Non-cooperative Game and Cooperative Operation of Multi-level Supply Chain under Background of Carbon Emission Reduction

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ABSTRACT In the context of global efforts to develop low-carbon economy and curb the growth of fossil energy, it is particularly important for supply chain enterprises to make scientific decisions on emission reduction and energy conservation. This paper investigates supply chain enterprises to make emission reduction decisions by considering cost-benefit of carbon emission reduction and internal and external factors changes. We analyze the dynamic game model of a three-level supply chain consisting of suppliers, manufacturers, and retailers in cooperative and non-cooperative states. The change of optimal emission reduction is calculated by differential game and dynamic analysis. The optimal profit is obtained from the corresponding optimal decision of enterprises, and the optimal proportion of manufacturers’ share of emission reduction cost is studied. We adopt numerical simulation method to simulate decision-making evolution process of emission reduction. Finally, the impact of different influencing factors on product emission reductions, supply chain decisions and profits are shown. These findings can provide theoretical support and reference for multi-level supply chain decision-making.

INDEX TERMS Carbon emission reduction, Multi-level supply chain, Non-cooperative game, Cooperation operation, Optimal profit.

I. INTRODUCTION

The great pressure of global warming and greenhouse gas emissions highlight the importance of low carbon supply chain management. Understanding these trends is central to the design of current and future climate change mitigation policies, requiring up-to-date methodologically robust emission inventories [1]. Since the use of fossil fuels and the emission of greenhouse gases have increased with the increase of various industries and transportations around the world. Environmental pollution and climate change have become very important global issues in nearly a century. As a result, the governments all over the world are paying particular attention to these issues and have tried different policies to encourage producers to produce at lower emissions. To improve ecological environment and promote sustainable development of economy, many countries have put forward the low-carbon development strategies including low-carbon economy, industry, technology and consumption. For example, Chinese President Xi Jinping attended the Leaders’ Climate Summit (LCS) (April 22, 2021) and declared that China will strive to achieve carbon peak by 2030 and carbon neutral by 2060. A lot of research achievements have shown that low-carbon awareness of producers and consumers is increasing obviously under the appealing and guide of governmental policies and public opinions.

Some scholars discussed and studied carbon emission reduction and control from the perspective of participants and emission reduction differences. Considering uncertain demand and production costs for more compatibility with
the real world industries, a robust approach was proposed by Rahmania et al. [2] to discuss the expression of the model in order to overcome the uncertain parameters. By opening up carbon emission trading market, Cao et al. [3] investigated the government’s role in allocating the appropriate emission quota to maximize social participant’ utilities and analyzed the emission-dependent enterprise revenues through supply chain collaboration. As an impact factor of low-carbon strategy adoption, the government subsidies were introduced. The emission reduction performance for supply chain members in both single-channel and exclusive dual-channel cases were investigated [4-5]. Some researchers investigated manufacturer and retailer decision under decentralized decision and centralized decision and taking into account the impact of carbon price, inventory related costs, recovery times and conscious decisions [6-7]. Xiang et al. [8] proposed differential game models for the joint carbon emission reduction in a three-echelon supply chain. The dynamic equilibrium strategy and optimal emission reduction track were obtained. Jiang et al. [9] adopted differential game method to construct a dynamic carbon emission reduction decision model of a three-echelon supply chain. From the above analysis, it can be seen that there are many researchers who have achieved a lot of results on supply chain emission reduction, which has laid a solid foundation and provided a specific direction for the future investigations [10-15]. Especially, evolutionary game models for carbon emission reduction are very popular.

Based on above research background, this paper highlights the different influences of government’s emission reduction cost control and internal and external environmental impacts on manufacturers, suppliers and retailers. In order to grasp the key feature of dynamic carbon emission reduction process, the differential game equation is adopted in the proposed models. We will discuss the following several problems: (1) how does emission reduction cost control in supply chain in non-cooperative mode and cooperative mode? (2) How can work joint emission reduction and optimal strategies? (3) How does analyze internal and external environmental impacts on manufacturers, suppliers and retailers?

To solve these puzzles, we propose an improved model with consideration on the government’s emission reduction cost control, internal and external environmental impacts on manufacturers, suppliers and retailers. Our work contributes to the relevant studies in the following three aspects. (1) We consider the government’s emission reduction cost control and internal and external environmental impacts on manufacturers, suppliers and retailers in an inter-organizational setting. The internal and external impacts are two different strategies for manufacturers, suppliers and retailers. Those components need to make choice according to their different goals. However, many previous studies neglected these factors. (2) The relationship of manufacturers, suppliers and retailers are more prominent and important. It considers that the influence of manufacturers will share part of the abatement costs of suppliers and retailers to motivate them to take the initiative to reduce emissions. Previous work did not emphasize this enough. (3) It integrates both joint emission reduction and optimal strategies into the proposed model in centralized and decentralized systems from dynamic perspective. The specific cooperative relationship proposed in this paper can be conducive for the manufacturer to perform lead role and motivate other parts in global view.

