Investment Game Model Analysis of Emission-Reduction Technology Based on Cost Sharing and Coordination under Cost Subsidy Policy

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Abstract: Climate change and greenhouse gas emission reduction have become common concerns. Carbon trading systems and low-carbon cost subsidies are important emission reduction measures. Impacts of a combination of the two policies on micro-supply chain emission-reduction technology investment have become a focal research area. This paper: (1) constructs an investment game model based on cost-sharing coordination under a cost subsidy between manufacturers and retailers; (2) examines the equilibrium strategy and optimal results according to the interests and game relationships of each stakeholder; and (3) explores the effectiveness of supply chain enterprise behavior based on cost-sharing coordination under the cost subsidy. This paper uses a numerical simulation method to compare the path evolution under different scenarios and to analyze the sensitivity of parameters, identifying the influence of various parameters on the general structure and pathways. The study finds that the cost subsidy policy has a regulatory effect on enterprise emission reduction investment and enterprise profit under a carbon trading system, and the difference caused by the regulation effect is enhanced over time. The study also shows that the dynamic path of each parameter strengthens over time.

Keywords: carbon emission trading system; cost subsidy; investment of emission reduction technology; differential game theory; climate change

1. Introduction

Global warming has emerged as the foremost environmental challenge worldwide. From the Kyoto Protocol in 1997 to the Copenhagen Climate Conference in 2010 and the Paris Agreement in 2016, the international community has begun to focus on various policies to address the issue. Goals include internalizing external costs caused by production, limiting the damage of human beings to the environment, and ultimately, achieving the coordinated development of economies and the environment. To achieve this goal, governments enact laws and regulations such as carbon quota trading, carbon taxes, and carbon quota policies. Governments also actively take measures to promote emission reduction technology. Government commitments to the environment will be transmitted to the production decision-making of enterprises through corresponding carbon control policies.

Economists believe that carbon emission trading policies may be the most effective, and such policies can achieve a "double dividend" effect. Therefore, with the demand for carbon emission-dependent enterprises gradually emerging, countries are exploring the establishment of carbon emission trading markets. As such, it is important to study how carbon emission-dependent enterprises conduct production, operations, and carbon emission reduction investment under a carbon trading policy. With increased consumer awareness of environmental protection, consumers’
low carbon preferences are enhanced. Consumers are willing to buy and pay extra for green low carbon products, and their demand for products is affected by carbon emissions. Low carbon generation of the supply chain has been an important concern. It is emphasized that supply chain enterprises should work together to reduce carbon emissions of supply chains.

Based on the dual background of carbon emission trading and cost subsidies and considering the low-carbon preference of consumers, this paper adopts differential game theory to analyze the relationship among government, manufacturers, retailers, and consumers under cost-sharing coordination from a dynamic perspective. It seeks to obtain an equilibrium strategy and describe pathways of emission reduction, supply chain profit, and social welfare.

The objectives of this paper are to: (1) measure reduction emission, supply chain profits, social welfare, and the cost-sharing ratio; (2) investigate the equilibrium strategy among government, supply chain, and consumers for pathways of emission reduction, profit and social welfare under the cost subsidy; and (3) explore parameter sensitivities to emission reduction through a numerical experiment.

The theoretical importance of this paper related to an in-depth exploration of the cooperation mechanism of supply chain enterprises and the design of emission reduction investment pathways for carbon emission rights, thereby contributing to relevant theories of supply chain enterprise decision-making under environmental regulations. The practical value of the study is to analyze the optimal decision-making pathways of cost-sharing and coordination decision-making under a carbon trading system and cost subsidy policy from a static point of view, to provide theoretical support for technology investment and output decision-making for supply chain enterprises, as well as suggestions for appropriate government design and planning.

2. Literature Review

The Kyoto Protocol was established in 1992, a landmark development in global climate change policymaking [1]. In 2005, the U.S. Environmental Protection Agency applied carbon emission trading to air and river pollution control for the first time, and the European Union also issued carbon trading policies accordingly. In European countries, the contribution of policy and technological changes to energy conservation and greenhouse gas emission reduction have been explored, such as the use of emission trading systems [2]. Also, China has introduced a series of emission reduction measures. The 13th Five-year plan indicates policies of energy conservation, emission reduction, and recycling. However, to achieve long-term development of carbon trading systems, it is necessary to formulate strict system contents and improve implementation procedures [3].

Zeng (2017) applied a DEA model to study the investment efficiency of China’s new energy industry and explained investment efficiency differences among companies and periods [4]. Sun et al. (2018) conducted a systematic review and meta-analysis of the pulp and paper industries and found that the main factor affecting greenhouse gas emissions was energy use [5]. Li et al. (2018) conducted quantitative research on carbon dioxide emissions of the non-ferrous metal industry, and results showed that if the central government of China can adhere to the 13th Five-year plan policy of carbon dioxide emission reduction, emissions of copper, lead, and zinc industries can reach a peak value by 2030 [6]. Zhu and Shan (2020) built a multi-objective optimization model to explore the impact of industrial transformation on energy conservation and emission reduction, and results show that carbon emissions and energy consumption have serious impacts on human beings and ecosystems [7].

Scholars in China and internationally have carried out significant research on carbon emission markets and carbon emission trading systems. Minx systematically analyzed the carbon footprint of supply chains based on an existing multi-region input-output model [8]. Sundarakani built a carbon emission model from dynamic and static points of view and verified it with empirical values. The experimental results showed that carbon emission played an important role in the supply chain [9]. Bian X H summarized relevant issues of carbon emission domestically and abroad [10]. Jaegler
simulated four stakeholders of supply chains under cooperative organization decision-making and studied carbon emissions under different decision-making contexts [11].

Scholars also have focused carbon quotas aimed at further improving the carbon trading market and carbon emission permit system. Park believed a greater impact on the marginal cost of emission reduction is achieved when the carbon quota is high [12]. Lin T and N J F conducted a DEA model to evaluate the fairness of a carbon emission permit quota [13]. Rose discussed the carbon quota under a carbon trading market system [14]. Boemare studied the carbon quota mechanism at the national level [15]. Rehdanz and Tol found that exporters must reduce carbon emissions to maximize benefits [16]. Smale discussed the influence of carbon emission decentralization according to the factors of enterprise economic benefits and market price [17]. Bode found that initial carbon emission permits given to enterprises by the government can improve profits [18]. Bonacinà discussed the impact of carbon trading price on business capacity under a carbon quota mechanism [19]. Wei D pointed out that carbon emission permits directly affect the normal operation of carbon trading markets [20]. Zeng M proposed an auction model of carbon emission permits based on a carbon trading market system [21]. Lee et al. discussed supply chain profit based on a game theory model [22].

