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The Optimal Decisions for a Sustainable Supply Chain with Carbon Information Asymmetry under Cap-and-Trade

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Abstract: In this paper, we firstly investigate issues of low carbon supply chain including one retailer and one manufacturer in the context of joint information asymmetry and cap-and-trade mechanism, where the retailer is a leader and faces a stochastic demand, and the manufacturer is a follower and keeps private information in carbon emissions. Our aim is to design an incentive contract to make the manufacturer disclose the carbon information. Furthermore, we quantify the effects of the carbon price, the carbon emissions and the carbon quota on the supply chain model and design an incentive contract for improving supply chain performance. Finally, we give a couple of numerical examples and undertake sensitivity analysis to illustrate the proposed model and provide some managerial inferences in the conclusions.

1. Introduction

Nowadays, global climate change, which has profoundly affected the world economic development and human survival, poses a challenge all over the world. Facing this challenge, many countries and regional organizations such as the EU, the US, and China have implemented some mechanisms for slowing down greenhouse effects. Carbon Trading (also known as Cap-and-Trade) is one of the most effective market mechanisms, which sets mandatory emissions limits to all the enterprises, and allows the enterprises to sell or buy carbon allowances for emitting carbon dioxide within the given cap in advance. To be specific, on the one hand, if the actual emissions exceed the given carbon cap, the enterprises need to buy carbon emission permits from the carbon trading market, thereby increasing their operating costs. On the other hand, if the actual emissions are less than the given carbon cap, the enterprises can gain extra earnings by selling surplus carbon permits. It is clear that the implementation of Carbon Trading will affect the operation of enterprises in the sustainable economy. In recent years, this mechanism has been widely adopted by many countries [1,2]. For example, the EU Emissions Trading System began to run on 1 January 2005 and until now it has entered the third phase and been expected to achieve greenhouse gases emissions in 2020 which is lower than 20% of the emissions level in 1990 [3]. For the purpose of promoting the sustainable development of human society, China, as one of the participants and advocates, signed the United Nations Framework Convention on Climate Change in 1992, the Kyoto Protocol in 1997,

the Copenhagen Accord in 2009, the Doha Amendment in 2012, and the Paris Agreement in 2016. In particular, in 2013, China formally launched the carbon trading emissions market, and the carbon quota market reached second place in the world in the same year.

With the implementation of emission reduction policies in some countries, many large organizations began to focus on the sustainable supply chain management issues such as emissions reduction of full-life-cycle product and large retailers that take the initiative to give attention to the energy conservation and emission reduction of upstream players and are willing to help their upstream players to deal with the energy conservation and emission reduction. For example, Walmart worked actively with the upstream suppliers to help them cut their location-based energy use through Supplier Energy Efficiency Program [4]. Meanwhile, some enterprises have also recently asked their suppliers to disclose their carbon emissions. For example, IBM joined the Carbon Disclosure Project in early 2008 as a step forward in promoting the reduction of greenhouse gas emissions produced by its suppliers. Walmart has also started to collect information about suppliers' product packaging to push for the transparency of emissions [5].

As mentioned above, in the process of the implementation of carbon trading, there is no denying that, as the result of many industries involved, some firms often encounter some problems that are difficult to solve in the short term. For example, quality speculation, the transparency of emissions data and the imperfection of relevant laws [6]. Among them, the transparency of emissions data is one of the biggest obstacles in carbon emissions trading market [7]. This is because, for a sustainable supply chain system, the upstream and downstream firms always seek to maximize their own profits. Because carbon emissions are a person's private information, it is is hard for the other members in the supply chain to obtain relevant information. Therefore, this will also lead to asymmetric carbon emissions information.

The phenomenon of carbon emissions information asymmetry is common in some industries. For example, Volkswagen inflated the emission reduction data to defraud its consumers and the government [8]. In China, the special supervision of the State Ministry of environmental protection pointed that there is also a lack of supervision on carbon emissions in some industries, leading to the result that the transparency of emissions data is not very clear for the manufacturing industries. In addition, carbon emission information asymmetry between the players involved in the supply chain will also affect their interests, thereby reduce the efficiency of the whole system. Fortunately, supply chain coordination can balance the benefits of supply chain members [9–12]. An incentive contract mechanism can greatly reduce the information asymmetry among players in the supply chain, and meanwhile, supply chain's players can also develop the punishment mechanism to avoid the asymmetry information through cooperation [13].

Motivated by the issue of the carbon emissions information asymmetry in some industries, we investigate the effect of the asymmetry carbon emissions information on the sustainable supply chain under Cap-and-Trade mechanism. In contrast to the existing literature on the asymmetry information [14–19], under carbon emissions information asymmetry, the introduction of Cap-and-Trade mechanism may incur extra operating costs for enterprises or make enterprises more profitable, these changes in costs or profits depend on the carbon quotas allocated by the government. Until now, few studies have focused on exploring the carbon information asymmetry issues from the perspective of supply chain contract design. In this paper, we mainly study how to make the manufacturer truly disclose his/her carbon emission information by a appropriate mechanism design, so as to improve the overall performance of the supply chain.

Specifically, in this paper, we address the following research questions:

(1)　How do the players in the sustainable supply chain make strategic choices to maximize their profits with information asymmetry under Cap-and-Trade mechanism?

(2)　How does the carbon emissions information asymmetry affect the sustainable supply chain performance?

(3)　　How to design the effective contract to make the manufacturer disclose his or her carbon information truly in sustainable supply chain system?

The paper is organized as follows. In Section 2, a literature review is provided from two aspects, that is, supply chain contract with information asymmetry and supply chain with environmental constraints. In Section 3, a game-theoretic model is formulated and some contracts are designed to coordinate the low carbon supply chain. Some numerical analyses are given in Section 4. Finally, conclusions are provided in Section 5.

2. Related Literature

To highlight our contributions, we mainly focus on the two streams of supply chain literature relevant to this paper, that is, supply chain contract with information asymmetry and supply chain with environmental constraints.

2.1. Supply Chain Contract with Information Asymmetry

In today's business environment, The phenomenon of information asymmetry often occurs between the supply chain players in the transaction process. The players who have the full information are always in a superior position, while the other ones who have poor information are in an inferior position. However, an incentive contract mechanism may greatly reduce the influence of information asymmetry on the efficiency of the whole supply chain system [20]. In recent years, many researchers have devoted more attention to a supply chain contract with information asymmetry. This problem can in general be classified into two categories: supply chain contract with demand information asymmetry and supply chain contract with cost information asymmetry.