The remainder of this paper is arranged as follows. In section II, we investigate the combined impact of the efforts on total carbon emissions of supply chain considering internal and external factors. Section III discusses and tests non-cooperative decision-making strategy and cooperative decision-making strategy. The numerical simulation is performed to demonstrate theoretical results. Finally, section IV presents conclusions and summarizes the work.

II. LITERATURE REVIEW

A. SUPPLY CHAIN COOPERATIVE EMISSION REDUCTION

In supply chain cooperative emission reduction, some researchers integrated multiple disciplines into realize multidisciplinary cooperative emission reduction. The cooperative emission reduction studied by scholars not only restrict to order cycle time, quantity, cost and yield, but also the production, emission reduction technology and new business modes. What is more, cooperative style could be extended to the delivery process, the location of suppliers, and the selection of suitable partners [16-18]. Considering emission responsibility-allocation, Gopalakrishnan et al. [19] adopted a cooperative game-theory methodology to derive a footprint-balanced scheme for reapportioning the total carbon emissions amongst the firms in supply chain. An evolutionary game model for suppliers and manufacturers was developed by Zhi et al. [20], which represents the attempt to investigate collaborative carbon emission reduction within supply chains. The investigation of multiple factors deepened understanding of the collaborative role required for the carbon emission reduction. Considering the carbon tax policies and government subsidies, supply chain game model is established and the contract forms and parameters are given according to coordination condition [21]. Zu et al. [22] adopted the differential method to study the Stackelberg game between a manufacturer and a supplier in four situations. Especially, they provided theoretical insights to the optimal control of low-carbon production in cooperative situation.

In order to explore the impact of consumers’ reference low-carbon effect and product low-carbon goodwill on the balanced emission reduction decisions and profit of dual-channel supply chain members, a dual-channel supply chain
emission reduction dynamic optimization model was established. By using differential game theory to solve the manufacturer’s optimal emission reduction investment and the retailer’s optimal low-carbon publicity investment strategies under four different decision scenarios [23].

It can be seen from the above literature that the current research by using differential game theory to solve the manufacturer’s optimal emission reduction. But few studies have involved the comprehensive integration of government’s emission reduction cost control and internal and external environmental impacts on manufacturers, suppliers and retailers. The low-carbon economy mature, low-carbon concepts and cooperation of multiple supply chain participants have become increasingly prominent. In addition, more and more traditional suppliers, manufacturers and retailers have realized that joining forces to achieve carbon reduction is good for industry development and social responsibility. It is very necessary to discuss the issue of joint emission reduction cost control and internal and external environmental impacts on manufacturers, suppliers and retailers in an inter-organizational setting. Considering the shortcomings of previous studies and based on the actual situation, we think there still exists some work to be done.

B. CARBON EMISSIONS ALLOCATION AND ABATEMENT COSTS

An important research direction of carbon emission reduction is the allocation of carbon emissions and abatement costs. With the consideration of carbon-tax policy and consumers’ low-carbon preferences, the pricing, emission reducing and advertising decisions in three different games were compared [24]. A dual-channel supply chain emission reduction and low carbon promotion strategy is studied considering brand differences [25]. He et al. [26] adopted option contract to study the retailer’s optimal retail price and order quantity, as well as the manufacturer’s optimal ratio of total carbon emission abatement and production quantity under the carbon tax considering uncertain market demand. In order to reduce carbon emissions, cap and trade policy, Jiang and Chen investigated the optimal production, pricing, carbon trading, and green technology investment strategies of the low carbon supply chain [27]. Considering service provider and service integrator, three differential game models was established to explore the optimal decisions and identify the conditions [28]. Based on the data of industrial carbon emissions in 30 provinces of China from 2008 to 2016, the impact of carbon emission trading system on carbon emission reduction and economic growth of enterprises is empirically tested [29]. Wu et al. [30] investigated marginal abatement cost of agricultural carbon emissions in China (1993-2015) to provide a reference emission right price and guidance to make use of cropping structure adjustment and optimization for exploring the emission reduction strategy.

Tan et al. [31] integrated the multi-index method and zero-sum gains-data envelopment analysis model to obtain provincial carbon emission quota allocation scheme in China from the perspective of abatement cost and regional cooperation.