Carbon emission distribution focuses on the change of economic benefits such as carbon emission reduction costs. Petrikis et al. studied the optimal subsidy of enterprises with carbon emission reduction [23]. Zhang et al. studied how to achieve optimal carbon trading under the goal of maximizing profit and output of products [24]. Based on the carbon quota trading mechanism, Ma Q Z discussed how to realize price rationalization and profit maximization under a carbon trading system when enterprises consider consumers’ preferences and the free allocation of quotas by the government [25].

Emission reduction technology investment is an important component to achieve coordination and development of a carbon emission supply chain. Zhao D Z et al. established a Stackelberg game model with carbon constraints, primarily considering retailers and manufacturers. The results showed that retailers can always encourage manufacturers to improve the efficiency of emission reduction under carbon emission and carbon trading systems [26]. Targeting sustainable investment in products, Dong considered supply chain emission reduction management under decentralized and centralized decision-making and studied the impact of sustainable investment on optimal solutions [27]. Luo R L established a two-level game model to explore the impact of the carbon footprint sensitivity coefficient, cost coefficient, and carbon emission quota on investment decision-making under uncertain carbon emission market demands [28]. Ji et al. suggested that consumer preferences had a significant impact on the carbon market, and they established a Stackelberg game model based on consumer preference and studied the profit strategy of a single manufacturer and retailer [29].

Li Y D studied carbon emission reduction of low-carbon supply chains and constructed three different game models: Nash game, Stackelberg game and supply chain relationship under centralized decision-making [30]. Liu J and Qiu G B systematically analyzed the impact of the supply chain, sales price, and profit based on the cooperative and non-cooperative game between manufacturers and retailers under a government subsidy policy [31]. Yang S H and Fu J used Stackelberg game theory to establish decentralized decision-making and centralized decision-making game models under the leadership of two-level supply chain manufacturers and studied the optimization and coordination of supply chains under the government’s carbon emission reduction subsidy to consumers [32]. Li analyzed the impact of carbon emissions on three kinds of supply chain profits and carbon emissions. The results showed that the government should only implement carbon subsidies when the recovery price is within a specific range [33].

In general, current research is mainly focused on carbon finance, environmental protection, and other fields based on a macro-perspective, but there is less research on the supply chain emission reduction cooperation area of enterprise decision-making (based on a micro-perspective). Existing research is also mainly on a static view of supply chain internal behavior, without considering the impact of social welfare and environmental benefits. Decision-makers should pay more attention to
the dynamic changes in supply chain emission reduction systems under the carbon trading market and generate corresponding policies.

3. Differential Game Model

3.1. Problem Description

Drawing on and expanding the market demand function model of Gurnani et al. and considering the dual objectives of supply chain revenue and carbon emissions, this paper considers a secondary supply chain, including a manufacturer and a retailer as well as an investment and emission reduction model under government subsidies and consumers’ low carbon preferences. The specific decision-making process is shown in Figure 1.

![Figure 1. Decision diagram.](image)

The following considerations are included:

1. The government determines the carbon quota based on carbon emission intensity and then takes the maximization of social welfare as the goal. The government works with manufacturers to determine the optimal R&D ratio of emission reduction technology.

2. Manufacturers control the carbon emission of products, reduce carbon emissions through emission reduction technology investment, and play a cost-sharing game with retailers.

3. Manufacturers sell products to retailers at wholesale prices.

4. According to market demand, the retailer purchases from the manufacturer, the purchase quantity is Q at the price P. In the process between manufacturer and retailer, the manufacturer has an initial position. Both sides of the game have symmetrical information and they make decisions to maximize their interests.

5. Consumers have a low carbon preference and a relatively high preference for products with low carbon emissions.

6. The paper makes the parameter conventions as shown in Table 1.

| Variable | Description | Variable | Description |
|----------|-------------|----------|-------------|
| P        | product retail price | w        | manufacturer’s wholesale price |
| a        | market size of the product | b        | marginal demand for the product |
| Q_e      | quantity demanded considering consumers’ low carbon desires | Z_M      | emission reduction effort by the manufacturer |
3.2. Model Assumptions

To simplify complex conditions without changing the underlying nature of the problem, the model assumptions are as follows:

**Assumption 1:** This paper assumes that the supply chain consists of two enterprises: an upstream manufacturer and a downstream retailer. By introducing new technologies and transforming production processes, a manufacturer invests in emission reduction technology and reduces carbon emissions during production and use. The government then gives a certain quota based on the enterprises, and the exceeding quota needs to be purchased from society.

**Assumption 2:** Enterprises produce low carbon products. Laroche et al. [42] divided the market demand factors into price factors and non-price factors and considered that the two factors have an impact on market demand through the form of separable multiplication. Other similar functional forms can be found in the literature [43-44]. We assume the price is \( p = a - bq \) (\( a \) is the market size, \( b \) is the marginal demand of the product, \( q \) is quantity demanded), \( E(t) \) is the carbon emission reduction at moment \( t \), and the demand function is expressed as:

\[
Q_E(t) = (a - bp(t))kE(t)
\]  

(1)

Where \( k \) represents the carbon-sensitive coefficient (\( k \geq 0 \) \( \sum kE(t) \geq 1 \)).

**Assumption 3:** Without considering inventory and shortage, the manufacturer’s abatement cost function is the convex function of emission reduction efforts. The abatement cost function draws on the assumption of the innovation cost [45] function, and the manufacturer’s abatement cost at time \( t \) is:

\[
C(Z_M(t)) = \frac{\mu_M}{2} Z_M^2(t)
\]  

(2)

Considering that the government gives part of the subsidies for carbon emission reduction to enterprises, and that is directly proportional to the effort to reduce emissions, then the government subsidies for the carbon emission unit cost of the enterprises:

\[
F(Z_M(t)) = \delta \frac{\mu_M}{2} Z_M^2(t)
\]  

(3)
Where $\tau (\tau \geq 0)$ represents the product subsidy coefficient.