For a supply chain contract with demand information asymmetry, Kostamis and Duenyas [21] modelled a supply chain system consisting of a supplier and an original equipment manufacturer (OEM). They assumed that, for the OEM, she/he possesses private information such as demand forecasts and component's production cost, and the product requires assembly of two major components, one of which is procured exclusively from the upstream supplier. Meanwhile, under the condition of without competition, the supplier is assumed to be able to make a take-it-or-leave-it offer to the OEM in the form of a menu of price-quantity contracts. For a supply chain system consisting of a powerful supplier and a retailer, Babich et al. [14] developed a buyback contract design problem, where the retailer owns private information about the demand distribution. They showed that this contract can lead to the first-best solution of the supplier holding the entire channel's performance. Under asymmetric demand information, Kalkanci and Erhun [22] studied the price-game in decentralized assembly system, the result shows that reducing information asymmetry cannot always increase the supplier's profit, but his/her profit will always be impaired. In contrast to the above-mentioned literature, Schmidt et al. [23] built the signaling game between manager and investor in the firm. They considered that the manager owns private information of the firm's demand and cares about the short-term stock price assigned by the investor. They studied the effect on a firm's capacity decisions of short-term objectives and asymmetric information between the firm and its equity holders. Under the market demand information asymmetry, Giri and Bardhan [17] studied the coordination issue in a two-level supply chain by adding supply disruption.

Except for demand information asymmetry, the cost information asymmetry issues in the supply chain frame have greatly attracted the attention of scholars. Considering the buyer's operating cost which depends on the supplier's lead time, Cachon and Zhang [15] investigated procurement strategies with asymmetric information by using a queuing model. The results show that the procurement mechanism can minimize the buyer's total cost. Different from the perspective of optimizing the entire supply chain's performance, Chen [16] discussed the information pertaining to the downstream part of the supply chain and reviewed the upstream information. He investigated some incentive issues in information sharing. Cakany et al. [24] discussed a two-level supply chain model with information asymmetry, where the supplier has the private unit production cost information, and the retailer

can offer a menu of contracts. They found that information asymmetry does not always decrease the channel efficiency. Shen and Willems [18] developed a supply chain model with private retail cost information, they showed that, for any retail cost, the incentive-compatible contracts including wholesale and buyback prices can also coordinate the manufacturer-retailer system. Fang et al. [25] explored a decentralized assembly supply chain system, where an assembler assembles a set of n components, each of them produced by a different supplier who holds private cost information, into a final product to meet an uncertain demand. They proved the existence and uniqueness of optimal menu of the contracts for the assembler, an efficient algorithm with a complexity of $O(n)$ is developed to compute the optimal contract. Ma et al. [26] considered a two-stage supply chain system including a manufacturer contract and a brand name retailer, designed optimal contracts with information asymmetry, and also proposed two-part tariff contracts for both the symmetric and asymmetric cases. Under information asymmetry, Akan et al. [27] designed the relevant contract problems and found that, two parts charging menu design can obtain the purpose of information share. Our present work is closer to the cost information asymmetry case; however, the aforementioned literatures do not consider the effect of carbon emissions regulation on supply chain performance. But for Cap-and-Trade regulation, as mentioned in the introduction section, the carbon quota can not only affect supply chain players' operation cost, but also increase their profit if it is properly controlled.

2.2. Supply Chain with Environmental Constraints

As mentioned above, as the environmental issues of human society has become increasingly prominent, more and more scholars have begun to focus on environmental constraints in the field of supply chain management, including sustainable supply chain and low carbon supply chain.

2.2.1. Sustainable Supply Chain

As the sustainable economy gains traction in business practice, several researchers have began to focus on the sustainable supply chain. For example, in the closed-loop supply chain, Turki et al. [28] conducted the optimization and analysis of Manufacturing-Transport-warehousing System by developing discrete flow model. In terms of green supply chain, Centobelli et al. [29] gave a review on the topic of environmental sustainability and energy-efficient supply chain management. In addition to the studies mentioned above, many famous scholars have studied related researches. From the point of the meso-level supply chains, Masi et al. [30] reviewed the body of circular economy literature and discuss the fragmented body of circular economy knowledge. Furthermore, using the triple bottom line (economic bottom line, environmental bottom line and social bottom line), Liu et al. [31] proposed a framework of sustainable service industry supply chain management by reviewing the related papers in 2006-2015. Centobelli et al. [32] contributed to enriching the body of knowledge concerning the diffusion of environmental sustainability in logistics service providers. They concerned a broad taxonomy of green initiatives by developing the WH2 framework which made by integrated green aims, green practices and technological tools, and regarded the diffusion among logistics service providers using the web-based document analysis methodology.

2.2.2. Low Carbon Supply Chain

Similar to environmental sustainability, many researchers have also given considerable attention to low carbon supply chain management. For example, Dmitry et al. [33] studied the Stackelberg game model between environmental regulator and monopolistic firm, in which the regulator forced the firm to invest technology to reduce emission through environmental taxes, the result shows that blindly increasing taxes does not necessarily encourage the firm to adopt cleaner technology. Under different emission regulations, Toptal et al. [34] investigated joint decisions on inventory replenishment and emission reduction investment, gave an analytical comparison between various investment opportunities, and compared different carbon emission regulations based on costs and emissions. Considering the cap-and-trade policy, Kroes et al. [35] studied the relationship between

corporate performance and environmental performance. From the point of view of a regulator, the result revealed that a government quota is negatively correlated with environmental performance. From the perspectives of technology, economy and risk, Wennersten et al. [36] gave an overview which includes the future potential for carbon capture and storage in climate change mitigation. Brandenburg [37] investigated the green supply chain by using a goal programming approach. The result showed that, decentralized configuration can reduce carbon emissions, while centralized economic optimization can amplify environmental impact caused by demand uncertainty. Under cap-and-trade mechanism, Xu et al. [38] explored the pricing and production issues in make-to-order supply chain frame. Drake et al. [39] studied the effect of carbon tax and cap-and-trade mechanism on a company's technology selection and capacity decision-making.

The above-mentioned research on supply chain with environmental constraints mainly focuses on sustainable supply chain and low carbon and energy-efficient supply chain, including closed-loop supply chain, circular economy, logistics service, inventory replenishment policy, production problem, green investment technology, and so on. However, few of them consider the effect of caborn information asymmetry on the supply chain performance under emission regulations.

