DESIGN OF AN ENVIRONMENTAL CONTRACT UNDER TRADE CREDITS AND CARBON EMISSION REDUCTION

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(Communicated by Ada Che)

Abstract. Most of the previous literatures proposed a single coordination contract to increase the total profit of the supply chain, while this paper focuses on how to design environmental contracts to increase economic and environmental performance in the context of sustainable development. This paper designs the environmental contract based on cap-and-trade mechanism and trade credits which has rarely been studied before, especially the impact of trade credit on environmental performance. We consider a green supply chain, assuming that the demand rate is linear with retail prices, joint carbon emission reduction efforts and trade credit. Two models, a decentralized one and a centralized one, are compared; four contracts are proposed. Via numerous examples and sensitivity analysis, we gain some insight into how to select supply chain contracts to better improve environmental performance. The results reveal that the manufacturer sharing the retailer’s revenue and cost contract obtains the highest profit. While revenue sharing contract between both parties is the optimal environmental contract, but it is difficult to increase the profit of supply chain. Furthermore, it is found that trade credit works well in protecting the environment and plays a significant role in achieving coordination.

1. Introduction. As our society strides forward at an alarming rate, people are facing severe challenges of environmental pollution (Kanada et al.[22]). Studies have shown that the growth of carbon emissions and other greenhouse gases has caused global warming. Many countries began to implement environmental tax and cap-and-trade mechanism to deal with the crisis of global warming (Xu and Fang [49]; Hu et al.[16]). Recently, cap-and-trade system received widespread popularity. Cap-and-trade was used successfully in the US to reduce emissions of sulphur dioxide

2020 Mathematics Subject Classification. Primary: 90B50, 91B34; Secondary: 91A40.

Key words and phrases. Green supply chain, joint emission reduction, pricing strategy, coor dinative contracts, trade credit.

The paper is supported by the 1311 Programs Foundation of Nanjing University of Posts and Telecommunications, the Scientific Research Foundation of Nanjing University of Posts and Telecommunications (NY220212), the Key Research Base of Philosophy and Social Sciences in Jiangsu–Information Industry Integration Innovation and Emergency Management Research Center.

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and nitrous oxide in coal-fired power generation. Since the early 1980s, the cap-
and-trade system has reduced the emissions resulting from acid rain by nearly half,
which has contributed to building a healthier environment. The European Union
adopted the system beginning in 2005 to reduce greenhouse gas emissions from
approximately 10,000 large manufacturers. In this system, the government has set
strict limits or caps on the overall level of industrial carbon emissions, then requires
the entities that are responsible for exceeding their emission quotas to buy unused
quotas from others. In addition, the government encourages the firms to reduce
their emissions and even to be able to sell rather than purchase emission quotas,
the price of which is determined by the market.

Faced with the regulatory requirements of the cap-and-trade system, enterprises
have begun to make efforts to reduce carbon emissions. For instance, Gree Electric
Appliances, the air-conditioning giant, pays more attention to innovation and de-
sign of energy-saving products. The production of more environmentally friendly
and energy-saving products can effectively reduce carbon emissions, thus increasing
the competitiveness of enterprises (Kennedy et al.[23]). However, it is difficult for
individual companies to reduce carbon emissions alone, since about 70% of emis-
sions come from activities throughout the supply chain. Therefore, cooperation
between supply chain enterprises and joint carbon emission reduction decision are
particularly significant for environmental protection.

Manufacturers’ green production and retailers’ green sales are called joint emis-
sion reduction. For example, Gree Electric Appliances cooperates with retailers
such as Suning and Gome to reduce carbon emissions. Gree Electric Appliances
mainly invests in new technologies to yield more low-carbon and environmentally
sustainable products. Correspondingly, retailers mainly promote these low-carbon
products through advertising investment for stimulating sales. The implementation
of joint carbon emission reduction can reduce carbon emissions by a large amount.

Trade credit, one of the short-term financing methods, is universally employed by
a variety of enterprises. According to the Financial Times, trade credit accounted
for 90% of world merchandise trade in 2007. Most buyers regard trade credit as
a new way to reduce prices. Trade credit provided to the retailer can attract the
retailer to order a larger volume, stimulate demand. And the target customer base
will be expanded if the retailer is willing to increase promotion efforts. However, in
the low-carbon environment, how trade credit affects the carbon emission reduction
decision and coordination has not been studied. Some related literature has stud-
ied joint emission reduction decisions in the supply chain (Zhou and Ye [53]). Cao
and Yu[6] and Heydari et al.[13]investigated how to realize supply chain coordina-
tion based on trade credit. However, few researches have discussed the problem of
introducing trade credit into green supply chain coordination and considering the
design of environmental contract to minimize carbon emissions. In fact, both sides
of the supply chain will consider the environmental performance and economic per-
formance when choosing the coordination contract. And under the cap-and-trade
system, how to design the optimal environmental contract is worth studying.

This paper focuses on the design of environmental contract, that is, how to
design a contract to maximize the protection of the environment when enterprises
are willing to accept it. Considering the contract needs to achieve the coordination
of economic performance and environmental performance, this paper puts forward
four compound contracts. Previous literature has shown that compound contracts
can better achieve supply chain coordination to a certain extent, such as revenue
and promotional cost-sharing contract (Bai et al.[3]), two-way cost-sharing contract (Wang et al.[46]), two-part tariff contract (Bai et al.[3]), buy-backs with promotional cost-sharing agreements (Krishnan et al.[25]), trade credit cost sharing with buy-back and modified trade credit with quantity-flexibility (Tsao[41]).

On this basis, the paper combines cost sharing contract with revenue sharing contract and proposes and compares four combination contracts, in which low-carbon investment cost sharing (Pakhira et al.[29]; Tu et al.[44]) and revenue-sharing contract (Ji et al.[20]) are very common in reality. The four combined contracts are: (1) the manufacturer shares the retailer’s revenue and cost (expressed by contract A), (2) the revenue sharing of both parties (expressed by contract B), (3) the cost sharing of both parties (expressed by contract C), and the retailer shares the manufacturer’s revenue and cost (expressed by contract D). Thus, this paper mainly studies the following questions:

1. How can the members formulate optimal carbon emission reduction decisions and trade credit period to maximize their profits under centralized and decentralized decision? 2. How does trade credit affect carbon emission reduction and supply chain coordination? 3. Can four contracts facilitate a win-win situation? Which contract is the optimal one to achieve the balance between the optimal profit and minimum carbon emissions?

