_R\left(I - A_R\right) & 0 & A_R \end{bmatrix} + \begin{bmatrix} 0 & 0 & \eta_M & 0 \\ 0 & 0 & 0 & \eta_R \\ 0 & 0 & -\eta_M C_M & 0 \\ 0 & 0 & 0 & \eta_R C_R \end{bmatrix}$$

Since $A_0$ is a lower triangular block matrix, the eigenvalues from Lemma 1 are the ensemble of $A_M, \quad A_R$, and since $A_M, \quad A_R$ are all row random matrices and all elements are positive and the topology of the system is strongly connected, $A_M, \quad A_R$ all have an eigenvalue with a single root of 1 and all other eigenvalues have mode less than 1.

Therefore, the eigenvalues of $A_0$ satisfy the following conditions.

$$1 = \mu_1\left(A_0\right) = \left|\mu_2\left(A_0\right)\right| \geq \left|\mu_3\left(A_0\right)\right| \geq \cdots \geq \left|\mu_n\left(A_0\right)\right| \tag{A6}$$

Next, prove that the matrix $A_0$ satisfies, under the influence of the perturbation matrix $H$.

$$1 = \mu_1\left(A\right) > \left|\mu_2\left(A\right)\right| \geq \left|\mu_3\left(A\right)\right| \geq \cdots \geq \left|\mu_n\left(A\right)\right| \tag{A7}$$

It follows that 1 is the $m$ dimensional right eigenvector of $A_M$ and $1^T$ is the left eigenvector of $A_R$ associated with 1. Then the left and right eigenvectors of the matrix $A_0$ are

$$u_1 = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{m}1 \\ \frac{1}{n}1 \end{bmatrix}$$

$$u_2 = \begin{bmatrix} 1 \\ 1 \\ -\frac{\sigma_1}{m}1 \\ -\frac{\sigma_2}{m}1 \end{bmatrix}$$

$$\gamma_1^T = \begin{bmatrix} 1^T C_M & 1^T C_R & 1^T & 1^T \end{bmatrix}$$

$$\gamma_2^T = \begin{bmatrix} \frac{1}{m}1^T & \frac{1}{n}1^T & 0^T & 0^T \end{bmatrix}$$

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$$\begin{bmatrix} \lambda_M\left(k+1\right) \\ \lambda_R\left(k+1\right) \\ \xi_M\left(k+1\right) \\ \xi_R\left(k+1\right) \end{bmatrix} = \begin{bmatrix} A_M & 0 & \eta_M & 0 \\ 0 & A_R & 0 & \eta_R \\ C_M\left(I - A_M\right) & 0 & A_M - \eta_M C_M & 0 \\ 0 & C_R\left(I - A_R\right) & 0 & A_R - \eta_R C_R \end{bmatrix} \begin{bmatrix} \lambda_M\left(k\right) \\ \lambda_R\left(k\right) \\ \xi_M\left(k\right) \\ \xi_R\left(k\right) \end{bmatrix} \tag{A5}$$

where

$$\sigma_1 = \sum_{i=1}^{m} \frac{1}{2a_i}$$

$$\sigma_2 = \sum_{i=1}^{n} \frac{1}{2\alpha_i}$$

$u_1, u_2$ and $\gamma_1^T, \gamma_2^T$ are the left and right eigenvectors of the matrix $A_0$, respectively, and

$$\begin{bmatrix} \gamma_1^T \\ \gamma_2^T \end{bmatrix} \begin{bmatrix} u_1 & u_2 \end{bmatrix} = I$$

Based on the eigenvalue regression theory of matrices, the calculation gives

$$\begin{bmatrix} \sum\limits_{i=1}^{m+n} (\gamma_1^T \frac{\partial H}{\partial \eta_i} u_1) & \sum\limits_{i=1}^{m+n} (\gamma_1^T \frac{\partial H}{\partial \eta_i} u_2) \\ \sum\limits_{i=1}^{m+n} (\gamma_2^T \frac{\partial H}{\partial \eta_i} u_1) & \sum\limits_{i=1}^{m+n} (\gamma_2^T \frac{\partial H}{\partial \eta_i} u_2) \end{bmatrix}$$

Namely,

$$\begin{bmatrix} 0 & 0 \\ \sum\limits_{i=1}^{m} \frac{1}{m^2} + \sum\limits_{i=1}^{n} \frac{1}{n^2} & -\left( \sum\limits_{i=1}^{m} \frac{\sigma_1}{m^2} + \sum\limits_{i=1}^{n} \frac{\sigma_2}{n^2} \right) \end{bmatrix}$$