The products subsidized by the government are to enterprises with carbon emission reduction investment. The manufacturer implements investment in emission reduction technology and does not reduce emissions. Therefore, when the manufacturer obtains subsidies for carbon emission reduction products, the profit per unit of the manufacturer’s products is expressed as follows:

$$U_M = w + \tau Z_M(t) - c$$  \hspace{1cm} (4)

**Assumption 4:** The quantity of a product’s emission reduction is used as a state variable, and there is a natural constant depreciation rate for the product’s emission reduction due to equipment aging and old technology. The accumulation equation of emission reduction becomes:

$$\dot{E}(t) = \alpha Z_M(t) - \sigma E(t)$$  \hspace{1cm} (5)

### 3.3. The Basic Expression of Economic Relations

The determinants of carbon trading mainly include the carbon market supply and demand relationship as well as trading environment policies and regulations. For the convenience of measurement, this paper assumes exogenous variables. $E_{MT}(t)$ is the total amount of carbon quota in the carbon market. $E_{MT}(t) < 0$ is the carbon quota that needs to be purchased when it is insufficient, $E_{MT}(t) > 0$ is the value of the surplus carbon profits that are obtained through carbon emission reduction technology investment. Under the carbon emissions trading policy, the government implements a dual-control management system for carbon intensity and total volume. Based on this, this paper assumes the emissions quota set by the government regulations are expressed by $g_M(t)$, which represents the upper limit of the government’s allowance for enterprises’ carbon emissions, and $e_M(t)$ is the level of carbon emissions per unit product without a carbon emission reduction investment. It is assumed here that the unit’s carbon allowance and carbon emissions per unit of product given by the government are constant for a certain period. The carbon emissions trading costs are as follows:

$$E_{MT(t)} = p_M[g_M Q_E(t) - E(t) - e_M Q_E(t)]$$  \hspace{1cm} (6)

The manufacturer and the retailer have a common discount rate $\rho (\rho > 0)$ at all times. For an emission reduction enterprise regulated by government carbon emissions, the manufacturer’s profit function consists of three parts: sales revenue, carbon emission reduction cost, and carbon quota transaction cost. For simplicity, it is not included in the equations that follow.

The profit of the enterprise is in the cost subsidy scenario given by the government. The profit function of manufacturer and retailer in the infinite time domain are:

$$J_M = \int_0^\infty e^{-\rho t} \{(w-c)Q_E - (1-\delta)(1-\xi)\frac{\mu_M}{2}Z_M^2 + p_M(g_M Q_E + E - e_M Q_E)\} \, dt$$  \hspace{1cm} (7)

$$J_R = \int_0^\infty e^{-\rho t} \{(p-w)Q_E - (1-\delta)\xi\frac{\mu_M}{2}Z_M^2\} \, dt$$  \hspace{1cm} (8)

According to the sensitivity of the consumer to low carbon products, the consumer surplus is as follows:

$$Q_E = (a-bp)kE$$  \hspace{1cm} (9)
\[ p(y) = \frac{1}{b} \left( a - \frac{y}{kE} \right) \]  

\[ CS(E) = \int_0^{\infty} p(y) dy - p(Q_E)Q_E = \frac{1}{2bkE}Q_E^2 = \frac{1}{2b}(a - bp)^2kE \]  

When the government gives a carbon emission reduction cost subsidy, social welfare is the sum of producer surplus and consumer surplus minus the government subsidies for low-carbon products. The social welfare function of supply chain emission reduction technology investment can be expressed as:

\[ SW^2(E) = \int_0^\infty e^{-\rho t} \left( (p - c - p_eM + p_eg_M)Q_E - (1 - \delta) \frac{\mu_M}{2}Z_M^2 + p_eE \right) \]

\[ + \frac{1}{2b}(a - bp)^2kE - \delta \frac{\mu_M}{2}Z_M^2 \] \[ dt \]  

3.4. Differential Game Model

The government, manufacturers, and retailers adopt the progressive Stackelberg game. The systematic differential game model is expressed as follows:

\[ \max_{\delta} SW(d; Z_M, w, \xi; p) \]

\[ s.t. \max_{Z_M, w, \xi} J_M(d; Z_M, w, \xi; p); \]

\[ s.t. \max_{p} J_R(d; Z_M, w, \xi; p); \]

\[ E(t) = \alpha Z_M(t) - \sigma E(t). \]  

4. Equilibrium Analysis and Path Evolution

4.1. Equilibrium Results

Under the situation that the government gives carbon emission reduction subsidies to enterprises, retailers maximize their profits in response to government policies and enhance their visibility. First, the government determines the proportion of emission reduction subsidies, and then the retailer determines the cost-sharing proportion. The manufacturer determines emission reduction efforts at different times and the retailer’s pricing based on the sharing proportion.

**Theorem 1**: The equilibrium results of the game are as follows:

\[ \delta = \frac{2(a - bc - bp_eM + bp_eg_M)^2 k + 9bp_e}{5(a - bc - bp_eM + bp_eg_M)^2 k + 18bp_e} \]  

\[ w = \frac{1}{3b} (a + 2bc + 2bp_eM - 2bp_eg_M) \]  

\[ Z_M^* = \frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M} \left( \frac{5}{18} A + p_e \right) \]  

\[ p^* = \frac{1}{3b} (2a + bc + bp_eM - bp_eg_M) \]
\[ \xi^* = \frac{A-9p_e}{5A+18p_e} \]  

**Proof:** In the carbon trading coordination model under the cost subsidy, to get feedback equilibrium, it is assumed that the subsidy rate of emission reduction cost and the cost-sharing proportion of retailers are fixed values. For retailers, according to optimal control theory, any decision-making problem is transformed into the following form:

\[ \rho V_R^s = \max_{p(t)} \{(p-w)(a-bp) - \xi \frac{\mu_M}{2} Z_M^2 + V_R^s(\alpha Z_M - \sigma E)\} \]  

The retailer’s function on the \( p(t) \) for the first derivative is equal to zero, which can be solved as:

\[ p = \frac{a+bw}{2b} \]  