There are three contributes to our research. Firstly, both manufacturers and retailers have made efforts to reduce carbon emissions. Furthermore, the paper also studies how trade credit affects carbon reduction efforts and supply chain coordination, which has rarely been studied before. Second, this paper considers how to design an environmental contract to protect the environment while increasing the profit of the supply chain. While the previous literature mostly designs and selects contracts from the perspective of economic performance. Third, this paper compares four composite contracts in the supply chain, whereas most previous studies only involved a single contract. We are trying to find an optimal contract to achieve the coordination of profit and environment.

2. Literature review. The priority of our work should be given to supply chain coordination considering trade credit with joint carbon emission reduction. Cap-and-trade mechanism and coordination contracts under trade credit have been widely studied in the previous literature. Having reviewed the previous literature, we unfold the motivation of this paper.

2.1. Cap-and-trade mechanism. At present, an enormous amount of literature related to supply chain management combine profit and environmental goals for research, especially the carbon emissions problem, which has attracted wide attention. Hua et al.[17] introduced the cap-and-trade system when solving the optimal order quantity, providing management insights for enterprises on how to manage carbon footprint in inventory management. Bouchery et al.[5] extended the EOQ model to take sustainability into account. Sustainable order quantity model is developed by assuming that each order and shortage produced certain carbon emissions. Zhang and Xu[52] studied the issue of multi-project production planning considering cap-and-trade mechanism. They demonstrated the effectiveness of cap-and-trade mechanism. Xu et al.[48] studied supply chain coordination based on cap-and-trade system and found that the two-part tariff contract could better realize supply chain coordination. Ji et al.[19] discussed the green decisions of supply chain under retail-channel and dual-channel environment, considering customers
with green preference. The results showed that the supply chain is more profitable under the cap-and-trade mechanism when customers have a higher green preference.

Cao and Yu[6] conducted relevant research on financial and operational decisions based on the low-carbon environment. It was found that the retailer can buy more products at a lower price, while reducing carbon emissions via decentralized decision. In general, a single contract can effectively coordinate a low-carbon supply chain based on the retailer’s financial constraints. Zhou and Ye [53] studied the problem of joint emission reduction under a dual-channel supply chain, and compared the obtained results with those under the traditional retail environment. Furthermore, this paper also discusses the efficiency of contract and its impact on decisions. Peng et al.[30] studied the optimal green decision problem of supply chains in a centralized and decentralized mode. Two contracts are proposed, and it is established that quantity discount contracts can facilitate a win-win scenario under the green environment. Tong et al.[40] considered that both members can decide whether to reduce carbon emissions in a retailer-led supply chain. And the impacts of the cap-and-trade system and low carbon preference on supply chain decision is studied. Su et al.[37] designed an optimized cooperation mechanism considering cost profit sharing contract to improve the overall coordination and profit of green closed-loop supply chain. Qian et al.[33] developed four special contracts to coordinate a sustainable supply chain, which includes a socially responsible manufacturer and a fair-minded retailer under cap-and-trade regulation. Ji et al.[20] studied the government quota setting of wholesale price and revenue sharing contract under the cap-and-trade regulations.

The results show that the cap-and-trade mechanism has a significant effect on decisions in green supply chains. In our work, we investigate the joint carbon emission reduction efforts under cap-and-trade mechanism. The difference from the above research is that we take the trade credit into account in our model to make it more realistic.

2.2. Promotional efforts. Under most circumstances, the importance of the retailer’s sales efforts is also reflected in its influence on market demand. There are many studies explored the coordination contracts on the assumption that demand depends on promotional efforts. For instance, Taylor[38] found that whether the demand depended on promotion efforts or not, designing reasonable channel rebates and return contracts could achieve valid coordination. Krishnan et al.[25] found that the strategy of buy-back fails to coordinate the channel effectively, while combining promotional cost-sharing with the buy-back contract, or adding other restrictions to the buy-back finally result in the expected coordination. Tsao and Sheen[43] introduced the sales learning curve into promotion costs and then discuss the coordination of supply chains. It is found that the promotion costs sharing coefficient can realize a win-win situation within a certain range. Ma et al.[28] discovered, through their studies, the impact on channel coordination with demand is affected by promotional efforts and quality efforts.

An innovative supply chain contract has been proposed via integrating the members’ endeavours. Bai et al.[3] evaluated how the contract affects a green supply chain, which assumed that demand is related to sales price, promotion effort and green effort. The results showed that the combination of two-part tariff and cost-sharing contract could facilitate a win-win situation preferably. Hosseini-motlagh et al.[15] investigated the coordination of a supply chain comprising two retailers and one manufacturer. Among them, demand is related to the promotion level and
trade credit period. Heydari and Asl-Najafi[12] proposed a sales rebate contract to coordinate promotion level and order quantity simultaneously. Ebrahimi et al. [8] designed a contract based on delay payment, considering the impact of promotional efforts on random demand. Phan et al.[32] considered a supply chain where the retailer failed to conduct effective promotions, considering their finance dilemma resulting from the low credit rating. And they proposed a coordinating contract which can achieve the mutual benefit for the manufacturer and retailer when the interest rate is competitive. Ranjan and Jha[35] investigated the coordination of a dual-channel supply chain, assuming that price, green level and promotion level all affect market demand. Considering that both the promotion efforts of the e-retailer and the logistics service efforts of the third-party logistics will affect the demand, Tu et al.[44] established and solved the game model under different time series and different contract scenarios. Jian et al.[21] designed a profit-sharing contract to coordinate the green closed-loop supply chain with fairness concern on the basis of the retailer’s sales efforts.

The above literature proves that sales efforts have a significant influence on supply chain management. Under the low-carbon environment, promotion efforts are often used as a way for downstream enterprises to reduce carbon emissions. Therefore, this paper studied joint carbon emission reduction decisions, including manufacturers’ emission reduction efforts and retailers’ promotion efforts.

2.3. Contracts under trade credits. In recent years, trade credit policies have raised much attention in the field. If a credit payment period is provided, the consumers’ purchase demand increases (Kreng and Tan[24]). Many researchers have noted the importance of trade credits. Goyal [10] firstly introduced delay payment into the EOQ model. Giannetti et al.[9] demonstrated that whether in a large company with sufficient funds or a small company with limited funds, trade credits are easily offered. Lee et al.[26] discovered that when suppliers provide trade credits at an industrial average, the trade credits are conducive to both parties’ performance. When suppliers provide trade credits at a level above the industrial average, the trade credits are not conducive to buyers’ performance. Peura et al.[31] expounded how trade credit affects the price decisions of two competing enterprises. Recent researches have demonstrated that trade credit can soften price competition when firms have limited capital. Compared with other financing methods, some literature shows that trade credit, as an internal financing method, can effectively alleviate the problem of capital shortage. Lin et al.[27] compared confirmed warehouse financing and trade credit financing under the assumption of retailer capital constraints. Xu et al.[49] assumed that the manufacturer borrows two loans to implement the ordering decision and low-carbon investment, and compared the strategies of partial credit guarantee (PCG) and trade credit combined with PCG. An et al.[2] analysed and compared green credit financing and trade credit financing. An important prerequisite for green loans is that products are green upgraded to meet predetermined environmental standards. Qin et al.[34] studied the value of advance payment financing on carbon emission reduction and production in supply chain. In the case of manufacturer capital constraints, they compared bank financing and mixed financing.

