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Research on Intelligent Decision of Low Carbon Supply Chain Based on Carbon Tax Constraints in Human-Driven Edge Computing

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ABSTRACT Edge computing moves data and storage to one end of edge nodes. The advantages of direct data collection and intelligent analysis are gradually being considered as disruptive technologies to promote social progress. Many fields and industries are exploring the use of edge technologies. To achieve the goal of improving efficiency and optimizing business models, the supply chain is one of the areas where edge computing technology can be prioritized. Therefore, the organization and coordination of the supply chain must take into account both energy saving and emission reduction and intelligent decision-making effects. This paper establishes a basic decision-making model for the supply chain under the carbon tax constraint and compares and analyzes the optimal decision-making problem of the supply chain between the centralized and decentralized decisions of producers and retailers under the carbon tax constraint. Then, the supply chain optimization under the three conditions of considering the repurchase contract, the subsidy policy and the joint strategy of both the repurchase and the subsidy under the constraint of carbon tax are discussed. Research shows that carbon tax can play a role in reducing carbon emissions, but for some industries with smaller profit margins, relying solely on carbon tax policy may lead to reduced benefits and make business development difficult. Therefore, considering the combined strategy of repurchase and subsidy at the same time, the dual goals of emission reduction and economic benefits can be achieved.

INDEX TERMS Edge computing, carbon tax constraint, low carbon supply chain, intelligent decision.

I. INTRODUCTION

In a global warming environment, to achieve effective allocation of pollution responsibility and pollution control, there are usually two methods to implement carbon tax policies and carbon emission permits, but the implementation of carbon tax policies has the advantage of low management costs and economic costs low, social acceptance is high, so the implementation of carbon tax policy can more effectively control greenhouse gas emissions [1]. If this policy context exists, companies need to reduce emissions and reduce corporate costs by adjusting production volumes, logistics, and transportation methods.

Therefore, under the low-carbon control of the government, enterprises need to find a proper way to reduce emissions by adjusting production mode, and at the same time, they need to find an appropriate way to maximize their profits (to minimize costs) [2]. Based on this background, this paper mainly studies the optimal decision-making of the supply chain under different circumstances.

In recent years, supply chain research and low-carbon supply chain contracts have become a hot topic in the academic field. In the producer's repurchase contract, Pastemack *et al.* studied the sales channel consisting of a supplier and a retailer and emphasized that the appropriate repurchase price can coordinate the supply chain [3]. Padmanabhan V *et al.* discussed the applicability of the repurchase contract [4]. Ramanathan R *et al.* assumed that retailers choose inventory and choose their level of effort before determining demand.

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According to exploration, only repurchase contracts cannot ensure reverse coordination of the supply chain. The higher the product repurchase price, the lower the profit of the recycling channel [5]. To investigate the balance between environmental sustainability and supply chain development, Darom N A *et al.* proposed a supply chain recovery model considering carbon emissions and safety stocks. The results show that the optimal safety stock level is significantly affected by the holding cost if the interruption period is short [6].

Besides, in the research on the low-carbon supply chain, Cachon G *et al.* analyzed the density of retail stores and the cost of carbon emissions and concluded that the price of the carbon tax is not an effective method to reduce emissions or to improve energy consumption [7]. As part of the carbon tax, Wei S D *et al.* studied the low-carbon technology R & D competition and cooperation model based on the research and development of upstream and downstream low-carbon technologies to analyze the low-carbon R & D strategy [8]. Rui Z *et al.* used the Olympic theory to study the best emission reduction decisions for companies in voluntary and involuntary emission reduction scenarios [9]. Liu Z *et al* consider the action path, waiting time and personalized characteristics of urban public transport passengers, and make reasonable pricing for different passengers in different stages through model construction [10]. Xu Q *et al* analyze the optimization of supply chain and the impact of demand disruption on O2O supply chain performance through the construction of supply chain model considering online subsidies [11]. Yang J *et al.* analyzes the feasibility of strict environmental policies, and research shows that environmental subsidies are more conducive to achieving sustainable development than restrictive environmental policies [12]. Chen X *et al.* considered carbon tax, studies corporate production policies and incentives for sustainable pricing. Studies have shown that, with the same carbon tax and no carbon tax, the optimal pricing for low-efficiency companies is always higher than for high-efficiency companies [13]. Luo T L and others study the impact of the government's price subsidy strategy on inland waterways of the low-carbon supply chain of bulk cargo [14]. To adapt the price of low-carbon products to the customer's affordability, Taleizadeh A A *et al.* investigated a two-level supply chain composed of a retailer and a manufacturer and analyzed the supply chain through two forms of cooperation and non-cooperation. The results show that the profit of the former is always higher than that of the latter [15]. In the construction industry, some researchers also analyzed from the perspective of the supply chain. Kesidou S *et al.* proposed that we should start from the perspective of the supply chain, optimize the energy structure of the construction industry, and achieve low-carbon construction work [16]. In addition to exploring the traditional fossil fuel supply chain, Diaz-Trujillo L A *et al.* proposed a new model called the ''biogas supply chain''. A feasibility analysis was conducted using Mexico as an example. From the perspective of economic and environmental benefits, it was found that, with the promotion of carbon tax and carbon trading systems, a higher input-output ratio can be achieved by investing in biogas projects [17]. What's easier to overlook is that Kondo R *et al.* considered the carbon leakage caused by the different carbon prices of different countries [18].