In addition, multi-level supply chain strategy of carbon emission is the subject of extensive attention and research. He et al. [32] considered a dual-channel closed-loop supply chain through an independent retailer and sell remanufactured products via a third-party firm or platform in the presence of possible government subsidy. This research studied channel structure and pricing decisions for the manufacturer and government’s subsidy policy with competing new and remanufactured products. Reference [33] contended with the joint emission reduction and pricing decision problems, as well as coordination contract design issue for a class of two-echelon low-carbon supply chain system. The dyadic supply chain system consisting of manufacturer and retailer or production inventory system were discussed, which considered the influence of consumers’ low-carbon preferences on random variable demand and the impact of uncertainty on carbon emission-reduction behavior [34]. Through numerical analysis and case study, the validity and feasibility of the viewpoint are verified.

On the basis of above reviewed literature, carbon emissions allocation and abatement costs have been widely concerned. What is more, multi supply chain strategies of carbon emission have attracted many scholars’ interest. However, the carbon emission abatement target among supply chain members (manufacturers, suppliers and retailers) has not yet been studied adequately. To fill the gap, this paper investigates supply chain enterprises to make emission reduction decisions by integrating joint emission reduction cost control and internal and external environmental impacts on manufacturers, suppliers and retailers in an inter-organizational setting. We analyze the dynamic game model of a three-level supply chain consisting of suppliers, manufacturers, and retailers in cooperative and non-cooperative states. The impact of different influencing factors on product emission reductions, supply chain decisions and profits are shown. These results can provide theoretical support and reference for multi-level supply chain decision-making.

III. METHODOLOGY

In this section, we investigate the combined impact of the efforts on total carbon emissions of whole supply chain considering internal and external factors. Meanwhile, we can’t ignore carbon emission limitation and examines the differential game and coordination of emission reduction in three-level supply chain consisting of suppliers, manufacturers and retailers. Therefore, let’s make some assumptions:
(1) $C_s$ and $C_M$ denote the abatement cost of suppliers and manufacturers. As the abatement effort gradually increases, the speed of $C_s$ and $C_M$ gradually increases. That is, the following condition is satisfied $C'_s(E_s(t)) > 0, C'_M(E_M(t)) > 0, C''_s(E_s(t)) > 0, C''_M(E_M(t)) > 0$. According to the prior studies, a quadratic cost function is considered [20-21], [35]. So we can assume that the abatement cost is

$$C_s = \frac{1}{2}(k_{s_1} + k_{s_2})E_s^2(t)$$

and

$$C_M = \frac{1}{2}(k_{M_1} + k_{M_2})E_M^2(t)$$

Where $k_{s_1}, k_{s_2}$ denotes the influence coefficient of supplier on abatement cost. $k_{M_1}, k_{M_2}$ denotes the influence coefficient of manufacturer on abatement cost.

(2) $C_R$ denotes the retailer’s promotional costs. As low-carbon promotional efforts rise gradually, the speed of $C_R$ gradually increases. That is, it meets $C'_R(E_R(t)) > 0, C''_R(E_R(t)) > 0$. It can be assumed that the retailer’s low-carbon promotional costs:

$$C_R = \frac{1}{2}(k_{R_1} + k_{R_2})E_R^2(t)$$

where $k_{R_1}, k_{R_2}$ denotes the coefficient of influence of the retailer’s internal operation and external environment on abatement cost.

(3) From the perspective of final emission reduction, the degree of effort of suppliers and manufacturers will directly affect the carbon emissions [22]. So it can be assumed that $\beta_s$ and $\beta_m$ denote the coefficient of their respective efforts on emission reduction. $\lambda$ denotes the natural decay of product emission reduction. We assume that the increase rate is proportional to emission reduction of suppliers and manufacturers and the decrease rate is proportional to the natural decay of product emission reduction. So, the differential equation of emission reduction process can be obtained as:

$$\dot{x}(t) = \beta_s E_s(t) + \beta_m E_m(t) - \lambda x(t)$$

According to the model of [22], a linear market demand function is assumed in our paper. There is linear relationship between the market demand and the total amount of carbon emission reduction and retailer promotion, that is,

$$D(x(t), E_s(t), E_M(t), E_R(t)) = \mu + \eta x(t) + \varepsilon E_s(t) + \delta E_m(t) + \omega E_R(t)$$

where $\mu > 0$ is the product demand if nothing is done to reduce emissions; $\eta > 0$ represent the impact of emission reductions. $\varepsilon > 0, \delta > 0, \omega > 0$ are represent the impact of supplier’s effort, retailer promotion and manufacturer’s on emission reduction, respectively.

(5) In order to reduce the abatement costs of suppliers and retailers and to motivate them to take the initiative to reduce emissions, manufacturers will share part of the abatement costs of suppliers and retailers $0 < \theta(t) < 1, 0 < \sigma(t) < 1$.