Many studies on supply chain contract with information asymmetry and supply chain with environmental constraints have been published. However, most of them fail to combine the two streams of research to investigate the effect of carbon information asymmetry on supply chain performance under carbon emissions regulations. It is worthwhile to note that, especially under Cap-and-Trade mechanism, carbon emissions are tradable in the external carbon market. Thus, under information asymmetry, the player in the supply chain who has private information about the product's carbon emissions may be in a beneficial position through disguising real carbon emissions information, and thus, it is necessary to restrain the manufacturer's misreporting behavior to improve the overall efficiency of the supply chain. In this paper, the main contribution of our work is to incorporate information asymmetry of carbon emissions into supply chain dynamic game model with stochastic market demand under Cap-and-Trade mechanism, and meanwhile, we design the incentive contracts between a manufacturer and a retailer which can improve the whole supply chain's performance.

3. Model Development

3.1. Model Description

In our model, as shown in Figure 1, we consider that a traditional supply chain consisting of one retailer and one manufacturer for a single product. Noting a fact that, in the current era of low carbon economy, e.g., in order to please the end consumers, Wal-Mart as the retailer has taken the lead and proposed the request that its manufacturers (e.g., Procter and Gamble) produce low carbon products, and thus, we assume here that the retailer acts as a leader and announces the order quantity to the upstream manufacturer, and the manufacturer decides his or her wholesale price according to the retailer's order quantity. We model a Stackelberg game problem with Cap-and-Trade mechanism and take into account the information asymmetry setting. The manufacturer is regulated by Cap-and-Trade mechanism and has a private product's carbon emissions information, which is hard for the retailer to accurately obtain in the early period of production. For the manufacturer, to reduce the carbon footprint and enhance the market product's competitiveness, he/she goes in for emission reduction and sells his/her low-carbon product to the downstream retailer, the market demand is stochastic and the production is make-to-stock. Meanwhile, we here assume that the manufacturer may hide the true carbon emissions for earning additional returns.
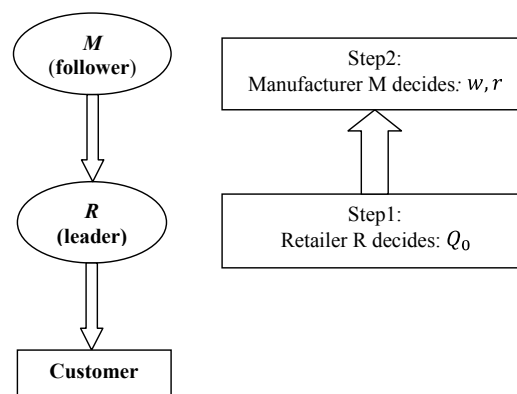
Figure 1. The supply chain structure and decision process.

In addition, according to Hua and Li [9], the retailer's order quantity can influence the manufacturer's wholesale price, we here assume that $Q = Q_0 - \beta\omega$, where Q is order quantity, Q_0 is the potential maximal order quantity in the retail market, and ω is the unit wholesale price. The retailer's carbon emissions caused by logistic and storing process are neglected, and both the manufacturer and the retailer are assumed to be risk neutral.

The notations used in our paper are summarized in Table 1.

Table 1. The model notations.

Notations	Descriptions
ω	the unit wholesale price (decision variable)
p	the unit selling price
c	the unit production cost
D	market demand
$f(x)$	probability density function (PDF) of market demand
$F(x)$	cumulative distribution function (CDF) of market demand
Q_0	the retailer's maximal order quantity(decision variable), where $Q_0 \geq 0$
β	demand sensitive parameter, where $\beta > 0$
γ	misreporting coefficient(decision variable)
ν	penalty factor from the government
λ	sharing coefficient
Q	the retailer's order quantity, where $Q = Q_0 - \beta\omega$
e_g	unit product's carbon quota
e_m	unit product's carbon emissions
P_c	unit carbon price
$S(Q)$	the potential sales of market, where $S(Q) = min\{Q, D\}$
$\prod_M(\cdot)$	the manufacturer's profit operator
$\prod_R(\cdot)$	the retailer's expected profit operator
$\prod_T(\cdot)$	the supply chain's expected profit operator

In the following analysis, we investigate how both the information symmetry and the information asymmetry influence the supply chain players' strategic choices. For convenience, we add superscript "S" or "A" to differentiate the information symmetry case and information asymmetry case, for example, $\prod_M^S$ refers to the manufacturer's profits under information symmetry. In addition, we also add "*" to denote their optimal values.

3.2. Information Symmetry Case

Under information symmetry, there is a full-information setting, that is, the manufacturer reveals his/her real carbon emissions information, so the manufacturer's profit function is described as follows.

$$\Pi_M^S = [w - c - (e_m - e_g)P_c](Q_0 - \beta\omega),\tag{1}$$

In Equation (1), for the part $(e_m - e_g)P_c$, when $e_m > e_g$, the part can be considered as operation cost for reducing emissions; when the opposite holds, this part can also be regarded as returns due to investment in reducing emissions, and the retailer's expected profit function is

$$\Pi_R^S = p \int_0^{Q_0 - \beta\omega} xf(x)dx + p \int_{Q_0 - \beta\omega}^\infty (Q_0 - \beta\omega)f(x)dx - \omega(Q_0 - \beta\omega).\tag{2}$$

We have the following theorem.

Theorem 1. *Under information symmetry case, we can get equilibrium solution pair* (ω^{S*}, Q_0^{S*}) *and the optimal profit pair* (Π_M^{S*}, Π_R^S), *where* ω^{S*} *is given by*

$$w^{S*} = \frac{Q_0^{S*}}{2\beta} + \frac{c + (e_m - e_g)P_c}{2},\tag{3}$$

Q_0^{S*} *is uniquely determined by*

$$p\{1 - F(\frac{Q_0^{S*}}{2} - \frac{\beta[c + (e_m - e_g)P_c]}{2})\} - \frac{Q_0^{S*}}{2\beta} = 0,$$

The manufacturer's optimal profit is

$$\Pi_M^{S*} = [\omega^{S*} - c - (e_m - e_g)P_c](Q_0^{S*} - \beta w^{S*}),$$

And the retailer's optimal expected profit is

$$\Pi_R^{S*} = p \int_0^{Q_0^{S*} - \beta\omega^{S*}} xf(x)dx + p \int_{Q_0^{S*} - \beta\omega^{S*}}^\infty (Q_0^{S*} - \beta\omega^{S*})f(x)dx - \omega^{S*}(Q_0^{S*} - \beta\omega^{S*}).$$