The two eigenvalues of the matrix are 0, $-\left( \sum\limits_{i=1}^{m} \frac{\sigma_1}{m^2} + \sum\limits_{i=1}^{n} \frac{\sigma_2}{n^2} \right)$, and hence

$$\frac{d\mu_1(t)}{dt} = 0 \tag{A8}$$

$$\frac{d\mu_2(t)}{dt} = -\left( \sum_{i=1}^{m} \frac{\sigma_1}{m^2} + \sum_{i=1}^{n} \frac{\sigma_2}{n^2} \right) < 0 \tag{A9}$$

That is, 1 is a single eigenvalue of the matrix $A$ and all other eigenvalues have modes less than 1, satisfying equation (A8), i.e. we have

$$\begin{bmatrix} \lambda_M(k) \\ \lambda_R(k) \\ \xi_M(k) \\ \xi_R(k) \end{bmatrix} = A^k \begin{bmatrix} \lambda_M(0) \\ \lambda_R(0) \\ \xi_M(0) \\ \xi_R(0) \end{bmatrix} \to \lambda^* \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{A10}$$

where $\lambda^*$ is the optimal value of the consistency variable, so the state variables $\lambda$ of the follower can achieve consistency, and the algorithm convergence theorem holds.

Similarly, through the above process, it can be proved that when the retailer is the dominant node, the consistency variable (17) also converges, and the paper no longer describes the proof process.

## REFERENCES

[1] Y. Zhang, Z. Hong, Z. Chen, and C. H. Glock, "Tax or subsidy? Design and selection of regulatory policies for remanufacturing," *Eur. J. Oper. Res.*, vol. 287, no. 3, pp. 885–900, Dec. 2020.

[2] S. Elgie and J. McClay, "BC's carbon tax shift after five years: Results," Sustainable Prosperity, Ottawa, ON, Canada, Tech. Rep., Jul. 2013.

[3] Z. Li, S. Y. Chen, and W. J. Dong, "Low carbon transition pathway of power sector under carbon emission constraints," *Proc. CSEE*, vol. 41, no. 12, pp. 3987–4001, Jan. 2021.

[4] C. Lu, Q. Tong, and X. Liu, "The impacts of carbon tax and complementary policies on Chinese economy," *Energy Policy*, vol. 38, no. 11, pp. 7278–7285, Nov. 2010.

[5] Z.-M. Chen, Y. Liu, P. Qin, B. Zhang, L. Lester, G. Chen, Y. Guo, and X. Zheng, "Environmental externality of coal use in China: Welfare effect and tax regulation," *Appl. Energy*, vol. 156, pp. 16–31, Oct. 2015.

[6] X. Chen and G. Hao, "Sustainable pricing and production policies for two competing firms with carbon emissions tax," *Int. J. Prod. Res.*, vol. 53, no. 21, pp. 6408–6420, Nov. 2015.

[7] Y. Zhou, F. Hu, and Z. Zhou, "Pricing decisions and social welfare in a supply chain with multiple competing retailers and carbon tax policy," *J. Cleaner Prod.*, vol. 190, pp. 752–777, Jul. 2018.

[8] Y. Y. Yi and J. X. Li, "Cost-sharing contracts for energy saving and emissions reduction of a supply chain under the conditions of government subsidies and a carbon tax," *Sustainability*, vol. 10, no. 3, p. 895, Mar. 2018.

[9] W. Ran and T. Xu, "Low-carbon supply chain coordination based on carbon tax and government subsidy policy," *Sustainability*, vol. 15, no. 2, p. 1135, Jan. 2023.

[10] S. Zhang, Y. Yu, Q. Zhu, C. M. Qiu, and A. Tian, "Green innovation mode under carbon tax and innovation subsidy: An evolutionary game analysis for portfolio policies," *Sustainability*, vol. 12, no. 4, p. 1385, Feb. 2020.

[11] D. Ghosh and J. Shah, "Supply chain analysis under green sensitive consumer demand and cost sharing contract," *Int. J. Prod. Econ.*, vol. 164, pp. 319–329, Jun. 2015.