Similar to price discount and quality improvement strategies, trade credit has an important impact on supply chain performance. The role of trade credit in supply chain coordination is deeply studied. Jaber and Osman[18] studied how supply chain members coordinate orders through trade credit to minimize costs. The study found
that trade credit benefits supply chain. Heydari et al.[13] proposed a two-level trade credit contract that can achieve the outcome of win-win. The order quantity and promotion decisions can be coordinated simultaneously. Cao and Yu[6] proposed four composite contracts to analyse the supply chain coordination problem under the two-level trade credit.

Pakhira et al.[29] constructed an uncertain multi-item supply chain to study the profit maximization problem considering the trade credit and promotion cost-sharing. Both coordinated and uncoordinated models are considered. Cao and Yu[6] studied the coordination problem considering the existence of certain default risk in trade credit. The study found that trade credit needs to be combined with other contracts (such as buybacks or quantitative flexibility) to facilitate a win-win situation. Phan et al.[32] assumed that the supplier provided internal financing to the retailer engaged in promotional efforts and investigated whether the existing coordination contracts are still valid. Furthermore, a new coordination contract is proposed to realize the arbitrary distribution of profits among members.

The above literature proves that trade credit can affect the decision and coordination of the supply chain, but how trade credit affects environmental performance in a green environment is rarely studied. Aljazzar et al.[1] found that delay payment can boost the profit and also contribute to sustainable development. However, supply chain coordination is not involved. Thus, the paper will focus on green supply chain coordination with trade credit.

2.4. Motivations and highlights. Table 1 also summarizes the main differences between the models in the literature and those in this paper. The following factors are considered: (i) trade credit, (ii) carbon reduction efforts, (iii) retail price, (iv) promotional efforts, (v) single contract, and (vi) composite contract. It can be observed from table 1 that the management and coordination of sustainable supply chain is getting more and more attention. Only a few papers probing into joint emission reduction strategies launched by the members under the low carbon environment. What’s more, fewer studies had shed light on bringing trade credit into green supply chains coordination. Likewise, little research has been done to improve economic and environmental performance by introducing composite coordination contract. Therefore, we will focus on the coordination problems under cap-and-trade and trade credits.

3. Model assumptions and notations. A two-level sustainable supply chain consisting of one manufacturer and one retailer is considered. Assume that the manufacturer and retailer are in Nash equilibrium and make decisions at the same time. Trade credit and cap-and-trade mechanism are considered. This paper aims to analyse how to design an environmental contract to minimize carbon emissions and which contract can achieve the coordination of economic performance and environmental performance at the same time when both enterprises of the supply chain are making efforts to reduce carbon emissions.

3.1. Notations. For the sake of convenience, the symbols are categorized into the following three types: parameters, decision variables, and functions, as described in Table 2.

3.2. Assumptions. Assumption 1. Considering customers’ environmental awareness, member’s carbon emission reduction efforts will have a positive impact on the customers’ demand. In addition, trade credit will also stimulate demand.
Table 1. Summary of Related Literature

| source                        | Decision variables | Demand dependency | Contract |
|-------------------------------|--------------------|-------------------|---------|
| Taylor[38]                    | x                  | x                 | x       |
| Krishnan et al.[25]           | x                  | √                 | x       |
| Tsao and Sheen[43]            | x                  | √                 | x       |
| Ma et al.[28]                 | x                  | √                 | x       |
| Xu et al.[48]                 | x                  | √                 | x       |
| Ji et al.[19]                 | x                  | √                 | x       |
| Bai et al.[3]                 | x                  | √                 | x       |
| Heydari et al.[13]            | x                  | √                 | x       |
| Zhou and Ye[53]               | x                  | √                 | x       |
| Yang et al.[50]               | x                  | √                 | x       |
| Hosseini-Motlagh et al.[15]   | x                  | √                 | x       |
| Pakhira et al.[29]            | x                  | √                 | x       |
| Phan et al.[32]               | x                  | √                 | x       |
| Tsao[42]                      | x                  | √                 | x       |
| Ranjan and Jha[35]            | x                  | √                 | x       |
| This paper                    | x                  | √                 | x       |

Table 2. Symbols in this paper

| Parameters | Description |
|------------|-------------|
| C          | The production cost per unit |
| W          | The wholesale price per unit |
| I          | The market interest rate |
| v          | The effectiveness of carbon reduction efforts on carbon emissions for making a unit, $v > 0$ |
| ε          | The manufacturer’s carbon emissions for making a product without efforts on carbon reduction |
| C_M        | The manufacturer’s carbon pollution limit or cap |
| W_e        | The trading price of carbon emissions |
| η1         | The investment cost coefficient on carbon reduction efforts, $η1 > 0$ |
| η2         | The investment cost coefficient on promotional efforts, $η2 > 0$ |
| a          | Market scale parameter, $a > 0$ |
| b          | Price influence on the demand rate, $b > 0$ |
| γ1         | Effect of carbon reduction effort on demand, $γ1 > 0$ |
| γ2         | Effect of promotional effort on demand, $γ2 > 0$ |

Decision variables

| s           | The retailer’s promotional efforts |
| P           | The retail price per unit |
| M           | The length of the trade credit period offered by the manufacturer in years. $M > 0$ represents a credit payment, $M = 0$ represents an advance payment, and $M < 0$ represents a cash payment |
| θ           | The manufacturer’s carbon reduction efforts |

Functions

| $\pi_i$     | The supply chain member i’s profit per year; $i = s, r, sc$ refer to the manufacturer, the retailer and the supply chain, respectively |
| *           | Represents the optimal value of a decision variable |
According to the Bai et al.\cite{3} and Heydari et al.\cite{13}, we assume the customers’ demand is:

\[ D = a - bp + \gamma_1 \theta + \gamma_2 s + \beta M \] (1)

The linear demand functions, which are widely used in previous literature, are inherited in this paper (Yang et al.\cite{51}, Yang et al.\cite{50}, Xiao et al.\cite{47}). Such linear demand functions are used because they can achieve approximate and satisfactory fit to certain types of demand (Sayman et al.\cite{36}). In practice, there are three simple ways to represent an increasing demand of the credit period \( M \): linear, polynomial, or exponential. For simplicity, we assume that the demand rate is a positive linear function of the credit period (Teng et al.\cite{39}).