The manufacturer profit function for all \( E \geq 0 \) must satisfy the HJB (Hamilton-Jacobi-Bellman) equation:

\[ \rho V_M^s = \max_{Z_M\geq 0} \{(w-c-p_e e_M + p_e g_M)(a-bp)kE - (1-\delta-\xi) \frac{\mu_M}{2} Z_M^2 \]

\[ + \frac{p_e Z_M}{2} V_M^s(\alpha Z_M - \sigma E)\} \]  

The manufacturer’s function on \( Z_M \) for the first derivative is equal to zero, which can be solved as:

\[ Z_M = \frac{V_M^s \alpha}{(1-\delta-\xi)\mu_M} \]  

The retailer determines an optimal strategy based on the manufacturer’s emission reduction effort, and the emission reduction cost-sharing ratio is:

\[ \xi = \frac{(2 V_R^s - V_M^s)(1-\delta)}{V_M^s + 2 V_R^s} \]  

Substituting, for simplification, the manufacturer’s emission reduction effort is:

\[ Z_M = \frac{(V_M^s + 2 V_R^s)\alpha}{2(1-\delta)\mu_M} \]  

Considering the coordinated decision-making under the cost subsidy, the retailer cooperates with the manufacturer to negotiate the wholesale price \( w-c-p_e e_M + p_e g_M = p-w \), that is, the marginal profit of the manufacturer and retailer is equal.
\[
\begin{align*}
w &= \frac{1}{3b} (a + 2bc + 2bp_e e_M - 2bp_e g_M) \\
\text{Assuming the linear expression of the optimal value function is:} \\
V_M' &= x_{23} E + x_{24} \\
V_R' &= y_{23} E + y_{24}
\end{align*}
\]

Where \( x_{23}, x_{24}, y_{23}, y_{24} \) are constants, and substituting the first partial derivative of the value function to \( E \) into Formula (26), the results are as follows:

\[
\begin{align*}
x_{23} &= \frac{1}{\rho + \sigma} \left[ \frac{1}{9b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right] \\
x_{24} &= \frac{1}{\rho} \frac{x_{23} (x_{23} + 2 y_{23}) \alpha^2}{4u_M (1 - \delta)} \\
y_{23} &= \frac{1}{\rho + \sigma} \frac{1}{9b} (a - bc - bp_e e_M + bp_e g_M)^2 k \\
y_{24} &= \frac{1}{\rho} \frac{(x_{23} + 2 y_{23})^2 \alpha^2}{8u_M (1 - \delta)}
\end{align*}
\]

Calculating the social welfare function, and solving:

\[
\begin{align*}
\rho V_{SW}' &= \max_{s \geq 0} \left\{ (p - c - p_e e_M + p_e g_M)(a - bp)kE - (1 - \delta) \frac{\mu_M}{2} Z_M^2 + p_e E \\
&+ \frac{1}{2b} (a - bp)^2 kE - \delta \frac{\mu_M}{2} Z_M^2 + V_{SW}'(\alpha Z_M - \sigma E) \right\}
\end{align*}
\]

The social welfare function on subsidy rate \( \delta \) for the first derivative is equal to zero, and the social subsidy rate given by the government to enterprises can be obtained:

\[
\delta = \frac{2V_{SW}' - V_{M}' - 2V_{R}'}{2V_{SW}'}
\]

Assuming the linear expression of the social welfare optimal value function is:

\[
V_{SW}' = g_{23} E + g_{24}
\]

Similarly, substituting the derivative of the social welfare function to \( E \) into Formula (33):

\[
\begin{align*}
g_{23} &= \frac{1}{\rho + \sigma} \left[ \frac{1}{18b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right] \\
g_{24} &= \frac{1}{\rho} \frac{g_{23}^2 \alpha^2}{2\mu_M}
\end{align*}
\]

The subsidy rate given by the government to carbon emission enterprises can be simplified:

\[
\delta = \frac{2(a - bc - bp_e e_M + bp_e g_M)^2 k + 9bp_e}{5(a - bc - bp_e e_M + bp_e g_M)^2 k + 18bp_e}
\]
The retailer emission reduction cost-sharing ratio is:
\[ \xi^* = \frac{(a - bc - kp_e e_M + bp_e g_M)^2 k - 9bp_e}{5(a - bc - bp_e e_M + bp_e g_M)^2 k + 18bp_e} \]  
(36)

The manufacturer’s emission reduction effort is:
\[ Z^*_M = \frac{1}{\rho + \sigma} \alpha \left[ \frac{5}{18b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right] \]  
(37)

Assuming \[ A = \frac{1}{b} (a - bc - bp_e e_M + bp_e g_M)^2 k \] and solving, the manufacturer’s emission reduction effort, the retailer product pricing, and the retailer’s emission reduction cost-sharing ratio are:
\[ Z^*_M = \frac{1}{\rho + \sigma} \alpha \left[ \frac{5}{18} A + p_e \right] \]  
(38)

\[ p^* = \frac{1}{3b} (2a + bc + bp_e e_M - bp_e g_M) \]  
(39)

\[ \xi^* = \frac{A - 9p_e}{5A + 18p_e} \]  
(40)

4.2. Evolution Path Analysis

**Theorem 2:** Under the coordinated decision-making based on the cost subsidy, the trajectories of carbon emissions, manufacturer’s and retailer’s profits, and social welfare optimal value concerning time are:
\[ E(t)^* = e^{-\sigma t} E_0 + \frac{\alpha^2}{\mu_M} \frac{1}{\sigma (\rho + \sigma)} \left[ \frac{5}{18} A + p_e \right] (1 - e^{-\sigma t}) \]  
(41)

\[ J_M(t)^* = \frac{1}{\rho + \sigma} \alpha^2 u_M \left( \frac{5}{18} A + p_e \right) \frac{1}{\sigma} \left[ 1 - e^{-\sigma t} \right] + \frac{1}{2\rho} \]  
(42)

\[ J_R(t)^* = \frac{1}{\rho + \sigma} \alpha^2 u_M \left( \frac{5}{18} A + p_e \right) \frac{1}{\sigma} \left[ 1 - e^{-\sigma t} \right] + \frac{1}{3\rho} \left( A + p_e \right) \frac{1}{4\rho} \]  
(43)

\[ J_T(t)^* = \frac{1}{\rho + \sigma} \alpha^2 u_M \left( \frac{5}{18} A + p_e \right) \frac{1}{\sigma} \left[ 1 - e^{-\sigma t} \right] + \frac{1}{3\rho} \left( A + p_e \right) \frac{1}{4\rho} \]  
(44)

\[ SW(t)^* = \frac{1}{\rho + \sigma} \alpha^2 u_M \left( \frac{5}{18} A + p_e \right)^2 \frac{1}{\sigma} \left[ 1 - e^{-\sigma t} \right] + \frac{1}{2\rho} \]  
(45)

\( E2^{S*} \) is the product carbon emission reduction. \( J2^{S*}_M, J2^{S*}_R, J2^{S*}_T, SW2^{S*} \) are manufacturer, retailer, supply chain profit, and social welfare optimal values, respectively.