Proof of Theorem 1. For any fixed $Q_0 \in [0, +\infty)$, using backwards induction method, from the necessary condition for Π_M^S to be maximized is $\frac{d\Pi_M^S}{d\omega} = 0$, we have

$$\omega^S = \frac{Q_0}{2\beta} + \frac{c + (e_m - e_g)P_c}{2}.\tag{4}$$

Substituting Equation (4) into Equation (2), we get

$$\Pi_R^S(Q_0) = p \int_0^{Q_0^S - \beta\omega^S} xf(x)dx + p \int_{Q_0^S - \beta\omega^S}^\infty (Q_0^S - \beta\omega^S)f(x)dx - \omega^S(Q_0^S - \beta\omega^S).\tag{5}$$

By solving the equation $\frac{d\Pi_R^S(Q_0)}{dQ_0} = 0$, we can gain the retailer's optimal order quantity Q_0^{S*} such that the following equation

$$\frac{p}{2}\{1 - F(\frac{Q_0^{S*}}{2} - \frac{\beta[c + (e_m - e_g)P_c]}{2})\} - \frac{Q_0^{S*}}{2\beta} = 0.\tag{6}$$

Substituting Q_0^{S*} into Equation (4), we can get the optimal wholesale price $\omega^{S*} = \frac{Q_0^{S*}}{2\beta} + \frac{c+(e_m-e_g)P_c}{2}$. Then, substituting Q_0^{S*} and ω^S into Equations (1) and (2), we thus gain Π_M^{S*} and Π_R^{S*}. □

Theorem 1 investigates the supply chain members' optimal decision under the information symmetry case, that is, without considering the manufacturer's misreporting behavior in carbon emissions. In the following section, we will discuss whether the manufacturer has the misreporting behavior and hides his/her real product's carbon emissions information.

3.3. Information Asymmetry Case

Similar to information symmetry case, considering the manufacturer's misreport behavior in carbon emissions information, the manufacturer's profit function is expressed as follows

$$\Pi_M^A(\omega, \gamma) = [\omega - c - (e_m(1+\gamma) - e_g)P_c](Q_0 - \beta\omega). \tag{7}$$

Combining with Equations (1) and (7), we here use $\Pi_M^{At}(\omega)$ to denote the manufacturer's true profits function. Clearly, $\Pi_M^{At}(\omega) = \Pi_M^A(\omega, 0)$. We have the following theorem.

Theorem 2. *Under the information asymmetry, for any fixed γ, the retailer's maximal order quantity Q_0^{A*} satisfies the equation*

$$\frac{p}{2}\{1 - F(\frac{Q_0^{A*}}{2} - \frac{\beta[c + ((1+\gamma)e_m - e_g)P_c]}{2})\} - \frac{Q_0^{A*}}{2\beta} = 0, \tag{8}$$

The manufacturer's optimal wholesale price ω^{A*} is uniquely determined by

$$\omega^{A*} = \frac{Q_0^{A*}}{2\beta} + \frac{c + (e_m(1+\gamma) - e_g)P_c}{2}. \tag{9}$$

Correspondingly, we have the optimal expected profit pair $(\Pi_M^{A*}(\omega^{A*}, \gamma), \Pi_R^{A*}(w^{A*}, \gamma))$, where

$$\Pi_M^{A*}(\omega^{A*}, \gamma) = [\omega^{A*} - c - (e_m - e_g)P_c](Q_0^{A*} - \beta\omega^{A*}),$$

Moreover,

$$\Pi_R^{A*}(w^{A*}, \gamma) = p \int_0^{Q_0^{A*} - \beta\omega^{A*}} xf(x)dx + p \int_{Q_0^{A*} - \beta\omega^{A*}}^{\infty} (Q_0^{A*} - \beta\omega^{A*})f(x)dx - \omega^{A*}(Q_0^{A*} - \beta\omega^{A*}).$$

Proof of Theorem 2. This proof is similar to the proof procedures of Theorem 1, thus we here omit. □

Remark 1. *Theorem 2 shows that, for any fixed γ, both the retailer's maximal order quantity Q_0^{A*} and the manufacturer's optimal wholesale price ω^{A*} are dependent on the misreporting parameter γ. Thus, it is clear that, when $\gamma = 0$, the information asymmetry case reduces to the asymmetry one; when $\gamma \neq 0$, in order to search the manufacturer's optimal optimal misreporting factor γ^*, we can substitute $w^{A*}(\gamma)$ and $Q_0^{A*}(\gamma)$ into the manufacturer's true profits function $\Pi_M^{At}(\omega)$, and the optimal misreporting factor γ^* can be obtained by the equation $\frac{\partial \Pi_M^{At}(\omega)}{\partial \gamma} = 0$. It should be pointed out that this article does not attempt to encourage the manufacturer's misreporting behavior, but identify the unethical behavior by model optimization. Noting that, if $\Pi_M^{At*} = \Pi_M^{S*}$, the manufacturer will reveal his/her carbon emissions information; but if $\Pi_M^{At*} > \Pi_M^{S*}$, then the manufacturer always has an incentive to hide the real carbon emissions. To avoid this misreporting behavior, it is necessary to design the contract to make the manufacturer share real carbon emissions information, so we will discuss the contract design problem in the next section.*

3.4. Contract Design

Before our discussion, we adopt the definition of coordination provided in Cachon [20] as follows: (i) the retailer and the manufacturer gain expected profits not less than their respective reservation expected profits; (ii) the supply chain's expected profit is maximized. From the above definition, we can see that, case (i) is necessary to guarantee that both players are willing to accept this contract. In this paper, we will adopt the players' expected profits gained in the information asymmetry case as their reservation expected profits. Through the analyses in Section 3.3, we know that the manufacturer has a motivation to misreport the carbon emissions when $\Pi_M^{At*} > \Pi_M^{S*}$. Our main aim in this section is to design an effective contract to restrict the manufacturer's misreporting behavior, we have the following theorem.