(6) We assume that the discount rates of manufacturers, suppliers and retailers are identical $\rho(\rho > 0)$. The objective function maximizes profits as time becomes infinitely long.

### A. NON-COOPERATIVE DECISION-MAKING STRATEGY

The following is the set-up: The manufacturer $M$, as the core company in the supply chain, acts as the leader in the supply chain. The supplier $S$ and retailer $R$ act as the followers. In the long-term cooperation, three parties strengthen the vertical alliance and increase the intensity of joint emission reduction and the promotion of low-carbon products. The manufacturer $M$ also pays attention to the emission reduction investment of supplier $S$ and the promotion of retailer $R$. In the meantime, it shares a certain proportion of the costs for the upstream and downstream. The construction method refer to the References [20-22], [32-34]. Therefore, the decisions of three parties are proposed as.

$$J_s(x, t) = \int_0^\infty e^{-\rho t}[\pi_s D(x(t), E_s(t), E_M(t), E_R(t)]$$

$$-1/2(1-\theta)(k_{s_1} + k_{s_2})E_s^2(t)\,dt$$

$$J_m(x, t) = \int_0^\infty e^{-\rho t}[\pi_m D(x(t), E_s(t), E_M(t), E_R(t)]$$

$$-1/2(k_{M_1} + k_{M_2})E_m^2(t) - 1/2\theta(k_{s_1} + k_{s_2})E_s^2(t)\,dt$$

$$J_R(x, t) = \int_0^\infty e^{-\rho t}[\pi_r D(x(t), E_s(t), E_M(t), E_R(t)]$$

$$-1/2(1-\sigma)(k_{R_1} + k_{R_2})E_R^2(t)\,dt$$

Eq. (6) represents the supplier’s optimal decision when considering its own emission reduction and the retailer’s optimal decision when considering its own publicity. Eq. (7) indicates that the manufacturer determines its own abatement effort based on supplier and retailer decisions, as well as the proportion of abatement cost. Eq. (8) represents the optimal strategy of the retailer. Thus, it is derived that the optimal profit problem for the supplier as time $t$ varies as:

$$J'_s(x, t) = e^{-\rho t_1} \max_{E_s} \int_t^{t_1} e^{-\rho(t+s)}[\pi_s D(x(t), E_s(t), E_M(t), E_R(t))$$

$$ - 1/2(1-\theta)(k_{s_1} + k_{s_2})E_s^2(t)]ds$$

$$J'_m(x, t) = e^{-\rho t_1} \max_{E_m} \int_t^{t_1} e^{-\rho(t+s)}[\pi_m D(x(t), E_s(t), E_M(t), E_R(t))$$

$$ - 1/2(1-\sigma)(k_{R_1} + k_{R_2})E_R^2(t)]ds$$

$$J'_R(x, t) = e^{-\rho t_1} \max_{E_R} \int_t^{t_1} e^{-\rho(t+s)}[\pi_r D(x(t), E_s(t), E_M(t), E_R(t))$$

$$ - 1/2(1-\sigma)(k_{R_1} + k_{R_2})E_R^2(t)]ds$$

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Then, supplier’s carbon emission reduction problem becomes as:

\[
J^*_s(x,t) = e^{-\theta(t)}V^*_s(x)
\]  \hspace{1cm} (10)

\[
V^*_s(x)
\]  for any \( x \geq 0 \) must satisfy the Hamilton-Jacobi-Bellman (HJB) equation.

\[
\rho V^*_s(x) = \max_{\pi_s} [\pi_s [\mu + \eta x(t) + \varepsilon E^s_s(t) + \delta E^s_E(t) + \sigma E^s_M(t)]]
\]

\[
-1/2(1-\theta)(k_{s_1} + k_{s_2})E^2_s(t) + V^*_s(x)[\beta_s E^s_E(t) + \beta_M E^s_M(t) - \lambda x(t)]
\]  \hspace{1cm} (11)

By taking the first-order partial derivative of \( E^*_s(t) \) in Eq. (11) and making it zero, we get

\[
E^*_s = \frac{\pi_s \varepsilon + V^*_s(x)\beta_s}{(1-\theta)(k_{s_1} + k_{s_2})}
\]  \hspace{1cm} (12)

Similarly, the optimal problem of carbon reduction by retailers can be transformed into

\[
J^*_p(x,t) = e^{-\rho(t)}V^*_p(x)
\]  \hspace{1cm} (13)

\[
V^*_p(x)
\]  must satisfy HJB equation for any \( x \geq 0 \):

\[
\rho V^*_p(x) = \max_{\pi_p} [\pi_p [\mu + \eta x(t) + \varepsilon E^p_s(t) + \delta E^p_E(t) + \sigma E^p_M(t)]]
\]

\[
+\omega E^*_p(t)[\beta_s E^p_E(t) + \beta_M E^p_M(t) - \lambda x(t)]
\]  \hspace{1cm} (14)