Benjaaafar S *et al.* incorporated carbon emissions into the supply chain system and establishes strict carbon restrictions and carbon tax models [19]. Rosič and Jammernegg discussed transport emissions and profits in dual-channel procurement based on the Newsboy model and found that carbon trade policies are higher than carbon tax policies in dual-source procurement [20]. Bo Li *et al.* used the Stackelberg model to analyze the pricing strategies of supply chain members in both centralized and decentralized situations [21]. Liu X *et al.* proposed a histogram of oriented gradient feature and the support vector machine (HOG-SVM) model is used for multi-scale detection [22]. Gautier L discussed the impact of product differentiation on optimal decisions in the Cournot model. Studies have shown that when subsidies and emission reduction technologies exist, increased product differentiation can enable governments to withstand tax increases [23]. Kuo T C *et al.* use a supply chain network design to analyze the trade-off between carbon emission and cost. The results show that the two goals of reducing carbon emission and cost can be achieved at the same time [24]. Chelly A *et al.* proposed that when solving the problem of low-carbon supply chain management, we need to include external constraints such as environmental constraints into the mathematical model for analysis [25].

For data processing, Wang J *et al.* proposed a method that can ensure that released data will not compromise individual privacy, and improve the utility of released data simultaneously [26]. From the view of applied technology, Zhu R *et al.* proposes ERDT (Energy-efficient reliable decision transmission) that enables to increase of correct decision probability and reduces energy consumption [27]. Tseng S H *et al.* investigated how to balance the relationship between total cost and carbon emissions by combining the JIT system with ILOG CPLEX12.4 in two different return vehicle transportation scenarios [28]. In the field of alternative energy, Cerniauskas S *et al.* studied how to apply cost-competitive hydrogen energy to the transportation and industrial fields [29]. In addition, Many manufacturers and retailers are now keen to use the green supply chain services provided by third-party logistics companies. How to improve the sustainable development ability of the third-party logistics company's supply chain becomes crucial. Jamali M B *et al.* used a game theory approach to study the important role of third-party logistics in the supply chain to reduce carbon emissions [30]. Regarding edge computing, Liu X *et al.* utilized the advantages of single-layer clusters and multi-layer clusters to build an HDC model. The results of simulation experiments using the HDC model showed that the model helps optimize network performance and extend network life [22]. Not only that, they proposed a spectrum access algorithm for SUs and simulated it in the Cournot model.

Simulation results showed that Sus can use licensed spectrum dynamically and efficiently [31]. Huang Z H *et al* propose a multimodal representation learning-based model to deal with the challenges of heterogeneous and multi-modal project description information [32]. Chen Z J *et al* propose a method to understand the abnormal trajectories of pedestrian by using an improved sparse representation model [33]. In order to fully understand the preferences of the group and better predict the next preference item of the group, Z. H. Huang *et al* propose a multi-attention based group recommendation model, and confirmed the feasibility of the method through a large number of experiments [34]. In order to realize navigation strategy selection in the inland traffic separation scheme, B. Wu *et al* propose an intelligent decision-making method based on fuzzy logic by considering the dynamic characteristics of ship navigation, which can be used in other fields [35].

In summary, there are many types of research on the performance of low-carbon supply chain and repurchase contracts. However, in the case of the carbon tax, from the perspective of the entire supply chain, both the backlog of surplus products at the end of the season and the recycling of waste products are considered. And low-carbon subsidy research is rare. For this reason, from the above point of view, this article studies the optimal repurchase rate of the remaining products at the end of the season under the carbon tax, the waste product recycling subsidies, and the optimal production and ordering decisions of manufacturers and retailers when subsidizing corporate technology upgrades. In the case of supply chain coordination, how to implement the manufacturer's optimal repurchase strategy and recovery/technology research and development subsidy optimization strategy to analyze the optimal relationship between the carbon tax and carbon emissions and the reduction effect of the carbon tax, etc. This has important research significance for enterprises to achieve low-carbon goals and improve efficiency.