**Proof:** According to the three HJB equations, the manufacturer’s profit, retailer’s profit, and social welfare optimal value are:
\[ V_M = x_{23} E + x_{24} \]  
(46)
\[ V_R = y_{23}^*E + y_{24}^* \]  
\[ V_T = h_{23}^*E + h_{24}^* \]  
\[ V_{SW} = g_{23}^*E + g_{24}^* \]  
\[ x_{23}^* = \frac{1}{\rho + \sigma} \left( \frac{1}{9} A + p_c \right) \]  
\[ x_{24}^* = \frac{1}{\rho} \left[ \frac{1}{\rho} (\rho + \sigma)^2 \frac{1}{2} \left( \frac{A}{9} + p_c \right) \left( \frac{5}{18} A + p_c \right) \right] \]  
\[ y_{23}^* = \frac{1}{\rho} \left( \frac{1}{3} \right) \left( \frac{5}{18} A + p_c \right) \]  
\[ y_{24}^* = \frac{1}{\rho} \left[ \frac{1}{\rho} (\rho + \sigma)^2 u_M \left( \frac{5}{36} A + \frac{3}{4} p_c \right) \right] \]  
\[ h_{23}^* = \frac{1}{\rho + \sigma} \left( \frac{2}{9} A + p_c \right) \]  
\[ h_{24}^* = \frac{1}{\rho} \left[ \frac{1}{\rho} (\rho + \sigma)^2 \frac{1}{2} \left( \frac{5}{18} A + p_c \right)^2 \right] \]  
\[ g_{23}^* = \frac{1}{\rho + \sigma} \left( \frac{5}{18} A + p_c \right) \]  
\[ g_{24}^* = \frac{1}{\rho} \left[ \frac{1}{\rho} (\rho + \sigma)^2 \frac{5}{18} \left( \frac{5}{18} A + p_c \right) \right] \]  

Under the coordinated decision-making of cost subsidy emission reduction technology investment, \( x_{23}^* \) \( y_{23}^* \) \( h_{23}^* \) \( g_{23}^* \) represent manufacturer, retailer, supply chain profit, and social welfare, respectively. As a function of carbon emission reduction, \( x_{24}^* \) \( y_{24}^* \) \( h_{24}^* \) \( g_{24}^* \) represent the initial value of manufacturer, retailer, supply chain profit, and social welfare, respectively, when the enterprise does not invest in emission reduction technology.

Under the coordinated decision-making of the cost subsidy, substituting the manufacturer’s emission reduction effort into the carbon emission reduction dynamic equation and solving:

\[ E(t) = \frac{1}{\rho + \sigma} \frac{\alpha^2}{\mu_M} \left[ \frac{5}{18b} (a - bc - bp_c e_M + bp_c g_M)^2 k + p_c \right] - \sigma E(t) \]  

The trajectory of the carbon emission reduction dynamic is:

\[ E^S(t) = \frac{1}{\sigma (\rho + \sigma)} \frac{\alpha^2}{\mu_M} \left[ \frac{5}{18b} (a - bc - bp_c e_M + bp_c g_M)^2 k + p_c \right] (1 - e^{-\sigma t}) \]  

Similarly, when substituting the carbon emission into the equation, we can obtain the manufacturer’s long-term profits, the retailer’s long-term profits, and the optimal value function of the social welfare dynamic.
5. Parameter Sensitivity Analysis

5.1. Boundary Condition Determination

According to the actual situation of the carbon emission reduction trading market under the cost subsidy, parameters are subject to:

\[ \rho \geq \sigma \]  
\[ 0 \leq c + p_e e_M - p_e g_M \leq w \leq \frac{a}{b} \]  

That is:

\[ 0 \leq A \]  

For the stable development of the carbon trading market, the marginal profit per unit of manufacturer and retailer’s carbon emission should be greater than the profit of purchasing the carbon quota in the carbon trading market:

\[(w - c - p_e e_M + p_e g_M)(a - bp)kE \geq p_e E \]  
\[(p - w)(a - bp)kE \geq p_e E \]  

Under the cost subsidy decentralized decision-making:

\[ w = \frac{1}{2b}(a + bc + bp_e e_M - bp_e g_M), \quad p = \frac{1}{4b}(3a + bc + bp_e e_M - bp_e g_M) \]  

The marginal profit is greater than the carbon trading profit under the cost subsidy:

\[ \frac{1}{16b}(a - bc - bp_e e_M + bp_e g_M)k \leq p_e \]  

That is:

\[ 16p_e \leq A \]  

5.2. Sensitivity Analysis

The consumer’s low carbon preference coefficient is \( k \), the manufacturer’s emission reduction efforts influence-coefficient is \( \alpha \), emission reduction cost coefficient is \( \mu_M \), and carbon trading price is \( p_e \). These are used to calculate their relative impact on the optimal emission reduction effort \( Z_M^* \), wholesale price \( w^* \), the optimal subsidy rate \( \delta^* \), emission reduction \( E(t)^* \), manufacturer’s profit \( J_M(t)^* \), retailer’s profit \( J_R(t)^* \), supply chain profit \( J_T(t)^* \), and social welfare evolution \( SW(t)^* \). Results are as follows:
Table 2: Sensitivity analysis

|   | $Z_M^*$ | $w^*$ | $\xi^*$ | $\delta^*$ | $p^*$ | $E(t)^*$ | $J_M(t)^*$ | $J_R(t)^*$ | $J_T(t)^*$ | $SW(t)^*$ |
|---|---------|-------|---------|-----------|-------|---------|------------|------------|------------|-----------|
| $k$ | ↑ → ↑ ↓ → ↑ ↑ ↑ ↑ ↑ |
| $\alpha$ | ↑ → → → → ↑ ↑ ↑ ↑ ↑ |
| $\mu_M$ | ↓ → → → → ↓ ↓ ↓ ↓ ↓ |
| $p_e$ | ↑ ↓ ↓ ↑ ↓ ↑ ↑ ↑ ↑ ↑ |