The first-order partial derivative of \( E^*_p(t) \) on the right-hand side of the Eq. (14) is zero, which yields

\[
E^*_p = \frac{\pi_p \omega}{(1-\sigma)(k_{p_1} + k_{p_2})}
\]  \hspace{1cm} (15)

Denote the optimal price function of the manufacturer’s profit at time \( t \) as

\[
J^*_m(x,t) = e^{-\theta(t)}V^*_m(x)
\]  \hspace{1cm} (16)

\[
V^*_m(x)
\]  must satisfy HJB equation for any \( x \geq 0 \):

\[
\rho V^*_m(x) = \max_{\pi_m} [\pi_m [\mu + \eta x(t) + \varepsilon E^m_s(t) + \delta E^m_E(t) + \sigma E^m_M(t)]]
\]

\[
-1/2(1-\theta)(k_{m_1} + k_{m_2})E^2_m(t) + V^*_m(x)[\beta_s E^m_E(t) + \beta_M E^m_M(t) - \lambda x(t)]
\]  \hspace{1cm} (17)

Substituting Eq. (12) and (15) into (17), we make the first-order partial derivative of \( E^*_m, \theta, \sigma \) respectively. We get

\[
E^*_m(t) = \frac{\pi_m \omega + V^*_m(x)\beta_m}{(k_{m_1} + k_{m_2})}
\]

\[
\theta = \frac{(2\pi_m - \pi_s)\varepsilon + (2V^*_m(x) - V^*_s(x))\beta_s}{(2\pi_m + \pi_s)\varepsilon + (2V^*_m(x) + V^*_s(x))\beta_s}
\]  \hspace{1cm} (18)

\[
\sigma = \frac{2\pi_m - \pi_R}{2\pi_m + \pi_R}
\]

Substituting Eq. (18) into (11), (14) and (17), we rearrange

\[
\rho V^*_s(x) = \pi_s [\mu + \eta x(t) + \frac{\delta^2(2\pi_m + \pi_R)}{2(k_{s_1} + k_{s_2})}]
\]

\[
+\frac{\pi_s \varepsilon + V^*_s(x)\beta_s}{4(k_{s_1} + k_{s_2})}[(2\pi_m + \pi_s)\varepsilon + (2V^*_m(x) + V^*_s(x))\beta_s]
\]  \hspace{1cm} (19)

\[
+\frac{\pi_s \omega + V^*_s(x)\beta_m}{(k_{m_1} + k_{m_2})}[V^*_m(x)\beta_m + \pi_s \omega] - V^*_s(x)\lambda x(t)
\]

\[
\rho V^*_p(x) = \pi_p [\mu + \eta x(t) + \frac{\delta^2(2\pi_m + \pi_R)}{2(k_{p_1} + k_{p_2})}]
\]

\[
+\frac{(V^*_p(x)\beta_s + \pi_p \varepsilon)}{2(k_{p_1} + k_{p_2})} [(2\pi_m + \pi_s)\varepsilon + (2V^*_m(x) + V^*_s(x))\beta_s]
\]  \hspace{1cm} (20)

\[
\rho V^*_m(x) = \pi_m [\mu + \eta x(t) + \frac{\delta^2(4\pi_m^2 - \pi_R^2)}{8(k_{m_1} + k_{m_2})}]
\]

\[
+\frac{(2\pi_m + \pi_s)\varepsilon + (2V^*_m(x) + V^*_s(x))\beta_s}{8(k_{m_1} + k_{m_2})} - V^*_m(x)\lambda x(t)
\]  \hspace{1cm} (21)

The characteristics of the equations can be inferred from Eqs. (19)-(21). Assuming that the solution of HJB equation is a linear function with respect to \( x \).

\[
V^*_s(x) = a_s x + b_s
\]

\[
V^*_p(x) = a_p x + b_p
\]  \hspace{1cm} (22)

\[
V^*_m(x) = a_m x + b_m
\]

We substitute Eq. (22) into Eqs. (19)-(21) and organize them, and solve the terms on both sides of the equation:
solution of \( x(t) \) can be found. So, the equation for the change of production abatement is obtained as:

\[
\dot{x}(t) = \left( x_0 + \frac{B}{A} \right) e^{\lambda t} - \frac{B}{A} \tag{27}
\]

Substituting Eq. (23) into Eqs. (10), (13) and (16), the optimal profits of suppliers, manufacturers and retailers can be obtained as:

\[
J_S^*(x,t) = e^{-\lambda t} \left( a_1^* x + b_1^* \right)
\]

\[
J_R^*(x,t) = e^{-\lambda t} \left( a_2^* x + b_2^* \right)
\]

\[
J_M^*(x,t) = e^{-\lambda t} \left( a_3^* x + b_3^* \right)
\]

In the non-cooperative state, suppliers, manufacturers and retailers make their respective abatement decisions as:

1. The optimal trajectory of carbon emission reduction with time \( t \) in Eq. (26).
2. The equilibrium strategy of suppliers, manufacturers and retailers reach a relatively stable and optimal state when total carbon emissions of whole supply chain in Eq. (24).
3. The optimal profit for each of the supplier, manufacturer and retailer is described in Eq. (28).