In the demand functions, \( a \) represents the maximum potential demand and suppose \( a \) is big enough. Thus, the demand function is positive, and reversely affected by the retail price and has a direct relationship with the joint carbon reduction efforts. Also, trade credit provided by the manufacturer to the retailer, as a way to reduce prices, can directly promote the increase of demand.

**Assumption 2.** Both upstream and downstream enterprises in the supply chain will invest to reduce carbon emissions. Following the existing literature, e.g., Bai et al.\cite{4} and Hong and Guo\cite{14}, we denote the investment in low-carbon technology as \( C(\theta) = \eta_1 \theta^2 / 2 \), implying a convex increasing cost of emissions reduction, where \( \eta_1 \) is the low-carbon investment coefficient.

Moreover, similar to the work of Guo et al.\cite{11}, the retailer has an extra investment \( C(s) = \eta_2 s^2 / 2 \) for selling low-carbon products to the target market (i.e., the retailer’s promotional efforts investment cost), which can result from advertising, supervision, evaluation, and other non-price promotional activities. \( \eta_2 \) is the promotional efforts investment coefficient.

**Assumption 3.** For firms, carbon emissions are mainly generated in the production process (Xu et al.\cite{48}). For the sake of simplicity, this paper just considers carbon emissions produced in the production process and neglects other parts. Therefore, the total carbon emissions are assumed to be linear in production quantity. In addition, we assume that the unit amount of carbon emissions from the manufacturer’s production processes is exogenously given; this holds for the situation where the manufacturer only greens his production process. According to the notations, the unit carbon emission reduction of the manufacturer after low carbon efforts is \( \varepsilon - v\theta \).

The retailer’s carbon reduction efforts are mainly reflected in the increase of sales of low-carbon products, so the total carbon reduction after the joint efforts is \((\varepsilon - v\theta)D\). Carbon markets support the sale or purchase of carbon permits (Yang et al.\cite{51}). Thus, the carbon trading cost of the manufacturer is \( W_m[(\varepsilon - v\theta)D - C_m] \). Carbon trading costs can be positive or negative. Similar assumption can be found in Ji et al.\cite{19} and Ji et al.\cite{20}.

4. **Mathematical model without coordination contracts.** In this section, two basic supply chain models are considered. One is a decentralized supply chain (superscript \( d \)); the other is a centralized supply chain (superscript \( c \)). The optimal solutions are solved and analyzed.

4.1. **Decentralized decision.** Under this circumstance, the retailer and manufacturer have their own decisions respectively to acquire the highest profits. The
profits of the members are expressed as:

\[ \pi_r^d = (P - W)D + PMID - \frac{n_2s^2}{2} \]  

(2)

\[ \pi_m^d = (W - C)D - WMID - \frac{n_1\theta^2}{2} - W_e[(\varepsilon - v\theta)D - C_m] \]  

(3)

For the retailer, the profit function mainly includes profit from selling products, interest obtained from trade credit and promotion cost. For the manufacturer, the profit function mainly includes the profit of selling products, the interest lost due to trade credit, the investment cost as well as the cost (income) about purchasing (selling) carbon emission permits. We assume that there is a Nash equilibrium between the manufacturer and the retailer, and both sides make their own decision variables at the same time. We can obtain the Proposition 1.

**Proposition 1.** If \( -(\beta vW_e)^2 + 2WI\beta (\eta_1 - W_e\varepsilon y_1) - (IW\theta)^2 \geq 0, 2b\eta_2 - (1 + MI)y_2^2 \geq 0 \) and \( \eta_1 > 2v\eta_1W_e \) are met, which means that the profit functions \( \pi_m^d \) and \( \pi_r^d \) are concave in \( M, \theta, P \) and \( s \). The optimal values are given by the following:

\[ M^{d^*} = \frac{W (\beta + (bP^{d^*} - y_2s^{d^*} - y_2\theta^{d^*} - a)I) + \beta (v\theta^{d^*} W_e - W_e\varepsilon - C)}{2WI\beta} \]  

(4)

\[ \theta^{d^*} = \frac{(W - C - WM^{d^*}I - \varepsilon W_e) y_1 + vW_e (a - bP^{d^*} + y_2s^{d^*} + \beta M^{d^*})}{n_1 - 2v\eta_1W_e} \]  

(5)

\[ P^{d^*} = \frac{(a + y_1\theta^{d^*} + y_2s^{d^*} + \beta M^{d^*}) (1 + MI) + bW}{2b (1 + M^{d^*}I)} \]  

(6)

\[ s^{d^*} = \frac{(P^{d^*} - W + P^{d^*} M^{d^*}I) y_2}{n_2} \]  

(7)

All the proof processes and Symbolic expression in propositions of this paper are presented in the Appendix as a reference. Base on Proposition 1, Corollary 1 can be deduced as follows:

**Corollary 1**

(1) \( M \) and \( \theta \) decrease with \( I, C, \varepsilon \) and \( P \), and increase with \( v \). Also, \( \theta \) increases with \( M \).

(2) \( P \) decreases with \( M \) and \( I \), increases with \( W \) and \( \theta_1 \). \( s \) decreases with \( W \), increases with \( M, y_2 \) and \( I \). Also, \( P \) increases with \( s \).

The economic explanation of Corollary 1 is as follows. The manufacturer’s cost will increase when a higher market interest rate, cost and carbon emissions are had. Thus, the manufacturer will reduce its trade credit period and carbon reduction efforts to save its capital expenditure. When the low carbon technology can better reduce carbon emissions, the manufacturer will engage in more carbon reduction efforts. Meanwhile, the manufacturer has more capital to extend trade credit period for stimulating market demand. When the trade credit period is extended, the interest loss will correspondingly become higher from offering the trade credit of the manufacturer is, the higher the demand will be; in this sense, the manufacturer will increase his carbon reduction efforts with the trade credit period. Thus, trade credit can make the manufacturer make decisions on higher carbon reduction efforts to achieve environmental protection.

If the trade credit period and the market interest rate are sufficient, the retailer can gain more interest income and would be more inclined to lower the price and increase the promotional efforts to stimulate demand. The retail price will increase
as wholesale price due to increased cost. Besides, the promotion level of the retailer will be reduced to reduce the promotion cost. Therefore, the reduction of the wholesale price is conducive to the increase of market demand. The trade credit is also conducive to the increase of promotional efforts.