Theorem 3. *For any given $\gamma \neq 0$, When $\Pi_M^{At*} > \Pi_M^{S*}$, we have*

(1)   *If $\Pi_R^{A*} \geq \Pi_R^{S*}$, then both the retailer and the manufacturer have no motivation in making any contracts;*

(2)   *If $\Pi_R^{A*} < \Pi_R^{S*}$, then the retailer is willing to initiate the following behaviors, especially,*

(i)   *when $\Pi_R^{S*} - \Pi_R^{A*} \geq \Pi_M^{At*} - \Pi_M^{S*}$, then a revenue sharing contract can coordinate the whole supply chain if $\Pi_M^{S*} + \lambda(\Pi_R^{S*} - \Pi_R^{A*}) \geq \Pi_M^{At*}$, where $\frac{\Pi_M^{At*} - \Pi_M^{S*}}{\Pi_R^{S*} - \Pi_R^{A*}} \leq \lambda < 1$.*

(ii)   *when $\Pi_R^{S*} - \Pi_R^{A*} < \Pi_M^{At*} - \Pi_M^{S*}$, then the retailer will expose the manufacturer's misreporting behavior if $\nu \gamma e_m P_c \geq \Pi_M^{At*} - \Pi_M^{S*}$.*

Proof of Theorem 3. When the manufacturer misreports the carbon emissions, we have

(1)   If $\Pi_R^{A*} \geq \Pi_R^{S*}$, this implies that the retailer's expected profit is no less than that in the symmetric information case. Namely, the retailer acquiesces the manufacturer's false behavior, so there is no motivation in making any contracts between them.

(2)   If $\Pi_R^{A*} < \Pi_R^{S*}$, this is, the retailer's expected profit is less than that in the symmetric information case. This is implies that the misreporting behavior leads to a lowering of the retailer's expected profit. Thus, the retailer has a motivation to initiate contract behavior. We consider the following two cases.

(i)   when $\Pi_R^{S*} - \Pi_R^{A*} \geq \Pi_M^{At*} - \Pi_M^{S*}$, if the retailer, as a leader, can transfer fractional increment in profits to the manufacturers and the revenue sharing factor λ such that $\frac{\Pi_M^{At*} - \Pi_M^{S*}}{\Pi_R^{S*} - \Pi_R^{A*}} \leq \lambda < 1$, then we get $\Pi_M^{S*} + \lambda(\Pi_R^{S*} - \Pi_R^{A*}) \geq \Pi_M^{At*}$ and $\Pi_R^{S*} - \lambda(\Pi_R^{S*} - \Pi_R^{A*}) \geq \Pi_R^{A*}$. Thus, the revenue sharing contract can coordinate the whole supply chain.

(ii)   when $\Pi_R^{S*} - \Pi_R^{A*} < \Pi_M^{At*} - \Pi_M^{S*}$, it shows that, the retailer cannot make up for the manufacturer's profit loss by revenue sharing. However, if $\nu \gamma e_m P_c \geq \Pi_M^{At*} - \Pi_M^{S*}$, that is, government fine is no less than the manufacturer's profit increment gained by misreporting behavior, then the retailer will expose the misreporting behavior to make the manufacturer disclose the real carbon emissions.   □

Remark 2. *For comparison, combing with Theorem 3, we let $\Delta_M = \Pi_M^{At*} - \Pi_M^{S*}$, $\Delta_R = \Pi_R^{A*} - \Pi_R^{S*}$, $\Delta_T = \Pi_T^{A*} - \Pi_T^{S*}$, then some possible scenarios can be summarized in Table 2, clearly. For Scenario 1, it shows that the proposed model can be reduced to be information symmetry case; For Scenario 2, when the supply chain players' expected profits in information asymmetry case are higher than that in symmetry case, they will not try to change the current status. However, owing to negative externality, that is, the manufacturer's misreporting behavior has a negative effect on social welfare, the government may urge the manufacturer to make his or her carbon emissions information to the public by administrative regulations such as certification of carbon footprint. This finding is consistent with Du et al. [40], which mainly focused on the principal-agent problem*

between government and enterprises under carbon emissions regulations. They did not consider the problem of asymmetric carbon information from the perspective of supply chain. For Scenario 3, it means that, an incentive contract can avoid the manufacturer's misreporting behavior, and make both players in supply chain achieve Parto improvement. For the last Scenario, if the retailer can identify the manufacturer's false information in carbon emissions, he/she may choose to reveal this misreporting behavior in practice, and then the government can make the manufacturer become more rational by imposing a fine (i.e., $\nu\gamma e_m P_c$). In addition, he or she may also terminate cooperation in advance by market power. For example, in previous business practices, Wal-mart and IBM asked their suppliers to disclose their carbon information, and if they find this misreporting behavior in the process of cooperation, they would end up with the purchase contract [4,5].

Table 2. A summary in possible scenarios.

Scenarios i	Conditions	The Results
1	$\Delta_M = 0, \Delta_R = 0, \Delta_T = 0$	Information symmetry
2	$\Delta_M > 0, \Delta_R > 0, \Delta_T > 0$	Government regulation
3	$\Delta_M > 0, \Delta_R < 0, \Delta_T > 0$	Revenue sharing mechanism
4	$\Delta_M > 0, \Delta_R < 0, \Delta_T < 0$	Fine mechanism

3.5. Special Case

Noting Equations (8) and (9), because of the operator $F(\cdot)$, it is not easy to compare the optimal wholesale price and order quantity in the information symmetry and information asymmetry cases. For simplicity, we here consider that market demand D is uniformly distributed on $[a, b]$ and denote as $D \sim U[a, b]$, where $b > a \geq 0$. The following theorem is given as follows.

Theorem 4. *When $D \sim U[a, b]$, let $B = p\beta + 2(b - a), I = c + P_c(e_m - e_g), C = bp + (p\beta + b - a)I, E = p\beta b + (a - b)\beta I$, and $H = (a - b)\beta P_c e_m$ and $G = (p\beta + b - a)P_c e_m$, then*

(1) Under the symmetric information game model, there exist the equilibrium solution pair (w^{S*}, Q_0^{S*}) and the optimal expected profit pair $(\prod_M^{S*}, \prod_R^{S*})$, where $\omega^{S*} = \frac{C}{B}, Q_0^{S*} = \frac{E + \beta C}{B}, \prod_M^{S*} = [\omega^{S*} - c - (e_m - e_g)P_c](Q_0^{S*} - \beta\omega^{S*})$, and $\prod_R^{S*} = \frac{2bp(Q_0^{S*} - \beta\omega^{S*}) - p(Q_0^{S*} - \beta\omega^{S*})^2}{2(b-a)} - \omega^{S*}(Q_0^{S*} - \beta\omega^{S*})$.