Based on the above analysis, we can draw some results. Firstly, the manufacturer’s optimal carbon emission in the whole supply chain is obtained in non-cooperative case. The manufacturer can adjust and coordinate production plan according to different emissions in order to improve the control of total emissions. Secondly, the carbon emission targets of suppliers and retailers are calculated according to the changes of manufacturer’s carbon emissions. In addition, we calculate the ratio of manufacturer’s share of supplier’s and retailer’s costs in order to promote the reduction of emissions throughout supply chain. And the ratio is closely related to the profits of the supplier, manufacturer and retailer. In summary, non-cooperative decision-making strategy shows that in the long term, supply chain companies need to adjust their decisions to achieve their optimal emission reductions.

B COOPERATIVE DECISION-MAKING STRATEGY

In cooperative state, the companies in whole supply chain make decisions centrally. The level of emission reduction of different companies is the main object of decision making. We assume that the discount rates of the companies in the supply chain are the same. In order to maximize total profit of whole supply chain in a longer period of time, the profit optimization problem for supplier at time \( t \) can be classified as:

\[
x(t) = e^{\int_0^t A dt} \left( \int_0^t B e^{\lambda s} ds + C \right)
\]

where \( C \) denotes a constant. Since the abatement at the very beginning of the supply chain \( x(t) = x(0) \geq 0 \), the special
The first-order partial derivative of $E_M, E_s, E_R$ for the right-hand side of HJB equation gives:

$$
E_s = \frac{\left(\pi_M + \pi_s + \pi_R\right) e + V'(x)\beta_s}{(k_s + k_{s1})},
$$

$$
E_M = \frac{\left(\pi_M + \pi_s + \pi_R\right) \omega + V'(x)\beta_M}{(k_M + k_{M1})},
$$

$$
E_R = \frac{\left(\pi_M + \pi_s + \pi_R\right) \delta}{(k_R + k_{R1})}.
$$

Substituting Eq. (32) into (31) to organize:

$$
\rho V^{CO}_S(x) = \max \left\{ \frac{\left(\pi_M + \pi_s + \pi_R\right) \mu + \left(\pi_M + \pi_s + \pi_R\right) \delta^2}{\left(k_M + k_{M1}\right)} + \left(\pi_M + \pi_s + \pi_R\right)e \psi V'(x)\beta_s + \left(\pi_M + \pi_s + \pi_R\right) \omega + \omega V'(x)\beta_M + \frac{\beta_s e}{k_s + k_{s1}} + \frac{\beta_M \omega}{k_M + k_{M1}} + \frac{\delta}{k_R + k_{R1}} \right\}
$$

Let’s assume the expression of this equation,

$$
V^CO_S(x) = a_s x + b_s
$$

Substituting Eq. (34) into (33), we get

$$
\rho(a_s x + b_s) = \left(\frac{\left(\pi_M + \pi_s + \pi_R\right) \mu + \left(\pi_M + \pi_s + \pi_R\right) \delta^2}{\left(k_M + k_{M1}\right)} + \left(\pi_M + \pi_s + \pi_R\right)e \psi V'(x)\beta_s + \left(\pi_M + \pi_s + \pi_R\right) \omega + \omega V'(x)\beta_M + \frac{\beta_s e}{k_s + k_{s1}} + \frac{\beta_M \omega}{k_M + k_{M1}} + \frac{\delta}{k_R + k_{R1}} \right)
$$

We get the formula and the expression for the solution,

$$
a_s = \frac{\left(\pi_M + \pi_s + \pi_R\right) \eta}{\rho + \lambda},
$$

$$
b_s = \frac{\left(\pi_M + \pi_s + \pi_R\right) \mu + \left(\pi_M + \pi_s + \pi_R\right) \delta^2}{\left(k_M + k_{M1}\right)} + \left(\pi_M + \pi_s + \pi_R\right)e \psi V'(x)\beta_s + \left(\pi_M + \pi_s + \pi_R\right) \omega + \omega V'(x)\beta_M + \frac{\beta_s e}{k_s + k_{s1}} + \frac{\beta_M \omega}{k_M + k_{M1}} + \frac{\delta}{k_R + k_{R1}} \right)
$$