The innovations of this paper are as follows: (1) In the research method, the edge computing method is used to process and analyze the data in real-time, low cost and fast, to achieve the best matching of requirements and methods with higher application program and operation efficiency. (2) From the perspective of the research, taking the optimal decision-making of the supply chain of producers and retailers as a reference, we make centralized and decentralized decision-making under the carbon tax constraints, and analyze and compare the repurchase contract, subsidy policy and repurchase consideration under the carbon tax constraints. (3) The result shows that, compared with subsidy policy, repurchase contracts can coordinate supply chain under decentralized decision-making more effectively, and the corresponding profits are greater than the subsidy strategy; The joint repurchase and subsidy strategy can achieve the coordination of the decentralized decision-making supply chain, and the profit of producers, retailers and the total profits of the system under decentralized decision-making are greater than those of single subsidy strategy, but the total profit of the supply chain system under centralized decision-making is smaller than the single subsidy strategy.

The remainder of this paper is organized as follows: the hypothesis and basic decision-making model under the constraint of the carbon tax will be introduced in Section 2. Experimental results will be presented in Section 3 and Conclusions will be drawn in the last section.

II. HYPOTHESIS AND BASIC DECISION MODEL UNDER THE CONSTRAINT OF CARBON TAX

A. BASIC DECISION MODEL OF SUPPLY CHAIN UNDER CARBON TAX CONSTRAINT

The carbon tax is a tax levied on the emission of carbon dioxide by enterprises. Through carbon tax collection, companies can be urged to continuously increase low-carbon emission reduction and reduce carbon dioxide emissions. This section discusses a supply chain consisting of a manufacturer and a retailer under the carbon tax constraint, which is the optimal decision-making problem for the supply chain.

When producers and retailers make centralized decisions, the goals of both parties are the same, and the total supply chain profit is maximized by deciding the optimal order quantity. For this reason, assume that the market random demand is x, the probability density function of market demand is $f(\cdot)$, the probability accumulation distribution function is $F(\cdot)$, unit production cost is c, unit retail price is p, unit Handled Prices for Products Not Sold at the End of the Season, the residual value is v, meets $v < c < p$, unit carbon tax is s. According to related research [36], unit carbon tax and unit carbon emissions e are linear relationship. So assume $s = \lambda e$, among them, the tax rate per unit of carbon emissions. This article only considers the tax situation of manufacturers, because compared to retailers, manufacturers have more carbon emissions during the production process meets $v < c + s < p$, and then the expected profit function of the supply chain system under centralized decision-making is:

$$\begin{aligned} E\left[\prod(Q)\right] &= \int_0^Q [(p-c-s)x-(c+s-v)(Q-x)]f(x)dx \\ &\quad + \int_Q^{\infty}(p-c-s)Qf(x)dx \\ &= (p-c-s)Q \\ &\quad +(p-v)\int_0^Q xf(x)dx-(p-v)\int_0^Q Qf(x)dx \end{aligned} \quad (1)$$

About the above profit about order quantity Q find the first derivative, and make it equal to 0, the optimal order quantity of the retailer under centralized decision-making is: $Q = F^{-1}(\frac{p-c_M-s}{p-v})$

When manufacturers and retailers adopt decentralized decision-making, the goal of both parties is to maximize their profits. At this time, the manufacturer first determines the unit wholesale price w, the retailer then determines its optimized order volume Q, and meets $v < c < w < p$, the wholesale price of manufacturers here is affected by the carbon tax. The higher the carbon tax, the higher the wholesale price, obviously, and $w(s)$ meets $v < c + s < w < p$.

For retailers, the expected profit is related to the market demand. If the demand is less than the order quantity ($x < Q$), products not sold at the end of the season will be treated as residual value v, the corresponding retailer's expected profit function is:

$$\begin{aligned} E\left[\prod\nolimits_R (Q, w(s))\right] &= \int_0^Q [(p-w)x - (w-v)(Q-x)]f(x)dx \\ &\quad + \int_Q^\infty (p-w)Qf(x)dx \\ &= (p-w)Q + (p-v)\int_0^Q xf(x)dx - (p-v)\int_0^Q Qf(x)dx \end{aligned} \tag{2}$$

Find the first-order partial derivative Q of the above formula on order quantity, and make it equal to 0, get the retailer's optimal order quantity as: $Q^* = F^{-1}(\frac{p-w(s)}{p-v})$, back to the above formula, you can get the optimal profit of the retailer.

Manufacturer's profit depends on the retailer's optimal order volume Q^* and carbon tax s, its optimal profit is:

$$\prod\nolimits_M (Q^*, s) = (w(s) - c - s)Q^* \tag{3}$$

The optimal total profit of the supply chain system under decentralized decision-making is equal to the sum of the optimal profits of manufacturers and retailers, that is:

$$\prod\nolimits_{SC} (Q^*, s) = \prod\nolimits_M (Q^*, s) + \prod\nolimits_R (Q^*, w(s)) \tag{4}$$

In summary, when there is no incentive mechanism between members of the supply chain under the carbon tax constraint, the retailer's order quantity is affected by the wholesale price, retail price, and residual value. As the wholesale price increases, the order quantity gradually decreases, but the higher the price, the higher the carbon tax, so the carbon tax has a negative correlation with the retailer's order volume.