**Inference 1:** Under the cost subsidy, as consumer’s low carbon preference coefficient $k$ increases, consumer surplus and profits of the supply chain increases. As manufacturer’s emissions reduction efforts $Z_M^*$, retailer’s emission reduction cost-sharing coefficient $\xi^*$, carbon emission reduction of products $E(t)^*$, manufacturer’s profits $J_M(t)^*$, retailer’s profits $J_R(t)^*$, supply chain profits $J_T(t)^*$ and social welfare $SW(t)^*$ increase, manufacturer’s wholesale prices $w^*$ and retailer’s product pricing $p^*$ remain invariant, and the cost subsidy rate $\delta^*$ falls.

**Proof:**

\[
\frac{\partial Z_M^*}{\partial k} = \frac{1}{B} \frac{\alpha}{\rho + \sigma} \frac{5B}{\mu_M} 18 > 0
\]

\[
\frac{\partial w^*}{\partial k} = 0
\]

\[
\frac{\partial \xi^*}{\partial k} = \frac{63Bp_e}{(5A + 18p_e)^2} > 0
\]

\[
\frac{\partial \delta^*}{\partial k} = -\frac{9Bp_e}{(5A + 18p_e)^2} < 0
\]

\[
\frac{\partial p^*}{\partial k} = 0
\]

\[
\frac{\partial E(t)^*}{\partial k} = \frac{5B}{18\sigma(\rho + \sigma)} \frac{\alpha^2}{\mu_M} (1 - e^{-\sigma_t}) > 0
\]

\[
\frac{\partial J_M(t)^*}{\partial k} = \frac{B}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \frac{1}{\sigma} \frac{1}{2\rho} \left( \frac{5}{81} A + \frac{7}{18} p_e \right) > 0
\]
\[
\frac{\partial J_R(t)^*}{\partial k} = \frac{1}{(\rho + \sigma)^2} \alpha^2 \left[ \frac{1-e^{-\alpha t}}{\sigma} \frac{B(5A+p_c)}{9} + \frac{B(5A+11p_c)}{4\rho} \right]
\]

\[
\frac{\partial J_T(t)^*}{\partial k} = \frac{B}{(\rho + \sigma)^2} \alpha^2 \left[ \frac{1-e^{-\alpha t}}{\sigma} \left( \frac{10}{81} A + \frac{1}{2} p_c + \frac{25}{324} A + \frac{25}{72} p_c \right) \right] > 0
\]

\[
\frac{\partial SW(t)^*}{\partial k} = \frac{5B}{9(\rho + \sigma)^2} \alpha^2 \left[ \frac{1-e^{-\alpha t}}{\sigma} + \frac{1}{2\rho} \right] \left( \frac{5}{18} A + p_c \right) > 0
\]

For which
\[
B = \frac{1}{b} (a - bc - bp_e e_M + bp_e g_M)^2
\]

**Inference 2:** Under the cost subsidy, as the manufacturer's emission reduction effort influence coefficient \(\alpha\) increases, manufacturer's emissions reduction efforts \(Z_M^*\), carbon emission reduction of products \(E(t)^*\), manufacturer's profits \(J_M(t)^*\), retailer's profits \(J_R(t)^*\), supply chain profits \(J_T(t)^*\) and social welfare \(SW(t)^*\) increase; manufacturer's wholesale prices \(w^*\), retailer's emission reduction cost-sharing coefficient \(\xi^*\), cost subsidy rate \(\delta^*\), and retailer's product pricing \(p^*\) remain invariant.

**Proof:**

\[
\frac{\partial Z_M^*}{\partial \alpha} = \frac{1}{\rho + \sigma} \frac{1}{\mu_M} \left( \frac{5}{18} A + p_c \right) > 0
\]

\[
\frac{\partial w^*}{\partial \alpha} = 0
\]

\[
\frac{\partial \xi^*}{\partial \alpha} = 0
\]

\[
\frac{\partial \delta^*}{\partial \alpha} = 0
\]

\[
\frac{\partial p^*}{\partial \alpha} = 0
\]

\[
\frac{\partial E(t)^*}{\partial \alpha} = \frac{1}{\sigma(\rho + \sigma)} \frac{2\alpha}{\mu_M} \left( \frac{5}{18} A + p_c \right) (1-e^{-\alpha t}) > 0
\]

\[
\frac{\partial J_M(t)^*}{\partial \alpha} = \frac{1}{(\rho + \sigma)^2} \frac{2\alpha}{u_M} \left( \frac{1}{9} A + p_c \right) \left( \frac{5}{18} A + p_c \right) \left( \frac{1-e^{-\alpha t}}{\sigma} + \frac{1}{2\rho} \right) > 0
\]
\[
\frac{\partial J_R(t)^*}{\partial \alpha} = \frac{1}{(\rho + \sigma)^2} \frac{2\alpha}{u_M} \left( \frac{5}{18} A + p_e \right) \left[ \frac{1}{9} A \frac{1 - e^{-\alpha t}}{\sigma} + \left( \frac{1}{3} A + p_e \right) \frac{1}{4 \rho} \right] > 0
\]

\[
\frac{\partial J_T(t)^*}{\partial \alpha} = \frac{1}{(\rho + \sigma)^2} \frac{2\alpha}{u_M} \left( \frac{5}{18} A + p_e \right) \left[ \frac{1}{9} A \frac{1 - e^{-\alpha t}}{\sigma} + \left( \frac{5}{36} A + \frac{3}{4} p_e \right) \frac{1}{\rho} \right] > 0
\]

\[
\frac{\partial SW(t)^*}{\partial \alpha} = \frac{1}{(\rho + \sigma)^2} \frac{2\alpha}{u_M} \left( \frac{5}{18} A + p_e \right)^2 \left[ \frac{1}{2} e^{-\alpha t} + \frac{1}{2 \rho} \right] > 0
\]

**Inference 3:** Under the cost subsidy, as emission reduction cost coefficient \( \mu_M^* \) increases, manufacturer’s emissions reduction efforts \( Z_M^* \), carbon emission reduction of products \( E(t)^* \), manufacturer’s profits \( J_M(t)^* \), retailer’s profits \( J_R(t)^* \), supply chain profits \( J_T(t)^* \) and social welfare \( SW(t)^* \) decrease; manufacturer’s wholesale prices \( w^* \), retailer’s emission reduction cost-sharing coefficient \( \xi^* \), cost subsidy rate \( \delta^* \), and retailer’s product pricing \( p^* \) remain invariant.