and

$$
V^CO_S(x) = a_s x + b_s
$$

Substituting Eq. (36) into (32), the optimal decision can be obtained as:

$$
E_s = \frac{\left(\pi_M + \pi_s + \pi_R\right) \left(\rho + \lambda\right) e + \eta \beta_s}{(k_s + k_{s1})},
$$

$$
E_M = \frac{\left(\pi_M + \pi_s + \pi_R\right) \left(\rho + \lambda\right) \omega + \omega V'(x)\beta_M}{(k_M + k_{M1})},
$$

$$
E_R = \frac{\left(\pi_M + \pi_s + \pi_R\right) \left(\rho + \lambda\right) \delta}{(k_R + k_{R1})}.
$$

Substituting Eq. (38) into Eq. (4), we get

$$
\dot{x}(t) = -\lambda x + \beta_s \left(\pi_M + \pi_s + \pi_R\right) \left(\rho + \lambda\right) \frac{e + \eta \beta_s}{(k_s + k_{s1})} + \beta_M \left(\pi_M + \pi_s + \pi_R\right) \left(\rho + \lambda\right) \frac{\omega + \beta_M \eta}{(k_M + k_{M1})},
$$

Where set $A = -\lambda$ and
The abatement at the beginning of supply chain is \( x(t) = x(0) \geq 0 \). The special solution of \( x(t) \) can be found, then the equation for the change of production abatement is found.

\[
\dot{x}^{CO}(t) = \left( x_0 + \frac{B^{CO}}{A^{CO}} \right) e^{t\omega} - \frac{B^{CO}}{A^{CO}}
\]

(40)

Substituting Eq. (40) into (37) and (30), the optimal profit can be obtained as:

\[
J^C_{S}(x,t) = e^{\rho t} \left( a^*_S x + b^*_S \right)
\]

(41)

In cooperative state, all three parties in supply chain need to make decisions with reference to total profit of supply chain, which makes the companies in supply chain more closely connected. The total profit of the companies in supply chain increases and total carbon emission decreases significantly. It is important to note that the premise of cooperative emission reduction is that suppliers, manufacturers, and retailers will be more profitable. Otherwise, they will not choose to reduce emissions together.

IV. SIMULATION ANALYSIS

In order to gain insight into the influence of different parameters in emission reductions, this section illustrates the relationship between emission reductions and time \( t \) for different parameters by means of theoretical analysis. The relevant parameter values are set as follows[22], [24].

\[
k_{s_1} = 14; k_{s_1} = 7; k_{m_1} = 10; k_{m_2} = 5;
k_{r_1} = 8; k_{r_2} = 4; \mu = 1000; \eta = 2;\
\delta = 3; \beta_S = 2; \beta_M = 3; \lambda = 1; \pi_S = 4;\
\pi_M = 6; \pi_R = 5; \rho = 0.8; \epsilon = 0.2; x_0 = 0
\]

(42)

The parameters are substituted into the equation for the variation of product emissions with time \( t \) in non-cooperative or cooperative state.

FIGURE 1 is emission reduction change diagram of non-cooperative mode and cooperative mode. Two important trends can be summarized from FIGURE 1.

1) Both curves are steeply rising at the beginning, both cooperative and non-cooperative emission reductions are useful for carbon emission reduction in the short term. With the increase in time, emission reductions of cooperative mode increase faster than non-cooperative mode. Considering the influence of the internal and external environment of the enterprise, emission reductions of cooperative mode stabilize at a higher emission level in the late stage. However, emission reductions of non-cooperative mode do not dominate in long-term process.

2) As time changes, emission reduction of cooperative mode is always higher than that at the time of non-cooperative mode, which clearly shows that emission reductions of cooperative mode is more beneficial to the supply chain to achieve the goal of reducing carbon emissions.
FIGURE 2 is the effect of supplier effort coefficient on emission reductions of non-cooperative mode and cooperative mode. FIGURE 3 is the effect of manufacturer effort coefficient on emission reductions of non-cooperative mode and cooperative mode. FIGURE 4 is the effect of market demand guiding coefficient on emission reductions of non-cooperative mode and cooperative mode. FIGURE 5 is the effect of natural decay rate on emission reductions of non-cooperative mode and cooperative mode. As can be seen from FIGURE 2, the greater the supplier effort coefficient, the more beneficial to improve emission reduction for non-cooperative mode and cooperative mode. Moreover, emission reductions tend to stabilize after a certain period of time. We also know that the emission reduction effect of cooperative mode is much better than that of non-cooperative mode under the same coefficient. For manufacturer effort, something similar can be observed. Comparing with FIGURE 2 and 3, we can see that the greater the efforts of suppliers and manufacturers to reduce emissions, the better the effect of emission reduction will be. But no matter how hard they work, the emission reduction will reach an equilibrium state after a period of time. At this time, it is necessary to promote the external environment to further reduce carbon emissions. In addition, the emission reductions of both suppliers and manufacturers are higher in cooperative mode than in non-cooperative mode. The emission reductions of manufacturers are higher than those of suppliers in both cooperative and non-cooperative mode when increasing the same level of effort. It indicates that manufacturers are the leaders in emission reduction. In other words, the manufacturers’ efforts are more effective in reducing emissions.