4.2. Centralized decision. In this scenario, the retailer and manufacturer make decisions together to acquire maximal profit in the supply chain. According to the model, the profit function is:

$$\pi^c_{sc} = (P - C)D + (P - W)MID - \frac{\eta_1 \theta^2}{2} - \frac{\eta_2 s^2}{2} - W_e [(\varepsilon - v \theta)D - C_m]$$ (8)

The optimal solutions are made by derivation. With the first and second derivatives of $\pi^c_{sc}$ regarding $M, \theta, P$ and $s$. Proposition 2 can be obtained.

**Proposition 2.** In a centralized supply chain, if $|H| \geq 0$ and $2v y_1 W_e - n_1 < 0$ are met, which means that the $\pi^c_{sc}$ is concave in $M, \theta, P$ and $s$. The optimal values are given by the following:

$$M^c = \frac{(a - b P^c + y_1 \theta^c + y_2 s^c) (P - W) + \beta (v \theta W_e - W_e \varepsilon - C + P)}{2 \beta I (W - P)}$$ (9)

$$\theta^c = \frac{[P^c - C - \varepsilon W_e + (P^c - W) M^c I] y_1 + v W_e (a - b P^c + y_2 s^c + \beta M^c)}{n_1 - 2 v y_1 W_e}$$ (10)

$$P^c = \frac{b C + b W_e (\varepsilon - v \theta^c) + (1 + M^c I) (a + y_1 \theta^c + y_2 s^c + \beta M^c)}{2 b (1 + M^c I)}$$ (11)

$$s^c = \frac{[P^c - C - W_e (\varepsilon - v \theta^c) + (P^c - W) M^c I] y_2}{n_2}$$ (12)

Based on Proposition 2, Corollary 2 can be deduced as follows:

**Corollary 2**

1. Increases in $C, \varepsilon$ and $\eta_1$ cause decreases of $M$ and $\theta$, while increases in $v$ and $W$ cause increases of $M$ and $\theta$. Moreover, an increase in $M$ increases $\theta$.

2. Increases in $M, I, \theta$ and $v$ cause a decrease in $P$, while increases in $W_e$ and $\varepsilon$ increase $P$. Increases in $M, \varepsilon, W_e$ and $I$ decrease $s$, while increases in $v$ and $\theta$ increase $s$. Moreover, an increase in $s$ increases $P$.

Corollary 2 can be elaborated on in detail. The main difference between two scenarios is reflected in the influence on the carbon trading cost. The higher the unit carbon emissions and carbon trading price, the higher the carbon trading cost. Therefore, the supply chain would increase the price and decrease promotional efforts for cost reduction. When the effectiveness of the carbon reduction efforts on carbon emissions for making a unit and carbon reduction efforts reach a certain level, in another words, when green technology can effectively reduce carbon emissions, the carbon transaction cost will decrease. The supply chain would determine a lower price and a higher promotion effort to attract customers. The other related explanations remain the same as that of Corollary 1.

Comparing centralized decision with decentralized decision, we can find that the main difference is that the manufacturer and retailer make decisions as a whole to maximize the whole supply chain. Relatively speaking, decentralized decision will reduce the total profit of supply chain due to the double marginalization.

Therefore, a higher supply chain profit under centralized decision is realized. However, the increase in total profit may not necessarily increase the profits of both
parties. As a result, the profit of an individual member of the supply chain may be impaired under centralized decision. To facilitate further cooperation between the supply chain parties, four combination contracts are proposed in the following section. It is hoped that while improving the overall economic and environmental performance, it also can increase the respective benefits of the manufacturer and retailer.

5. Mathematical models with four composite contracts. In many supply chains, enterprises consent to achieve more value through contracts. In the contract arrangement, two contracts are widely used: cost sharing (Bai et al. [3]; Cao and Ke [7]) and revenue sharing contract (Ji et al. [20]). For example, Blockbuster Inc used a revenue sharing contract in its supply chain, and its market share increased from 24% in 1997 to 40% in 2002 (Warren and Peer [45]).

Thus, this section presents four mathematical models with four different contracts as follows: (1) the manufacturer shares both the retailer’s revenue and cost (denoted by Contract A), (2) revenue sharing between both parties (denoted by Contract B), (3) cost sharing between both parties (denoted by Contract C), and (4) the retailer shares both the manufacturer’s revenue and cost (denoted by Contract D).

5.1. Contract A: Manufacturer sharing the retailer’s revenue and cost. In this scenario, the promotion cost is shared by both parties. Besides, the retailer shares the income $\rho_1 PD$ with the manufacturer. The proportion of promotional cost borne by the manufacturer is $\lambda_1$. That is, the profit functions of both parties under the contract are respectively:

\[
\pi_r^A = (1 - \rho_1) PD - WD + PMID - (1 - \lambda_1) \frac{\eta_2 s^2}{2}
\]

\[
\pi_m^A = (W - C)D + \rho_1 PD - W M ID - \frac{\lambda_1 \eta_2 s^2}{2} - \frac{\eta_1 \theta^2}{2} - W \epsilon [v - \rho_1 D - C_m]
\]

The optimal solutions are made by derivation. Thus Proposition 3 can be obtained.

Proposition 3. The optimal decision variables are given by the following:

\[
M_A^* = \frac{(W - C + \rho_1 P - W M_A^* I - \epsilon W_e) \beta - M_A^* I (a - b P^* + y_1 \theta_A^* + y_2 s_A^*)}{2 W I \beta}
\]

\[
\theta_A^* = \frac{(a + y_1 \theta_A^* + y_2 s_A^* + \beta M_A^*) (1 + M_A^* I - \rho_1) + b W}{2 b (1 + M_A^* I - \rho_2)}
\]

\[
P_A^* = \frac{(1 - \rho_1) P_A^* - W + PM_A^* I}{(1 - \lambda_1) n_2}
\]

\[
s_A^* = \frac{(1 - \rho_1) P_A^* - W + PM_A^* I}{(1 - \lambda_1) n_2}
\]

Both parties show readiness and willingness to adopt the coordination contract only when the members’ profits after coordination are higher than before, which is obvious. Furthermore, to make sure that the profits after coordination outweigh members’ profits under decentralized decision, the following conditions need to be met: $\pi_r^A \geq \pi_r^{d^*}$, $\pi_m^A \geq \pi_m^{d^*}$. The validity analysis of Contract A will be given in the numerical examples section.
5.2. Revenue sharing between both parties. In this scenario, the members enjoy sales revenue mutually. The revenue sharing coefficient of the manufacturer and retailer is $\tau_1$ and $\rho_2$. That is, the profit functions of both parties under the contract are respectively:

$$\pi^B_r = (1 - \rho_2) PD - (1 - \tau_1) WD + PMID - \frac{\eta_2 s^2}{2}$$

$$\pi^B_m = (1 - \tau_1) WD + \rho_2 PD - WMD - CD - \frac{\eta_1 \theta^2}{2} - W_r [(e - v\theta)D - C_m]$$

The optimal solutions are made by derivation. Thus Proposition 4 can be obtained.