**Proof:**

\[
\frac{\partial Z_M^*}{\partial \mu_M} = -\frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M^2} \left( \frac{5}{18} A + p_e \right) < 0
\]

\[
\frac{\partial w^*}{\partial \mu_M} = 0
\]

\[
\frac{\partial \xi^*}{\partial \alpha} = 0
\]

\[
\frac{\partial \delta^*}{\partial \mu_M} = 0
\]

\[
\frac{\partial p^*}{\partial \mu_M} = 0
\]

\[
\frac{\partial E(t)^*}{\partial \mu_M} = -\frac{\alpha^2}{\mu_M^2} \frac{1}{\sigma (\rho + \sigma)} \left( \frac{5}{18} A + p_e \right) (1 - e^{-\alpha t}) < 0
\]

\[
\frac{\partial J_M(t)^*}{\partial \mu_M} = -\frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{u_M^2} \left( \frac{5}{9} A + p_e \right) \left( \frac{1}{9} A \frac{1 - e^{-\alpha t}}{\sigma} + \frac{1}{4 \rho} \right) < 0
\]

\[
\frac{\partial J_R(t)^*}{\partial \mu_M} = -\frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{u_M^2} \left( \frac{5}{18} A + p_e \right) \left[ \frac{1}{9} A \frac{1 - e^{-\alpha t}}{\sigma} + \left( \frac{1}{3} A + p_e \right) \frac{1}{4 \rho} \right] < 0
\]
\[
\frac{\partial J_f(t)^*}{\partial \mu_M} = -\frac{1}{(\rho + \sigma)^2 u_M^2} \left( \frac{2}{9} A + p_e \right) \left[ \frac{1}{\sigma} \left( 1 - e^{-\alpha t} \right) + \left( \frac{5}{36} A + \frac{3}{4} p_e \right) \frac{1}{\rho} \right] < 0
\]

\[
\frac{\partial SW(t)^*}{\partial \mu_M} = -\frac{1}{(\rho + \sigma)^2 u_M^2} \left( \frac{2}{9} A + p_e \right) \left( \frac{1}{\sigma} \left( 1 - e^{-\alpha t} \right) + \frac{1}{2\rho} \right) < 0
\]

**Inference 4:** Under the cost subsidy, as carbon trading price \( p_e \) increases, manufacturer’s emissions reduction efforts \( Z_M^* \), carbon emission reduction of products \( E(t)^* \), cost subsidy rate \( \delta^* \), manufacturer’s profits \( J_M(t)^* \), retailer’s profits \( J_R(t)^* \), supply chain profits \( J_T(t)^* \) and social welfare \( SW(t)^* \) increase; manufacturer’s wholesale prices \( w^* \), retailer’s emission reduction cost-sharing coefficient \( \xi^* \), and retailer’s product pricing \( p^* \) decrease.

**Proof:**

\[
\frac{\partial Z_M^*}{\partial p_e} = \frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M} \left( \frac{5C}{18} + 1 \right) > 0
\]

\[
\frac{\partial J_f(t)^*}{\partial p_e} = -\frac{1}{(\rho + \sigma)^2 u_M^2} \left( \frac{5}{18} A + \frac{3}{4} p_e \right) \left[ \frac{1}{\sigma} \left( 1 - e^{-\alpha t} \right) + \left( \frac{5}{36} A + \frac{3}{4} p_e \right) \frac{1}{\rho} \right] < 0
\]

\[
\frac{\partial SW(t)^*}{\partial p_e} = -\frac{1}{(\rho + \sigma)^2 u_M^2} \left( \frac{5}{18} A + \frac{3}{4} p_e \right) \left( \frac{1}{\sigma} \left( 1 - e^{-\alpha t} \right) + \frac{1}{2\rho} \right) < 0
\]
\[
\frac{\partial J_T(t)^*}{\partial p_e} = \frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left[ \left(1-e^{-\alpha t}\right) \left(A \left(\frac{10C}{81} + \frac{1}{2}\right) + p_e \left(\frac{1}{2}C + 2\right)\right) + \left(1 \over \rho\right) \left(A \left(\frac{25C}{324} + \frac{15}{72}\right) + p_e \left(\frac{25}{72}C + 3\right)\right) \right] > 0
\]

\[
\frac{\partial SW(t)^*}{\partial p_e} = \frac{2}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(1 - e^{-\alpha t}\right) \left(1 + \frac{5}{2\rho} A + p_e \left(\frac{5}{18}C + 1\right)\right) > 0
\]

Which \( C = 2k(a - bc - bp_e e_M + bp_e g_M) \left(g_M - e_M\right). \)

6. Numerical Example

6.1. Evolution Path Analysis

Intuitive analysis was used to identify the optimal strategy trajectory of the supply chain under four different decision-making scenarios by assigning values to parameters. The parameters are set as follows: \( q = 0.3, \sigma = 0.2, a = 4.5, b = 1, c = 3, \alpha = 0.8, pe = 0.02, k = 0.6, uM = 1, eM = 0.5, gM = 2. \) As shown in Figure 2, the trajectory of the manufacturer’s profit, the retailer’s profit, supply chain profit, carbon emission reduction, and social welfare under decentralized and coordinated decision-making can be obtained. The optimal strategy for supply chains in cost-sharing and coordination decision-making situations and sensitivity analysis of the optimal solution trajectory by the numerical simulation of scalar assignments were also identified.