(2) Under the asymmetric information, we can get the optimal decision pair $(\omega^{A*}, \gamma^*, Q_0^{A*})$ and the optimal expected profit pair $(\prod_M^{At*}, \prod_R^{A*})$, where $\omega^{A*} = \frac{IBD - EG + CH}{2BH}, \gamma^* = \frac{IBH - EG - CH}{2GH}$, $Q_0^{A*} = \frac{(1+\beta)BDI + (1-\beta)(EG - CH)}{4B^2 HG}, \prod_M^{At*} = [\omega^{A*} - c - (e_m - e_g)P_c](Q_0^{A*} - \beta\omega^{A*})$, and $\prod_R^{A*} = \frac{2bp(Q_0^{A*} - \beta\omega^{A*}) - p(Q_0^{A*} - \beta\omega^{A*})^2}{2(b-a)} - \omega^{A*}(Q_0^{A*} - \beta\omega^{A*})$.

Proof of Theorem 4. This proof is similar to the proof procedures of Theorem 1, thus we omit it here. □

Corollary 1. *Under the information asymmetry, the manufacturer's optimal wholesale price is positively related to the misreporting factor, but the retailer's optimal order quantity is negatively related to the misreporting factor.*

Proof of Corollary 1. According to Theorem 4, we have

$$\frac{\partial \omega^{A*}}{\partial \gamma} = \frac{(p\beta + b - a)P_c e_m}{p\beta + 2(b - a)} = \frac{G}{B} > 0,$$

And

$$\frac{\partial Q^{A*}}{\partial \gamma} = \frac{(a - b)\beta P_c e_m}{p\beta + 2(b - a)} = \frac{H}{B} < 0,$$

□

So the optimal wholesale price increases as misreporting factor increases, and the optimal order quantity decreases as misreporting factor increases.

Corollary 1 states that, as the manufacturer's misreporting factor varies, the values of Q^{A*} and ω^{A*} become more sensitive. Especially for the manufacturer, if he/she is inclined to hide the real information in carbon emissions, then the retailer has to decrease order quantity, and finally, leading to the result that the optimal wholesale price will become bigger than that in the information symmetry case.

4. Numerical Analysis and Sensitivity Analyses

Example 1. *In this section, the base values of the parameters are listed as follows: $p = 30$, $c = 5$, $e_g = 10$, $e_m = 10$, $P_c = 10$ and $\beta = 1$. the random component of the demand D is assumed to follow the uniform distribution with $a = 1$ and $b = 10$, according to Theorem 4, the optimal results are gained as follows.*

(1)   Under information symmetry, we have $(\omega^{S*}, Q^{S*}) = (10.3125, 5.3125)$ and $(\prod_M^{S*}, \prod_R^{S*}, \prod_R^{T*}) = (28.2227, 75.2604, 103.4831)$;

(2)   Under information symmetry, we have $(\omega^{A*}, \gamma^*, Q^{A*}) = (19.1667, 0.1090, 3.2692)$ and $(\prod_M^{A*}, \prod_R^{A*}, \prod_R^{A*}) = (46.3141, 28.5010, 74.8151)$.

(3)   Under the revenue sharing contract, according to Theorem 4, we get the revenue sharing coefficient range $0.3869 < \lambda < 1$, and the final revenue sharing coefficient depends on their bargaining power in the market. In order to further investigate the impact of the revenue sharing coefficient λ on the supply chain performance, we set $\lambda \in \{0.4, 0.5, \ldots, 0.8\}$, the results are shown in Table 3, where $i = S, A$ and C, S denotes information symmetry case, A denotes information asymmetry case, and C denotes revenue sharing contract case.

From Table 3, compared with the information asymmetry case, we can find that the performance of the supply chain can be improved significantly under the revenue sharing contract. After the coordination, the manufacturer's optimal profit under the revenue sharing contract is higher than that under information asymmetry, i.e., $\prod_M^{C*} > \prod_M^{A*}$. At the same time, the retailer's optimal profits under the revenue sharing contract also become higher compared with the profits under information asymmetry, i.e., $\prod_R^{C*} > \prod_R^{A*}$. This shows that the revenue sharing contract can motivate the manufacturer to share carbon emissions information truly, and raise their respective reservation expected profits compared with case that the manufacturer hides the carbon emissions. Namely, the revenue sharing contract can achieve Pareto improvement. These numerical results are consistent with our theoretical ones.

Table 3. The effect of revenue sharing coefficient λ on supply chain performance.

case i	λ	Π_M^*	Π_R^*	Π_T^*
S	–	28.2227	75.2604	103.4831
A	–	46.3141	28.5001	74.8151
C	0.4	46.9264	56.5567	103.4831
	0.5	51.6024	51.8807	103.4831
	0.6	56.2783	47.2048	103.4831
	0.7	60.9543	42.5288	103.4831
	0.8	65.6302	37.8529	103.4831

In addition, the manufacturer's optimal profit gradually increases as the revenue sharing coefficient increases; but the retailer's optimal profit decreases as the revenue sharing coefficient increases, and the final revenue sharing coefficient depends on their bargaining power. If we further observe the results of Table 3, we can obtain the result that the retailer's optimal profit under the contract is still less than that in the symmetric information case, i.e., $\prod_R^{C*} < \prod_R^{S*}$, but the manufacturer's optimal profit under the contract is always higher than that in information symmetry case, i.e.,

$\prod_M^{C*} > \prod_M^{S*}$. This also shows that the manufacturer who owns the private information can always obtain extra benefits from disclosure of information.