[12] X. Zhuo, F. Wang, and B. Niu, "Brand-owners vertical and horizontal alliance strategies facing dominant retailers: Effect of demand substitutability and complementarity," *Omega*, vol. 103, Sep. 2021, Art. no. 102449.

[13] W. Li and J. Chen, "Backward integration strategy in a retailer Stackelberg supply chain," *Omega*, vol. 75, pp. 118–130, Mar. 2018.

[14] T. Li, R. Zhang, and B. Liu, "Pricing decisions of competing supply chains under power imbalance structures," *Comput. Ind. Eng.*, vol. 125, pp. 695–707, Nov. 2018.

[15] R. C. Savaskan, S. Bhattacharya, and L. N. Van Wassenhove, "Closed-loop supply chain models with product remanufacturing," *Manag. Sci.*, vol. 50, no. 2, pp. 239–252, Feb. 2004.

[16] M. E. Ferguson and L. B. Toktay, "The effect of competition on recovery strategies," *Prod. Operations Manag.*, vol. 15, no. 3, pp. 351–368, Jan. 2009.

[17] T. Shi, D. Chhajed, Z. Wan, and Y. Liu, "Distribution channel choice and divisional conflict in remanufacturing operations," *Prod. Oper. Manag.*, vol. 29, no. 7, pp. 1702–1719, Jul. 2020.

[18] M. Ullah, I. Asghar, M. Zahid, M. Omair, A. Alarjani, and B. Sarkar, "Ramification of remanufacturing in a sustainable three-echelon closed-loop supply chain management for returnable products," *J. Cleaner Prod.*, vol. 290, Mar. 2021, Art. no. 125609.

[19] N. T. M. Hanh, J. M. Chen, and N. Van Hop, "Pricing strategy and order quantity allocation with price-sensitive demand in three-echelon supply chain," *Exp. Syst. Appl.*, vol. 206, Nov. 2022, Art. no. 117873.

[20] S. Khalifehzadeh, M. Seifbarghy, and B. Naderi, "A four-echelon supply chain network design with shortage: Mathematical modeling and solution methods," *J. Manuf. Syst.*, vol. 35, pp. 164–175, Apr. 2015.

[21] B. C. Giri and B. R. Sarker, "Improving performance by coordinating a supply chain with third party logistics outsourcing under production disruption," *Comput. Ind. Eng.*, vol. 103, pp. 168–177, Jan. 2017.

[22] G. Xu and D. Q. Yue, "Pricing decisions in a supply chain consisting of one manufacturer and two retailers under a carbon tax policy," *IEEE Access*, vol. 4, pp. 239–252, 2021.

[23] M. S. Fox, J. F. Chionglo, M. Barbuceanu, "The integrated supply chain management system," *Amer. Soc. Civil Eng.*, vol. 50, no. 2, pp. 39–252, Feb. 1993.

[24] J.-M. Frayret, S. D'Amours, A. Rousseau, S. Harvey, and J. Gaudreault, "Agent-based supply-chain planning in the forest products industry," *Int. J. Flexible Manuf. Syst.*, vol. 19, no. 4, pp. 358–391, Dec. 2007.

[25] W. Shen and D. H. Norrie, "Agent-based systems for intelligent manufacturing: A state-of-the-art survey," *Knowl. Inf. Syst.*, vol. 1, pp. 129–156, May 1999.

[26] M. S. Fox, M. Barbuceanu, and R. Teigen, “Agent-oriented supply-chain management,” *Int. J. Flexible Manuf. Syst.*, vol. 12, nos. 2–3, pp. 165–188, 2000.
[27] W. Shen, R. Kremer, M. Ulieru, and D. Norrie, “A collaborative agent-based infrastructure for internet-enabled collaborative enterprises,” *Int. J. Prod. Res.*, vol. 41, no. 8, pp. 1621–1638, Jan. 2003.
[28] M. Ramezani, M. Bashiri, and T. M. Reza, “A robust design for a closed-loop supply chain network under an uncertain environment,” *Int. J. Adv. Manuf. Technol.*, vol. 66, nos. 825–843, pp. 239–252, May 2013.
[29] R. Olfati-Saber, J. A. Fax, and R. M. Murray, “Consensus and cooperation in networked multi-agent systems,” *Proc. IEEE*, vol. 95, no. 1, pp. 215–233, Jan. 2007.
[30] A. Mordecai, *Nonlinear Programming: Analysis and Methods*. New York, NY, USA: Dover, 2003.

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