**Proposition 4.** The optimal decision variables are given by the following:

$$M^*_B = \frac{((1 - \tau_1) W + \rho_2 P - C - W_r (e - v\theta^*_B)) \beta - M^*_B I (a - bP + y_1 \theta^*_B + y_2 s^*_B)}{2WI\beta}$$

$$\theta^*_B = \frac{[(1 - \tau_1) W + \rho_2 P - C - W M^*_B I - \varepsilon W_e] y_1 + v W_e (a - bP^*_B + y_2 s^*_B + \beta M^*_B)}{1 - 2v y_1 W_e}$$

$$P^*_B = \frac{(a + y_1 \theta^*_B + y_2 s^*_B + \beta M^*_B) (1 + M^*_B I - \rho_2) + b(W(1 - \tau_1))}{2b(1 + M^*_B I - \rho_2)}$$

$$s^*_B = \frac{[P^*_B - \rho_2 P^*_B - W + \tau_1 W + PM^*_B I] y_2}{n_2}$$

Therefore, to guarantee that the profits after coordination outweigh members’ profits under decentralized decision, the following conditions need to be met: $\pi^B_r \geq \pi^d_r$, $\pi^B_m \geq \pi^d_m$. The validity analysis of Contract B will be given in the numerical examples section.

5.3. Contract C: Cost sharing of both parties. In this scenario, the members share their own effort cost mutually the members. The cost sharing coefficient of the manufacturer and retailer is $\varphi_1$ and $\lambda_2$. That is, the profit functions of both parties under the contract are respectively:

$$\pi^C_r = (P - W) D + PMID - (1 - \lambda_2) \frac{\eta_2 s^2}{2} - \varphi_1 \frac{\eta_1 \theta^2}{2}$$

$$\pi^C_m = (W - C) D - WMD - \lambda_2 \frac{\eta_2 s^2}{2} - (1 - \varphi_1) \frac{\eta_1 \theta^2}{2} - W_r [(e - \nu \theta) D - C_m]$$

The optimal solutions are made by derivation. Thus Proposition 5 can be obtained.

**Proposition 5.** The optimal decision variables are given by the following:

$$M^*_C = \frac{W (\beta + (bp^*_C - y_2 s^*_C - y_1 \theta^*_C - a) I) + \beta (v \theta^*_C W_e - W_e e - C)}{2WI\beta}$$

$$\theta^*_C = \frac{[W - C - W M^*_C I - \varepsilon W_e] y_1 + v W_e (a - bP^*_C + y_2 s^*_C + \beta M^*_C)}{(1 - \varphi_1) n_1 - 2v y_1 W_e}$$

$$P^*_C = \frac{(a + y_1 \theta^*_C + y_2 s^*_C + \beta M^*_C) (1 + MI) + b (1 - \tau_2 W)}{2b(1 + M^*_C I)}$$

$$s^*_C = \frac{[P^*_C - \rho_2 P^*_C - W + PM^*_C I] y_2}{(1 - \lambda_2) n_2}$$
Therefore, to guarantee that the profits after coordination outweigh members’ profits under decentralized decision, the following conditions need to be met: \( \pi^C_r \geq \pi^D_r \), \( \pi^C_m \geq \pi^D_m \). The validity analysis of Contract C will be given in the numerical examples section.

5.4. Contract D: retailer sharing both the manufacturer’s revenue and cost. In this scenario, the carbon emissions cost is shared by both parties. Besides, the manufacturer shares the income \( \tau_2 WD \) with the retailer. The proportion of carbon emissions cost borne by the retailer is \( \varphi_2 \). That is, the profit functions of both parties under the contract are respectively:

\[
\pi^D_r = (P - W)D + PMID - \eta_2 s^2 - \varphi_2 \frac{\eta_1 \theta^2}{2} + \tau_2 WD
\]

\[
\pi^D_m = (1 - \varphi_2) WD - CD - WMID - (1 - \varphi_2) \frac{\eta_1 \theta^2}{2} - W_c \left[ (\varepsilon - \nu \theta) D - C_m \right]
\]

The optimal solutions are made by derivation. Thus Proposition 6 can be obtained.

**Proposition 6.** The optimal decision variables are given by the following:

\[
M^*_D = \frac{(1 - \tau_2) W (\beta + (bP^*_D - y_2 s^*_D - y_2 \theta^*_D - a) I + \beta (v \theta^*_D W_e - W_c \varepsilon - C))}{2W I \beta}
\]

\[
\theta^*_D = \frac{[1 - (1 - \tau_2) W - C - WM^*_D I - e W_c] y_1 + v W_e (a - b P^*_D + \beta M^*_D + y_2 s^*_D)}{(1 - \varphi_2) n_1 - 2v y_1 W_c}
\]

\[
P^*_D = \frac{a + y_1 \theta^*_D + y_2 s^*_D + \beta M^*_D}{2b (1 + M^*_D I)} (1 + MI) + b (1 - t_2 W)
\]

\[
s^*_D = \frac{(P^*_D - W - P^*_D M^*_D I) y_2}{n_2}
\]

Similarly, to guarantee that the profits after coordination outweigh members’ profits under decentralized decision, the following conditions need to be met: \( \pi^D_r \geq \pi^*_r \), \( \pi^D_m \geq \pi^*_m \). The validity analysis of Contract D will be given in the numerical examples section.

6. Numerical analysis. Because of the complexity of the formula, it is still a challenge to compare the optimal profit function analytically and obtain the optimal contract selection. Therefore, we turn to numerical research for more insights. We set \( C = $2/unit, W = $10/unit, I = $0.7/unit/year, a = $60, b = 1, y_1 = 0.6, y_2 = 0.4, \beta = 1.5, n_1 = 6, n_2 = 5, W_c = 0.7/unit, \varepsilon = 10, \nu = 1, C_m = 1000 \) for the numerical study (Ma et al.[28]; Bai et al.[3]).