Derive the best profit of the above-mentioned retailers and manufacturers on the wholesale price and carbon tax respectively, will get $\frac{\partial \prod_R (Q^*, w(s))}{\partial w(s)} < 0$ and $\frac{\partial \prod_M (Q^*, s)}{\partial s} < 0$, explain that under the carbon tax constraint, the retailer's profit is negatively related to the wholesale price. Further, since the wholesale price is positively related to the carbon tax, it is negatively related to the carbon tax. Producer profits are also negatively related to carbon taxes. Besides, the profit is known as $w - c - s < 0$, that is, the production cost or carbon tax is too high. When the producer is not profitable, the producer will not produce at this time, so it is assumed $w > c - s$.

B. SUPPLY CHAIN OPTIMIZATION DECISION CONSIDERING REPURCHASE CONTRACTS

The repurchase contract refers to the manufacturer's repurchase of products that have not been sold out at the end of the season. The contract has a very wide application in supply chain practice, which can effectively reduce the double marginalization effect of supply chain members and increase profits for supply chain members. This section considers the introduction of repurchase contracts based on the carbon tax constraints of the previous section. Suppose the manufacturer repurchases the unsold product at the repurchase price b, the repurchased products are not resold. To ensure the validity of the repurchase contract, presume $v \leq b \leq w$. Also considers the manufacturers and retailers to take centralized and decentralized decisions, respectively, and conduct the following analysis:

The expected total profit function of the supply chain system under centralized decision-making is:

$$\begin{aligned} E\left[\prod\nolimits^B (Q)\right] &= (p-c-s)Q + p\int_0^Q xf(x)dx - p\int_0^Q Qf(x)dx \end{aligned} \tag{5}$$

Find the first-order partial derivative of the above formula on the order quantity Q, and let it be equal to 0, find the optimal order quantity of the retailer is: $Q = F^{-1}(\frac{p-c-s}{p})$.

The retailer's expected profit function under decentralized decision is:

$$\begin{aligned} E\left[\prod\nolimits_R^B (Q, w(s))\right] &= \int_0^Q [(p-w)x - (w-b)(Q-x)]f(x)dx \\ &\quad + \int_Q^\infty (p-w)Qf(x)dx \\ &= (p-w)Q + (p-b)\int_0^Q xf(x)dx \\ &\quad -(p-b)\int_0^Q Qf(x)dx \end{aligned} \tag{6}$$

Find the optimal order quantity for the retailer to obtain the maximum expected profit under the decentralized supply chain under the repurchase contract $Q^* = F^{-1}(\frac{p-w(s)}{p-b})$, back to the above formula to get the optimal expected profit of the retailer $E[\prod_R^B (Q^*, w(s))]$.

At this time, the maximum expected a profit of the producer when there is a repurchase contract under the carbon tax constraint is:

$$E\left[\prod\nolimits_M^B (Q^*, s)\right] = (w-c-s)Q^* - b\int_0^{Q^*} F(x)dx \tag{7}$$

Then, the maximum expected a total profit of the supply chain system under decentralized decision making when there is a repurchase contract is the sum of the above two profits:

$$E\left[\prod_{SC}^{B}(Q^*,s)\right] = E\left[\prod_{M}^{B}(Q^*,s)\right] + E\left[\prod_{R}^{B}(Q^*,w(s))\right] \tag{8}$$

Obviously, under the carbon tax constraint, when producers implement repurchase contracts for the remaining products at the end of the season, to achieve supply chain coordination, the optimal order quantity under centralized decision-making must be equal to the optimal order quantity under decentralized, that is:

$$F^{-1}(\frac{p-c-s}{p}) = F^{-1}(\frac{p-w(s)}{p-b}) \tag{9}$$

The optimal repurchase price reached by the supply chain system when the repurchase contract is implemented under the constraints of the carbon tax available from the above formula is:

$$b = \frac{p(w(s)-c-s)}{p-c-s} \tag{10}$$

It can be seen that when a repurchase contract is set up under the carbon tax constraint, the manufacturer's repurchase price is affected by the retail price, wholesale price, carbon tax, and production cost, which meets $b = \frac{p(w(s)-c-s)}{p-c-s}$, supply chains can be coordinated.