The effect of market demand guiding coefficient plays a very critical role shown in FIGURE 4. The greater the coefficient, the greater the efforts made by sellers in promoting emission reductions. It can be seen that with the gradual improvement of consumers’ awareness of environmental protection, more and more consumers are willing to pay more for low-carbon products. And the consumer body of the market takes emission reduction as an important indicator of whether to buy goods. So, low-carbon products are more popular among consumers in the same type of products. The emission reductions will be substantially increased in a period of time, which is conducive to the long-term goal.

The natural decay rate \( \lambda \) of products emission reduction in supply chain refers to the rate of change of emission reduction per unit of time. Shown in FIGURE 5, with the increase of the natural decay rate, the amount of emission reduction is significantly reduced, which indicates that the smaller the natural decay rate, the amount of emission reduction can be maintained in a higher state, which can promote the implementation of long-term emission reduction strategies. Therefore, it can be seen from the effect of the decreasing rate that carbon emission reduction is a long-term process. If the rate of emission reduction change is too large in short term, it is not conducive to emission reduction.
External environment of enterprises is constantly changing, such as government regulations to impose carbon tax on carbon emissions of enterprises. In addition, there will be carbon trading mechanism. The government sets a limit on carbon emissions according to specific regions, and then allocates it to enterprises in the form of quotas or licenses. If the quota is exceeded, it is necessary to buy other enterprises’ credits. However, for internal environment of enterprises, in order to reduce emissions, new technologies need to be upgraded and new methods need to be adopted. Different enterprises attach different levels of importance to carbon emissions reduction.

Therefore, this section will study the trend of emission reduction manufacturers due to the change of their internal and external abatement cost impact coefficients for cooperative mode shown in FIGURE 6. As the emission reduction coefficients become smaller, the greater the manufacturers’ abatement cost, the easier it is to achieve the emission reduction targets set by the enterprises. With the passage of time, the emission reductions have reached an equilibrium state. It can be seen that the impact of changes in the internal and external factors on the emission reduction effect of enterprises in supply chain is significant. For example, within the enterprise, the enterprises improve the processes and innovate new technology to increase the utilization rate of coal combustion, which greatly reduces carbon emissions. Under the influence of external environmental factors and in the case of cooperation, supply chain enterprises can reduce the total emission reduction cost in supply chain by reasonably allocating total carbon emission allowances.

VI. CONCLUSIONS

In this paper, we establish a three-level supply chain emission reduction model including suppliers, manufacturers and retailers in cooperative and non-cooperative mode. We solve the optimal decision problem of suppliers, manufacturers and retailers by using non-cooperative game and cooperative operation. This paper is analyzed and summarized as follows. The product emission reduction in cooperative mode has been higher than the
product emission reduction in non-cooperative mode. The cooperative emission reduction is more beneficial to supply chain to achieve the goal of reducing carbon emissions. Coupled with the influence of internal and external factors of the enterprises, cooperative emission reduction stabilizes at a higher level of emission reductions. However, non-cooperative emission reduction is not dominant. The emission reductions of manufacturers are higher than those of suppliers in both cooperative and non-cooperative mode when increasing the same level of effort. So, the manufacturers are the leaders in emission reduction. In other words, the manufacturer’s efforts are more effective in reducing emissions. The greater the market demand guiding coefficient, the greater the efforts made by retailers in promoting emission reductions. As the natural decay rate increases, the amount of emission reduction decreases significantly. The cooperative operation policy is helpful to build an environment-friendly and resource-conserving supply chain. Further, the enterprises should improve production technology to reduce carbon emission of the unit product. Further, the government guides the enterprises to improve cooperative consciousness. Meanwhile, the customers’ environmental aware of the public should be advocated.

Several tips of future research work are as follows: (1) this paper adds the internal and external factors to abatement cost in model. However, in practice, the internal and external factors are more complex, and the abatement problem for supply chain of enterprises is not only affected by the cost aspect. (2) The profit allocation and multi-lateral coordination need attention. Otherwise, the unbalanced interests of all participants will lead to the failure of the optimization strategy. (3) Participants’ risk attitudes and demand uncertainty are not examined in this research, which would have a significant effect on SC numbers’ optimal decisions.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

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