6.1. Optimal solutions for the example. Given the data, the computational results derived from the different models are summarized in Table 3. The optimal solutions for centralized and decentralized decisions without contracts are in the first and second rows of table 3. It is for the purpose of comparing the decision variables and profit changes concerning four composite contracts with different parameters. For this case, when the retailer’s revenue sharing coefficient in contract A is \( \rho_1 = 0.1 \) and the promotional cost sharing coefficient is \( \lambda_1 = 0.7 \), the associated manufacturer, retailer and supply chain profits would be \$407.49, \$796.88 and \$1204.37. The values are shown in the third row. Among them, \( E(D) \) means the total carbon emissions and \( E(D) = (\varepsilon - \nu \theta) D \).
| Model       | $M$  | $P$  | $\theta$ | $s$  | $\pi_r$ | $\pi_m$ | $\pi_{sc}$ | $E(D)$ |
|-------------|------|------|----------|------|---------|---------|------------|--------|
| Centralized | 0.74 | 33.694 | 7.916 | 3.401 | -       | -       | 4094.153  | 171.326|
| Decentralized | -0.39 | 37.683 | 3.402 | 1.389 | 228.357 | 762.078 | 990.434   | 94.911 |
| ContractA $[\rho_1, \lambda_1]$ |       |       |          |      |         |         |            |        |
| [0.1, 0.7] | -0.14 | 37.961 | 3.821 | 5.469 | 407.49  | 796.88  | 1204.37    | 131.86 |
| [0.1, 0.6] | -0.02 | 36.773 | 3.707 | 3.325 | 650.65  | 829.39  | 1480.03    | 172.24 |
| [0.1, 0.5] | 0.04   | 36.501 | 3.735 | 3.870 | 650.65  | 829.39  | 1480.03    | 172.24 |
| [0.2, 0.5] | 0.08   | 35.660 | 4.104 | 6.088 | 4116.45 | 1227.64 | 5344.10   | 554.05 |
| [0.3, 0.5] | 0.49   | 36.049 | 3.938 | 5.004 | 1724.03 | 967.01  | 2691.04   | 314.26 |
| ContractB $[\rho_2, \tau_1]$ |       |       |          |      |         |         |            |        |
| [0.1, 0.6] | -0.73  | 35.846 | 3.611 | 0.804 | 86.24   | 740.29  | 826.54     | 63.78  |
| [0.2, 0.6] | -0.25  | 34.136 | 3.864 | 1.387 | 327.23  | 788.97  | 1116.20    | 122.98 |
| [0.3, 0.6] | 0.21   | 33.440 | 3.985 | 1.953 | 953.53  | 884.78  | 1838.31    | 228.22 |
| [0.4, 0.6] | 0.68   | 33.057 | 4.060 | 2.519 | 2500.88 | 1077.13 | 3578.01    | 419.39 |
| [0.2, 0.5] | -0.10  | 34.401 | 3.841 | 1.608 | 470.48  | 810.54  | 1281.02    | 148.85 |
| [0.2, 0.4] | 0.05   | 34.613 | 3.825 | 2.519 | 2550.88 | 1077.13 | 3578.01    | 419.39 |
| ContractC $[\varphi_1, \lambda_2]$ |       |       |          |      |         |         |            |        |
| [0.5, 0.5] | -0.40  | 43.264 | 6.599 | 3.367 | 198.32  | 808.30  | 1006.62    | 42.36  |
| [0.5, 0.4] | -0.35  | 42.287 | 6.753 | 2.925 | 236.66  | 819.58  | 1056.24    | 45.20  |
| [0.5, 0.3] | -0.32  | 41.707 | 6.833 | 2.562 | 261.25  | 826.59  | 1087.83    | 46.95  |
| [0.4, 0.2] | -0.35  | 41.603 | 5.377 | 2.148 | 247.94  | 842.09  | 1090.03    | 63.22  |
| [0.5, 0.2] | -0.30  | 41.341 | 6.876 | 2.269 | 277.01  | 831.03  | 1108.03    | 48.07  |
| [0.6, 0.2] | -0.22  | 40.962 | 9.507 | 2.473 | 315.25  | 795.62  | 1110.88    | 9.18   |
| ContractD $[\varphi_2, \tau_2]$ |       |       |          |      |         |         |            |        |
| [0.6, 0.05] | -0.28  | 41.512 | 9.147 | 1.899 | 263.38  | 772.25  | 1035.63    | 13.98  |
| [0.6, 0.05] | -0.27  | 41.512 | 9.147 | 1.899 | 263.38  | 772.25  | 1035.63    | 13.98  |
| [0.6, 0.05] | -0.26  | 41.404 | 9.904 | 1.945 | 269.71  | 776.63  | 1046.34    | 1.66   |
| [0.6, 0.05] | -0.28  | 41.512 | 9.147 | 1.899 | 263.38  | 772.25  | 1035.63    | 13.98  |
| [0.6, 0.04] | -0.27  | 41.307 | 9.232 | 1.920 | 277.15  | 775.09  | 1052.24    | 13.03  |
| [0.6, 0.003] | -0.25  | 41.105 | 9.316 | 1.941 | 291.41  | 778.01  | 1069.42    | 12.02  |

Table 3 shows the optimal solutions for the example. The profits of supply chain members under different coordination parameters are also provided. Furthermore, the following insights can be deduced from Table 3:

1. Table 3 illustrates that, the price under centralized decision is lower outweighs that of decentralized decision, but the trade credit period, promotion efforts and carbon emission reduction efforts are higher. Therefore, there is a higher market demand under the centralized decision. Both sides of the supply chain should seek long-term cooperation to achieve higher profits.

2. Carbon reduction efforts under the centralized decision are higher, as are the carbon emissions. From the above analysis, we can see that the market demand will increase rapidly under the centralized scenario. Therefore, although the unit carbon emission is reduced, the total carbon emissions are increased.
(3) Four composite contracts proposed in this paper can coordinate the supply chain within limits. When the cost sharing coefficients are high, contract C fails to achieve the outcome of win-win. However, when the promotional cost sharing coefficient is small, the contract can help the manufacturer to increase demand and be able to coordinate effectively.

(4) As seen in Contract B, the manufacturer’s profit decreases when the revenue sharing coefficient is large (i.e., transfer more revenue to the retailer). Therefore, the contract cannot realize the increase of profit at this time. When the coefficient of the manufacturer’s revenue sharing is small and another contract coefficient is large, the manufacturer can obtain more capital through contract coordination to extend the trade credit period and increase the demand, thus achieving a win-win result.

(5) With the coefficients of manufacturer’s revenue sharing and promotional cost sharing increase, the members’ profits decrease. At this point, the manufacturer would decide to shorten the trade credit period to raise available funds. In Contracts A, B and D, the manufacturer’s profits increase when the contract coefficients are within a certain range. Therefore, the manufacturer will extend the trade credit period and carbon reduction efforts to increase the demand, which also benefits the retailer’s profit. In Contract C, the manufacturer’s profit decreases as the promotional cost sharing coefficient due to the prolonged advance payment period.