C. SUPPLY CHAIN OPTIMIZATION DECISION CONSIDERING SUBSIDY POLICY

Subsidy policies under the carbon tax constraint include government or related agencies subsidizing enterprises' emission reduction R & D or technological transformation and upgrading, and subsidies for recycling and reuse of waste products by enterprises. This situation refers to the manufacturer is committed to the upgrading of low-carbon technologies to reduce the carbon emissions in the production of products, for which the government has given certain preferential policies. Assume that the carbon emissions per unit of product produced by the manufacturer e_0 are, after adopting low-carbon emission reduction technology, the carbon emission reduction per unit product is $e < e_0$. According to related researchers such as Y. H. Cheng [37], assuming that the corresponding one-time input cost of R & D / technical transformation is $c_s = k(e_0 - e)^2$, including the cost of developing or purchasing energy-saving and low-carbon technologies and process equipment, where k is the abatement cost factor. The government subsidizes its costs, and the subsidy rate is β, the carbon tax is $s = \lambda e$, still discussing in two cases. First, the expected profit function of the supply chain system under centralized decision-making is as follows:

$$\begin{aligned}E\left[\prod^{S}(Q)\right] &= (p-v)\int_0^Q xf(x)dx - (p-v)\int_0^Q Qf(x)dx \\ &\quad +(p-c-s)Q - c_s + \beta \\ &= (p-v)\int_0^Q xf(x)dx - (p-v)\int_0^Q Qf(x)dx \\ &\quad +(p-c-s)Q - k(e_0-e)^2(1-\beta)\end{aligned} \tag{11}$$

Determine the retailer's optimal order quantity as: $Q = F^{-1}(\frac{p-c-s}{p-v})$.

Under decentralized decision making, the retailer's expected profit function is:

$$\begin{aligned}E\left[\prod_{R}^{S}(Q,w(s))\right] &= (p-w)Q + (p-v)\int_0^Q xf(x)dx \\ &\quad -(p-v)\int_0^Q Qf(x)dx\end{aligned} \tag{12}$$

Similarly, the optimal order quantity is $Q^* = F^{-1}(\frac{p-w(s)}{p-v})$, back to get the optimal expected profit of the retailer.

The optimal expected profit for available producers is:

$$E\left[\prod_{M}^{S}(Q^*,s)\right] = (w(s)-c-s)Q^* - k(e_0-e)^2(1-\beta) \tag{13}$$

It is further obtained that the total expected profit of the supply chain under this situation is:

$$E\left[\prod_{SC}^{S}(Q^*,s)\right] = E\left[\prod_{R}^{S}(Q^*,w(s))\right] + E\left[\prod_{M}^{S}(Q^*,s)\right] \tag{14}$$

D. SUPPLY CHAIN OPTIMIZATION DECISION CONSIDERING JOINT REPURCHASE AND SUBSIDY STRATEGY

If the combination of the repurchase contract and subsidy policy is considered under the carbon tax constraint, the supply chain decision-making optimization model under centralized and decentralized decisions is constructed as follows:

The expected profit function of the supply chain system under centralized decision-making is:

$$\begin{aligned}E\left[\prod^{BS}(Q)\right] &= (p-c-s)Q - (1-\beta)c_s \\ &\quad +p\int_0^Q xf(x)dx - p\int_0^Q Qf(x)dx\end{aligned} \tag{15}$$

Finding the optimal order quantity under centralized decision-making is: $Q = F^{-1}(\frac{p-c-s}{p})$.

First, the retailer's expected profit function under decentralized decision-making is as follows:

$$\begin{aligned}E\left[\prod_{R}^{BS}(Q,w(s))\right] &= (p-w)Q + (p-b)\int_0^Q xf(x)dx \\ &\quad -(p-b)\int_0^Q Qf(x)dx\end{aligned} \tag{16}$$

TABLE 1. Supply chain benefits only considering carbon tax.

λ	s	w	Q	Π_R	Π_M	Π_{SC}	Π
0.1	1.5	301.5	2496.2	495503.6	374436.0	869939.6	1029095.4
0.2	3	303	2492.5	491018.5	373872.0	864890.4	1022213.6
0.3	4.5	304.5	2488.7	486544.5	373307.8	859852.3	1015400.1
0.4	6	306	2485.0	482081.6	372743.5	854825.1	1008651.9

Similarly, the optimal order quantity at this time can be obtained: $Q^* = F^{-1}(\frac{p-w(s)}{p-b})$.

The corresponding manufacturer's optimal expected profit is:

$$E\left[\prod\nolimits_M^{BS}(Q^*, s)\right] = (w(s) - c - s)Q^* - (1-\beta)c_s - b\int_0^{Q^*} F(x)dx \quad (17)$$

At this time, the profit of the supply chain system is the sum of the profits of the retailer and the producer. With this joint incentive strategy, if the supply chain system can achieve coordination, the total profit of the distributed supply chain system is equal to the total profit of the centralized supply chain system. The corresponding optimal repurchase price is calculated $b = \frac{p(w(s)-c-s)}{p-c-s}$.