Example 2. *In order to get more general results, we will investigate the impacts of unit carbon emissions e_m, carbon emissions price P_c and carbon quota e_g on the manufacturer's optimal wholesale price ω^* and misreporting factor γ^*, the optimal of the retailer's optimal ordering quantity Q^* and the profits of supply chain $\prod^*$ under different cases.*

From Figure 2, no matter whether the carbon information shows symmetry or asymmetry, the optimal ω increases as e_m increases, and the optimal order quantity Q^* decreases as e_m increases. However, the optimal ω in the asymmetry case is higher than that in symmetry case, while the optimal Q^* in asymmetry case is less than that in the symmetry case. From Figure 3, for the two different cases in carbon information, the optimal ω decreases as e_g increases, and the optimal order quantity Q^* increases as e_g increases. However, the optimal ω in asymmetry case is higher than that in the symmetry case, while the optimal Q^* in asymmetry case is less than that in symmetry case. From Figure 4, for the two carbon information cases, the optimal ω decreases as P_c increases, and the optimal order quantity Q^* increases as P_c increases. However, the optimal ω in the asymmetry case is higher than that in the symmetry case, while the optimal Q^* in the asymmetry case is less than that in the symmetry case.
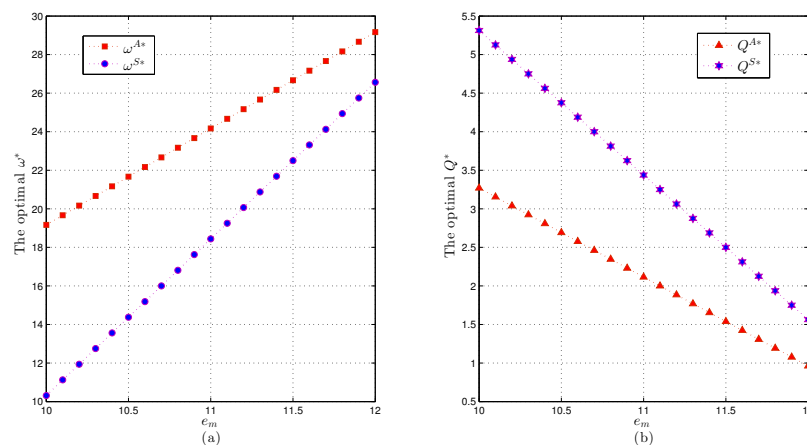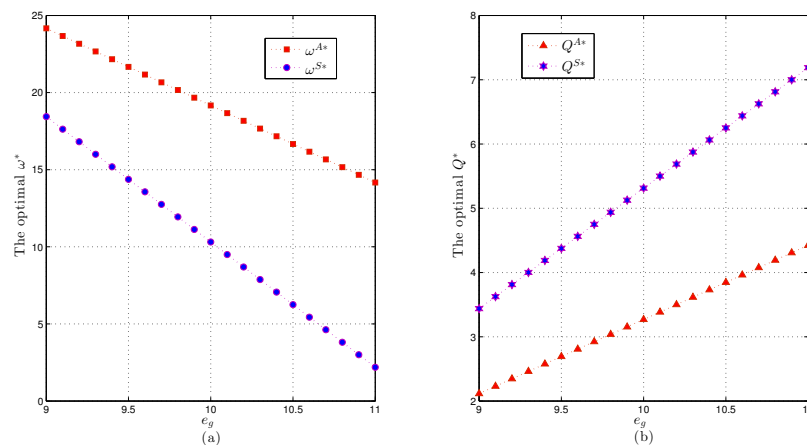

Figure 2. The effects of e_m on ω^* and Q^*.

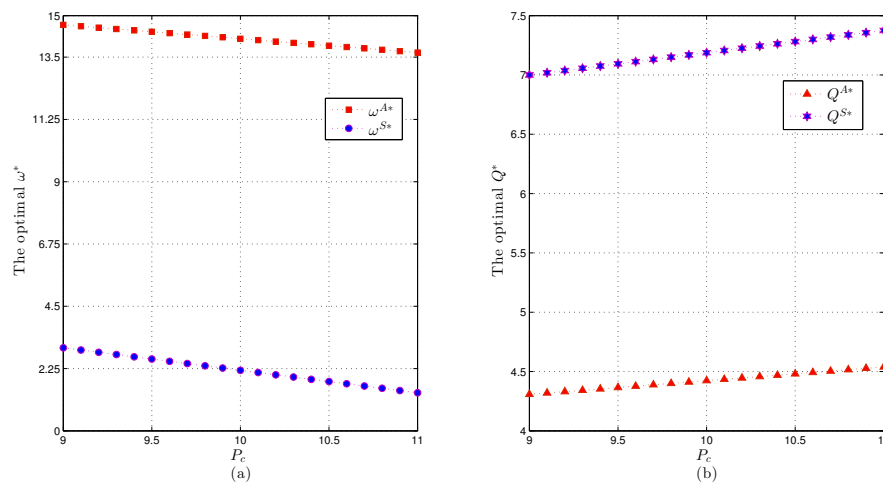**Figure 3.** The effects of e_g on ω^* and Q^*.

Figure 4. The effects of P_c on ω^* and Q^*.

These show that, when there are some external factors such as higher carbon price and lower carbon quota from the government, for the manufacturer, if the product is made with larger carbon emissions, it means that she/he takes on more costs outside of production, and thus the manufacturer will shift this cost to the downstream supply chain by raising the wholesale price. However, when carbon price from the carbon market is higher or carbon quota from government is larger, the manufacturer can gain more profits from the carbon trading market, and thus the manufacturer may adapt to lower the wholesale price for getting more orders.

From Figure 5, under the carbon information asymmetry case, the optimal γ decreases as P_c and e_m increase, but it increases as e_m increases. This is because, under the information asymmetry case, when carbon price is higher or carbon quota is larger, then the manufacturer can gain more benefits by reducing more carbon emissions. To slow down lowering the whole price, the manufacturer may hide these benefits by misreporting carbon emissions information.
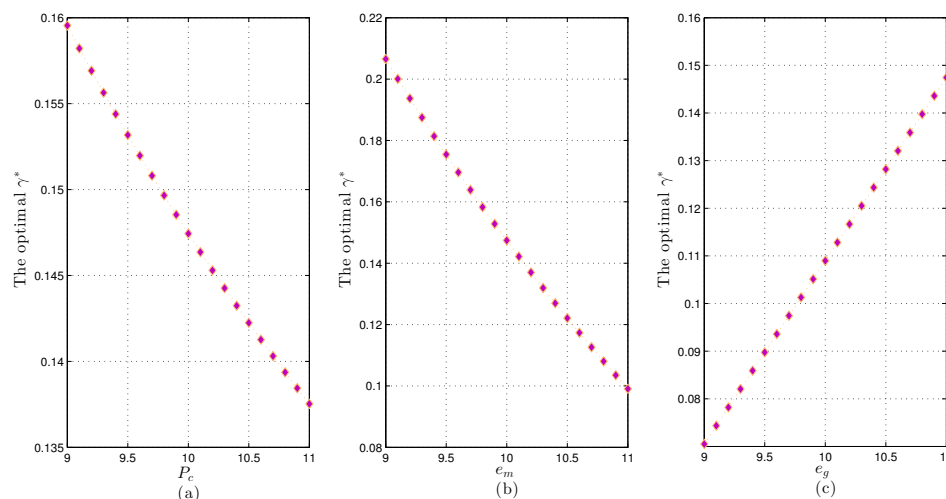

Figure 5. The effects of P_c, e_m and e_g on γ.