As shown in Figure 2, carbon emission reduction, the manufacturer’s profit, the retailer’s profit, supply chain profit, and social welfare show non-linear rising trends, eventually reaching stable levels. Retailer’s profit is only slightly higher than the manufacturer’s profit. Social welfare increases at a greater rate than does supply chain profits, reaching a higher level at the end of the study period.
6.2. Sensitivity Analysis

1. Low carbon sensitivity coefficient of consumers under cost subsidy.

Assuming the other parameters remain invariant, the simulation of the low carbon sensitivity coefficient is shown in Figure 3.

![Figure 3. Sensitivity analysis of consumers’ carbon sensitivity coefficient.](image)

With an increase of consumer’s low carbon sensitivity coefficient \( k \) under the cost subsidy, the carbon emission reduction and the manufacturer’s emission reduction effort have a linear rising trend, with carbon emission reduction faster than the manufacturer’s emission reduction effort. The product pricing and wholesale price remain invariant, and product pricing is significantly higher than the wholesale price. The cost-sharing coefficient, manufacturer’s profit, retailer’s profit, supply chain profit, and social welfare showed non-linear rising trends, and the manufacturer’s profit, retailer’s profit, supply chain profit and social welfare increase at a greater rate over time. The retailer’s profit is slightly higher than the manufacturer’s profit when the consumer’s low carbon sensitivity coefficient is low. With the increase of \( k \), the retailer’s profit increase is slightly greater than the manufacturer’s profit. The supply chain profit is similar to social welfare when the consumer's carbon sensitivity coefficient is low. With an increase of \( k \), the rate of increase in social welfare is slightly higher than supply chain profit. The rate of cost-sharing coefficient increase is low. The cost subsidy rate showed a small and insignificant decrease. Although the difference between the cost subsidy rate and the cost-sharing coefficient decreases, the cost subsidy rate is always greater than the cost-sharing coefficient.

2. The manufacturer’s emission reduction efforts influence-coefficient \( \alpha \).

Assuming other parameters remain invariant, the simulation result of the manufacturer’s emission reduction effort influence coefficient is shown in Figure 4.
With the increase of manufacturer’s emission reduction efforts under the cost subsidy, the manufacturer’s wholesale price, retailer’s emission reduction cost-sharing coefficient, cost subsidy rate, and retailer’s product pricing remain invariant. Product pricing is higher than the wholesale price, and the cost subsidy rate is greater than the emission reduction cost-sharing coefficient. The manufacturer’s profit, retailer’s profit, supply chain profit, carbon emission reduction, and social welfare showed a non-linear increasing trend in which the rates of carbon emission reduction and social welfare are similar. The retailer’s profit is slightly higher than the manufacturer’s profit when the manufacturer’s emission reduction effort influence coefficient is low. The supply chain profit and social welfare trends are similar.

3. Emission reduction cost coefficient $\mu_M$.

Assuming other parameters remain invariant, the simulation result of the emission reduction cost coefficient $\mu_M$ is shown in Figure 5.
Figure 5. Sensitivity analysis of the manufacturer’s emission reduction effort cost coefficient.

With the increase of emission reduction cost coefficient under the cost subsidy, the carbon emission reduction, the manufacturer’s emission reduction effort, manufacturer’s profit, retailer’s profit, supply chain profit, and social welfare had a non-linear descending trend. The retailer’s profit is slightly larger than the manufacturer’s profit when the manufacturer’s emission reduction cost coefficient is low. The manufacturer’s profit is slightly higher than the retailer’s profit. Social welfare is larger than supply chain profit. The manufacturer’s wholesale price, retailer’s emission reduction cost-sharing coefficient, cost subsidy rate, and retailer’s product pricing remain invariant. Product pricing is higher than the wholesale price and the cost subsidy rate is higher than the emission reduction cost-sharing coefficient.

4. Carbon trading price $P_e$.

Assuming the other parameters remain invariant, carbon trading price $P_e$ trends are shown in Figure 6.
Figure 6. Sensitivity analysis of carbon trading price.

With an increase in carbon trading price under the cost subsidy, the carbon emission reduction, manufacturer’s emission reduction effort, cost subsidy rate, manufacturer’s profit, retailer’s profit, supply chain profit, and social welfare showed a linear increasing trend. The retailer’s profit is higher than the manufacturer’s profit when the carbon trading price is low. However, the manufacturer’s profit increases at a faster rate than that retailer’s profit and eventually surpasses it. Social welfare is higher than supply chain profit. The manufacturer’s wholesale price, retailer’s emission reduction cost-sharing coefficient, and retailer’s product pricing showed linear descending trends, with product pricing higher than wholesale price. The cost subsidy rate is significantly larger than the emission reduction cost-sharing coefficient. With an increase in the carbon trading price, the cost subsidy rate has a slowly rising trend, and the cost-sharing coefficient a linear descending trend.

7. Conclusions

This paper considers the impact of a carbon quota system and a cost subsidy on emission reduction investment. We adopt differential game theory to obtain equilibrium strategies of government, supply chain and consumers as well as dynamic paths of emission reduction, profit, and social welfare. Specific conclusions are as follows:

By numerical simulation of scalar assignments, we obtained the optimal strategy of supply chain in cost-sharing and coordination decision-making situations. The carbon emission reduction, manufacturer’s profit, retailer’s profit, supply chain profit, and social welfare increase over time, and the retailer’s profit is always slightly larger than the manufacturer’s profit. Although the difference between social welfare and supply chain profit increases gradually, the rising rates slow and eventually stabilize.

Based on sensitivity analysis, the manufacturer’s emission reduction effort influence coefficient, the emission reduction cost coefficient, and carbon trading price have positive impacts on emission reduction, supply chain profit, and social welfare, but the impacts vary. Consumers’ low carbon sensitivity coefficient under cost subsidies negatively impacts carbon emission reduction, supply chain profit, and social welfare.
This paper establishes an optimal decision model for supply chain emission reduction technology investment based on a dynamic perspective consisting of an upstream manufacturer and downstream retailer. Innovation activities also are affected by other factors (including stochasticity), which should be considered in future studies. Multi-level supply chain emission reduction and the impact of emission reduction technology spillover also warrant further study.

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