III. EXPERIMENTAL RESULTS

A. SIMULATION ANALYSIS OF BASIC DECISION MODEL OF SUPPLY CHAIN

Further, we use an example to more intuitively analyze the impact of the carbon tax on supply chain-related profits. Suppose that the market demand for a certain fresh product obeys the normal distribution. Demand average μ is 2500, standard deviate σ is 400, wholesale prices w are the function of the carbon tax s, the retail price p is 500 RMB, and the residual value of unsold products at the end of the season v is 100 RMB. The producer's production costs c are 150 RMB, the carbon tax rate λ value range is 0.1-0.4, and the step size is 0.1. Corresponding to the carbon tax, wholesale price, and optimal order quantity, and put the above parameters into the corresponding profit formula, using NORMDIST function of Excel can find the profits of all parties (as shown in Table 1), of which unit carbon emissions e calculated according to British Environmental Resources Management Corporation. Assume that the fresh product is calculated based on carbon emission of 15 kg per unit.

It can be seen from Figure 1 that when the unit carbon emission of the product is constant, the impact of changes in the carbon tax rate λ on retailers and producers' profits. With the increase λ in, the profits of both the retailer and the producer are decreasing. At the same time, the decline in the retailer's profit is smaller than that of the producer. It shows that the carbon tax plays a restrictive role in reducing emissions, but in the case of a carbon tax only, the retailer

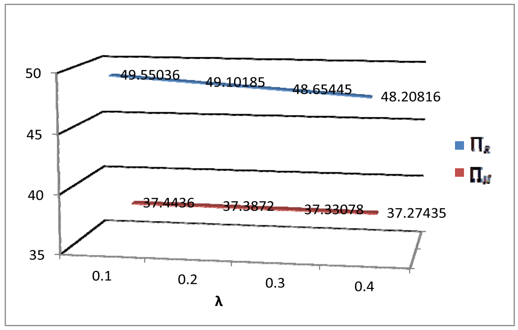

FIGURE 1. Impact of carbon tax rate on retailer profits and producer profits.

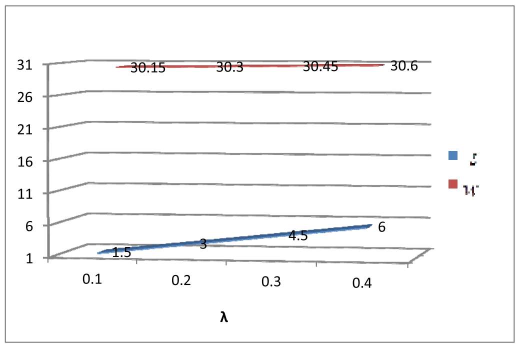

FIGURE 2. Impact of carbon tax rate on carbon tax cost and wholesale price.

is worried that the carbon tax cost of the producer will be transferred to the wholesale price, and he is unwilling to place more orders. Therefore, it is necessary to further consider the supply chain incentives, so that the supply chain is as coordinated as possible under the constraints of carbon taxes.

It can be seen from Figure 2 that when the carbon emissions per unit of the product are constant, the change in the carbon tax rate λ has an impact on the cost of the carbon tax and the wholesale price. As λ increases, both the carbon tax cost and wholesale price show a linear upward trend. The increase in the carbon tax rate means that producers spend more money on reducing emissions, and the cost of carbon taxes increases, so the standard for wholesale prices given to retailers has also increased. At the same time, we can also observe that with the increase of the carbon tax rate, the wholesale price increase of manufacturers is smaller than that under the linear relationship between the carbon tax rate and carbon emissions. Therefore, when there is no incentive

TABLE 2. Supply chain benefits considering repurchase contracts under carbon tax constraints.

λ	s	w	b	Q	Π_R	Π_M	Π_{SC}	Π
0.1	1.5	301.5	215.2	2706.3	537203.8	405947.5	943151.3	943151.3
0.2	3	303	216.1	2702.9	532469.0	405433.2	937902.2	937902.2
0.3	4.5	304.5	217.1	2699.5	527747.3	404921.2	932668.5	932668.5
0.4	6	306	218.0	2696.1	523038.7	404411.4	927450.0	927450.0

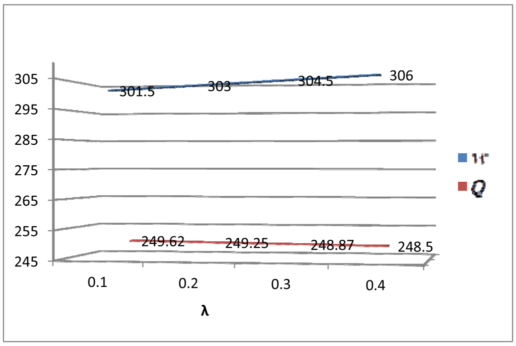

FIGURE 3. Impact of tax rate on wholesale price and order volume.