From Tables 4 and 5, when P_c and e_m or e_m and e_g vary, and the optimal misreporting factor satisfies $\gamma^* \neq 0$, the manufacturer's optimal profit under information asymmetry is always higher than that in the symmetric information case ($\Pi_M^{A*} > \Pi_M^{S*}$). This shows that the manufacturer's misreporting

behavior can raise his or her profit under information asymmetry, but the retailer's optimal profits under the information asymmetry are less than that under symmetric information ($\Pi_R^{A*} < \Pi_R^{S*}$), which means that the manufacturer's misreporting behavior hurts the retailer's profits, and meanwhile, the total supply chain optimal profit under the information asymmetry is less than that under the symmetric information ($\Pi_T^{A*} > \Pi_T^{S*}$). This shows that the manufacturer's misreporting behavior can also lower the total supply chain operation efficiency.

In addition, from Table 4, we find that, when the carbon emissions e_m are less than carbon quota e_g, then the manufacturers' profit increases as the carbon price P_c increases (see, $e_m = 9 < e_g = 10$, $P_c \in \{6, 8, 10, 12\}$); However, when the carbon emissions e_m are more than the carbon quota e_g, then the profit decreases as the carbon price P_c increases (see, $e_m = 11 > e_g = 10$, $P_c \in \{6, 8, 10, 12\}$). This shows that the impact of carbon prices on the profits depends largely on the carbon emissions and the carbon quotas.

Table 4. The effects of the parameters P_c and e_m on optimal decisions for supply chain.

P_c	e_m	γ^*	Π_M^{A*}	Π_R^{A*}	Π_T^{A*}	Π_M^{S*}	Π_R^{S*}	Π_T^{S*}
	09	0.2445	68.0064	41.8501	109.8565	41.4414	110.5104	151.9518
6	10	0.1816	46.3141	28.5010	74.8151	28.2227	75.2604	103.4831
	11	0.1301	28.7756	46.4836	46.4837	17.5352	46.7604	64.2956
	09	0.1941	76.1603	46.8679	123.0281	46.4102	123.7604	170.1706
8	10	0.1361	46.3141	28.5001	74.8151	28.2227	75.2604	103.4831
	11	0.0889	23.8526	14.6785	38.5311	14.5352	38.7604	53.2956
	09	0.1638	84.7756	52.1696	136.9453	51.6602	137.7604	189.4206
10	10	0.1090	46.3141	28.5001	74.8151	28.2227	75.2604	103.4831
	11	0.0641	19.3910	11.9329	31.3240	11.8164	31.5104	43.3268
	09	0.1436	93.8526	57.7554	151.6080	57.1914	152.5104	209.7018
12	10	0.0908	46.3141	28.5001	74.8151	28.2227	75.2604	103.4831
	11	0.0476	15.3910	9.4714	24.8624	9.3789	25.0104	34.3893

Table 5. The effects of the parameters e_m and e_g on optimal decisions for supply chain.

e_m	e_g	γ^*	Π_M^{A*}	Π_R^{A*}	Π_T^{A*}	Π_M^{S*}	Π_R^{S*}	Π_T^{S*}
	09	0.0394	15.0521	13.1706	28.2227	14.7449	17.2024	31.9473
9	10	0.0532	27.5521	24.1018	51.6602	26.9898	31.4881	58.4779
	11	0.0671	43.8021	38.3268	82.1289	42.9082	50.0595	92.9677
	09	0.0229	06.3021	05.5143	11.8164	06.1753	07.2024	13.3759
10	10	0.0354	15.0521	13.1706	28.2227	14.7449	17.2024	31.9473
	11	0.0479	27.5521	24.1081	51.6602	26.9898	34.4881	58.4779
	09	0.0095	01.3021	01.1393	02.4414	01.2755	01.4881	02.7636
11	10	0.0208	06.3021	05.5143	11.8164	06.1735	07.2024	13.3759
	11	0.0322	15.0521	13.1706	28.2227	14.7449	17.2024	31.9473

5. Conclusions and Future Research

Taking both the carbon information asymmetry and cap-and-trade mechanism into consideration, this paper studies the manufacturer's misleading behavior in carbon emissions information and the retailer's ordering decisions. We obtain the supply chain's equilibrium solutions under two different cases, namely: information symmetry and information asymmetry. By comparing the optimal performances between supply chain members, we design an effective contract to avoid the manufacturer's misreporting behavior. We investigate the effect of the carbon price, the carbon emissions and the carbon quota on these optimal equilibrium solutions and use numerical examples and sensitivity analysis to verify the proposed model.

Some key contributions in this research are made as follows. First, theoretically, our paper is one of few articles that have studied the effect of the carbon emissions information asymmetry on supply chain performance under cap-and-trade mechanism. Furthermore, we discuss the supply chain members' optimal strategies when the manufacturer owns private information and deliberately gives false carbon emissions information. Second, by contract design, our findings offer interesting managerial insights that will support supply chain enterprises making important strategic decisions to improve their environmental performance. For example, if the upstream manufacturer hides the real carbon emissions information, the dominant retailer can take more proactive actions to design the contact for achieving the players' pareto improvement in supply chain. Finally, our findings also provide some policy implications that government can use and some effective ways such as certification of carbon footprint and environmental regulation to avoid the misreporting behavior when there exists some false carbon emission information in the market.

From the perspective of the downstream retailer, this article considers a sustainable supply chain problem, where the upstream manufacturer owns the private carbon emissions information. Our aim is to design an incentive contract to make the manufacturer disclose the carbon information. When two scenarios happen in the contract design section (i.e., $\Delta_M > 0, \Delta_R > 0, \Delta_T > 0$ and $\Delta_M > 0, \Delta_R < 0, \Delta_T < 0$), we point out that there needs to be government regulation in business practice, and meanwhile, we also suggest that policymakers need to pay particular attention to the above two types of issues. This paper does not discuss the mechanism design after the government regulation, but in the future study, it is hoped to further incorporate the government regulation into the contract design under carbon emissions regulations. In addition, the stochastic demand adopted in the paper also does not take into account the customer's low-carbon awareness. One interesting research extension is to introduce the customer's low-carbon awareness into the low carbon supply chain system by using empirical methods.

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