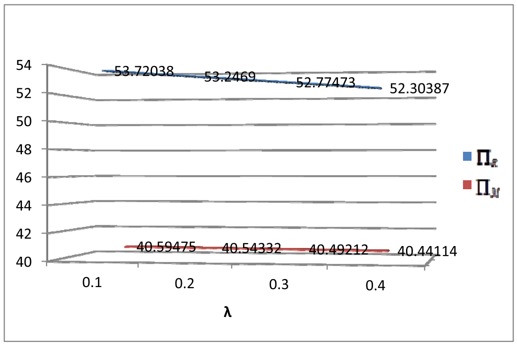

FIGURE 4. Impact of carbon tax rate on retailer profits and producer profits.

mechanism, the pure carbon tax policy makes producers bear more carbon tax cost risks. When having to pay carbon taxes, producers are more willing to linearly set carbon tax rates.

As can be seen from Figure 3, when the carbon emission per unit of the product is constant, the change in the carbon tax rate λ affects the wholesale price and order quantity. With the increase of λ, the wholesale price is on the rise, the order quantity is on the decline, the carbon tax rate is increased, and the manufacturers invest funds to reduce emissions, and the increase in product costs leads to the rise of the retailer wholesale price, so the market demand decreases and the order quantity decreases. At the same time, it has been observed that the decline in the retailer's order volume is larger in a linear relationship between carbon tax rates and carbon emissions than in a non-linear relationship. Therefore, when carbon taxes have to be paid, retailers are more willing to non-linearly tax rate.

B. SIMULATION ANALYSIS OF SUPPLY CHAIN OPTIMIZATION DECISION CONSIDERING REPURCHASE CONTRACTS

An example analysis of the above discussion is given below. The relevant values of the parameters in the example above are calculated. According to the profit expression in this section, Table 2 is calculated:

Figure 4 illustrates the impact of changes in the carbon tax rate λ on the profits of retailers and producers when the carbon emissions per unit of a product are constant. With the increase of λ, the profits of retailers and producers are decreasing. The increase in the carbon tax rate leads to an increase in emission reduction costs, which also affects the profits of both parties. By comparing with Figure 1, it can be seen that for manufacturers, although there is a repurchase cost, the wholesale price increases, and the profit of the manufacturer increases compared to when there is no repurchase contract; Although the wholesale price has increased, the repurchase price has made up for the loss, and the retailer's profit has increased compared to when there was no repurchase contract.

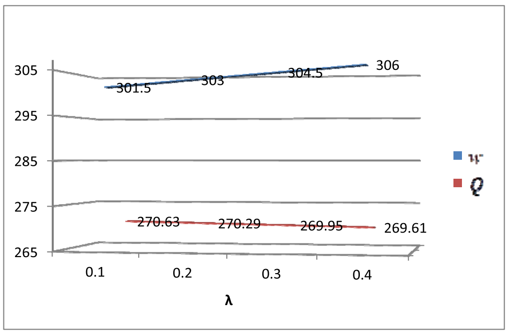

FIGURE 5. Impact of carbon tax rate on wholesale price and order volume.

Figure 5 illustrates the impact of changes in the carbon tax rate λ on wholesale prices and production (order quantity) when the carbon emissions per unit of a product are constant. With the increase in the carbon tax rate, the wholesale price is increasing and the production volume is decreasing. Regardless of the linear or non-linear relationship between the carbon tax cost and the unit carbon emissions, as the carbon tax rate increases, the carbon tax cost will inevitably increase, so the wholesale price will increase accordingly, and the order quantity will decrease accordingly. However,

TABLE 3. Benefit of supply chain considering technological transformation subsidy strategies under carbon tax constraints.

λ	s	w	Q	Π_R	Π_M	Π_{SC}	Π
0.1	1	301	2497.5	497001.2	374374.0	871375.2	1031155.1
0.2	2	302	2495.0	494007.3	373998.0	868005.3	1026543.6
0.3	3	303	2492.5	491018.5	373622.0	864640.4	1021963.6
0.4	4	304	2490.0	488034.6	373245.9	861280.5	1017413.9

TABLE 4. Benefits of supply chain considering joint repurchase and subsidy strategy under carbon tax constraint.

λ	s	w	b	Q	Π_R	Π_M	Π_{SC}	Π
0.1	1	301	214.9	2707.5	538785.1	405869.4	944654.5	944654.5
0.2	2	302	215.5	2705.2	535624.1	405525.8	941149.9	941149.9
0.3	3	303	216.1	2702.9	532469.0	405183.2	937652.2	937652.2
0.4	4	304	216.8	2700.6	529319.7	404841.6	934161.4	934161.4

by comparing it with Figure 3, we can find that due to the repurchase contract, the reduction in order quantity is smaller than that under the simple carbon tax policy.

By comparing Tables 1 and 2, we find that the total supply chain profits are relatively large when there are repurchase contracts, and when the repurchase price meets certain conditions, the supply chain can be coordinated, but the carbon tax rate has limited the growth of profits in general. Although it has played a role in reducing emissions, if it blindly relies on the constraints of the carbon tax for industries with high carbon emissions and small profit margins, it will bring higher burdens on enterprises, thereby restricting the industry's development. Therefore, it is necessary to consider the research and development of new materials upstream of the supply chain, the transformation of new technologies, and the recycling of waste products. This can reduce carbon emissions while offsetting the increase in costs brought by carbon taxes.

Besides, comparing Table 1, it can be found that the total profit of the supply chain system under centralized decision-making under the consideration of the repurchase contract under the carbon tax constraint has decreased, but the profits of manufacturers and retailers corresponding to decentralized decision-making have increased. It is a very interesting phenomenon, so for the supply chain under centralized decision-making, no contract is needed to avoid reducing profits, and for the supply chain under decentralized decision-making, contracts are needed to achieve member coordination and maximize profits.

C. SIMULATION ANALYSIS OF SUPPLY CHAIN OPTIMIZATION DECISION CONSIDERING SUBSIDY POLICY

We use examples to analyze the impact of the carbon tax on supply chain performance under low-carbon subsidy policies. It is known that the carbon emission of fresh products produced by fresh produce producers is 15 kg, after adopting low-carbon technology transformation and upgrading, the carbon emission reduction per unit of fresh products is 10kg. The abatement cost factor $k = 20$, government subsidy rate $\beta = 0.5$, the other parameters have the same values as in section 1. Known carbon tax rate λ the value from 0.1until 0.4, the step size is 0.1. According to the model in this section can be obtained as shown in Table 3. According to Table 3, as the tax rebate rate increases, the carbon tax increases, and the wholesale price of producers, the retailer's order volume and profit are in a decreasing mode. This is obvious. Therefore, to reduce the carbon tax, manufacturers need to increase carbon technology investment can reduce carbon emissions, which in turn can reduce carbon taxes, but this will inevitably increase the cost of emissions reduction and affect profits, so it is necessary to grasp a reasonable scale. Besides, it is not difficult to find that the total profit of the supply chain under decentralized decision-making is smaller than that of centralized decision-making. It can be seen that subsidy policies cannot enable decentralized systems to achieve coordination. Further strategies need to be selected to achieve supply chain coordination and maximize profits. Comparing to Table 2, it can be seen that compared to subsidy policies, repurchase contracts can more effectively implement decentralized decision-making supply chain coordination, and the corresponding profits are greater than the subsidy strategy.

D. SIMULATION ANALYSIS OF SUPPLY CHAIN OPTIMIZATION DECISION CONSIDERING JOINT REPURCHASE AND SUBSIDY STRATEGY

We further analyze the example, the parameter values are the same as in the previous sections, and the supply chain benefits under the joint repurchase and subsidy strategy are calculated, as shown in Table 4. Comparing Table 4 and Table 3, it can be seen that the joint repurchase and subsidy strategy can realize the coordination of decentralized decision-making supply chain, and the profits of producers and retailers and the total profit of the system under decentralized decision-making are greater than the single subsidy strategy, but concentrated the total profit of the supply chain system is lower than the single subsidy strategy.

IV. CONCLUSION

Under the carbon tax constraints, supply chain profits and the interests of members will be affected. In this article, the supply chain optimization decision-making of manufacturers and retailers under carbon tax constraints is taken as a reference, and the supply chain optimization decision-making and subsidy joint strategy under three circumstances are analyzed and compared: repurchase contract, subsidy policy and repurchase consideration under carbon tax constraints. Studies have shown that the total profit of the supply chain system under centralized decision-making under the consideration of carbon tax constraints under the repurchase contract is reduced, but the decentralized decision-making is the opposite. Therefore, no contract is needed for the supply chain under centralized decision-making to avoid lowering profits. For the supply chain under decentralized decision-making, contracts are needed to achieve member coordination and maximize profits. Considering the subsidy policy, the total profit of the supply chain under decentralized decision-making is smaller than that of centralized decision-making. Therefore, compared to subsidy policies, repurchase contracts can coordinate supply chain under decentralized decision-making more effectively, and the corresponding profits are greater than the subsidy strategy; The joint repurchase and subsidy strategy can achieve the coordination of the decentralized decision-making supply chain, and the profit of producers, retailers and the total profits of the system under decentralized decision-making are greater than those under single subsidy strategy, but the total profit of the supply chain system under centralized decision-making is less than that under single subsidy strategy.

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