(6) Under effective coordination, the optimal trade credit period and carbon reduction efforts are greater than those under the decentralized decision. From the above analysis, it can be concluded that the trade credit period is a key factor in achieving coordination, since it can greatly affect demand. Trade credits are extended when the manufacturer benefits from the contract because of his dominance over the supply chain, thus the contract can effectively achieve coordination. Furthermore, it is also observed that the carbon emissions after coordination are more than those under the decentralized decision in Contracts A and B, contrary to the results of Contracts C and D. Therefore, the increase in demand not only leads to profit increases but also leads to carbon emissions increases to a certain extent.

6.2. Effects of $W_c$ on the optimal solutions. Figure 1 unveils the effects of the carbon trading price $W_c$ on the optimal solutions and the members’ profits. The change in total carbon emissions is further given. Judging from Figure 1, the following insights can be obtained:

(1) The trade credit period will be shortened as the carbon trading price to obtain more available funds and increase the carbon reduction efforts to reduce carbon emissions to reduce costs. The trade credit period is gradually reduced, which changes from credit payment to advance payment. In response, retail price and effort level have increased and decreased for the sake of profit. This explains Figure 1 (a) and (b).

(2) The rise in the carbon trading price has led to a higher profit for the manufacturer when investing more in carbon reduction efforts. Meanwhile, as the retail price increases and the promotional efforts are lessened, the demand and the profit decrease correspondingly. At this point, the total profit would gradually decrease and then increase slightly afterwards, which explains Figure 1 (c) and (d).

(3) Figure 1 implies that although the rise in the carbon trading price is slightly conducive to the manufacturer, it is extremely detrimental to the retailer. Thus, the total profit shows a downward trend. However, considering the environment,
it is more advantageous to set up a higher carbon trading price. Therefore, the relevant institutions can increase the carbon trading price to reduce emissions.

6.3. Effects of $\varepsilon$ on the optimal solutions. Figure 2 unveils the effects of the initial emissions $\varepsilon$ on the optimal solutions and the members’ profits. The change in total carbon emissions is further given. We can obtain the following insights:

1. An increase in initial emissions causes an increase in the carbon emissions cost. Consequently, the manufacturer would shorten the trade credit period and reduce carbon reduction efforts from the cost standpoint, eventually resulting in a demand decrease. In response, the retailer will increase retail price and reduce promotional efforts for the sake of profit. This explains Figure 2 (a) and (b).

2. The member’s profit decreases with the initial emission, so does the total profit of supply chain. However, the total carbon emission is also reduced, which is caused by a large reduction in market demand. This explains Figure 2 (c) and (d).

3. Figure 2 suggests that the initial carbon emissions damages economic performance. Hence, considering the profits, the supply chain would expect to realize lower initial carbon emissions.

6.4. Comparison of the four composite contracts. Table 4 shows the joint impacts of the four composite contracts on supply chain performance. We change one parameter of the contract each time and then compare the contracts. The
increase rates could be obtained based on the decentralized decision. The following insights can be obtained:

1. The comparison of the four contracts above illustrates that the retailer can achieve a higher profit increase rate than the manufacturer in most cases, which means the retailer is more likely to benefit from contracts, as it effectively increases the profit. As a result, the retailer is more willing to cooperate with the manufacturer to obtain a greater profit.

2. Among the four contracts, the members’ profits increase most under Contract A, and increase smallest in Contract D. Therefore, contract A is more popular with supply chain members, which also benefits the overall profit when revenue sharing coefficient of the retailer is larger, the promotional cost sharing coefficient is smaller. However, at this point, the manufacturer will set a longer trade credit period for increasing the demand, which requires both parties of the supply chain to establish a good relationship. Thus, the composite Contract A can facilitate a win-win scenario, thus increasing the retailer’s profit more obviously.

3. Consider from environment aspect, Contract D has the best coordination efficiency, but fail to coordinate in the members’ profit. Therefore, coordinated contracts should meet both profit and environmental requirements. In general, Contract C is the optimal option to increase profits and reduce emissions simultaneously.

6.5. Managerial implications. Through the analysis of the results, we can get the following management implications.
Table 4. The increase rates with different contract coefficients.

| Parameter | \( \pi_r \) | \( \pi_m \) | \( \pi_{sc} \) | \( E(D) \) |
|-----------|---------|---------|---------|---------|
| **ContractA** [\( \rho_1, \lambda_1 \)] |
| 0.1, 0.7 | 78.45% | 4.57% | 21.60% | 38.93% |
| 0.1, 0.6 | 141.28% | 7.15% | 38.08% | 64.67% |
| 0.1, 0.5 | 184.93% | 8.83% | 49.43% | 81.48% |
| 0.1, 0.4 | 213.38% | 9.89% | 56.81% | 92.10% |
| 0.2, 0.5 | 654.97% | 26.89% | 171.70% | 231.11% |
| 0.3, 0.5 | 1702.6% | 61.09% | 439.57% | 483.76% |
| **ContractB** [\( \rho_2, \tau_1 \)] |
| 0.2, 0.5 | 106.02% | 6.36% | 29.34% | 56.83% |
| 0.2, 0.4 | 190.50% | 9.88% | 51.53% | 89.71% |
| 0.2, 0.3 | 303.66% | 14.26% | 80.99% | 129.38% |
| 0.2, 0.6 | 43.30% | 3.53% | 12.70% | 29.57% |
| 0.3, 0.6 | 317.56% | 16.10% | 85.61% | 140.46% |
| 0.4, 0.6 | 995.15% | 41.34% | 261.26% | 341.89% |
| **ContractC** [\( \varphi_1, \lambda_2 \)] |
| 0.5, 0.4 | 3.63% | 7.55% | 6.64% | -52.38% |
| 0.5, 0.3 | 14.40% | 8.46% | 9.83% | -50.53% |
| 0.5, 0.2 | 38.05% | 4.40% | 12.16% | -90.32% |
| 0.6, 0.2 | 38.05% | 4.40% | 12.16% | -90.32% |
| 0.5, 0.2 | 21.30% | 9.05% | 11.87% | -49.35% |
| 0.4, 0.2 | 8.58% | 10.50% | 10.06% | -33.39% |
| **ContractD** [\( \varphi_2, \tau_2 \)] |
| 0.6, 0.05 | 15.33% | 1.34% | 4.56% | -85.27% |
| 0.61, 0.05 | 16.77% | 1.61% | 5.10% | -91.33% |
| 0.62, 0.05 | 18.11% | 1.91% | 5.64% | -98.25% |
| 0.6, 0.05 | 15.33% | 1.34% | 4.56% | -85.27% |
| 0.6, 0.04 | 21.37% | 1.71% | 6.24% | -86.27% |
| 0.6, 0.03 | 27.61% | 2.09% | 7.98% | -87.34% |

(1) The results provide theoretical support for managers to make wise decisions in contract selection. Only from the perspective of the environment, contract D is optimal, which can effectively reduce the carbon emissions in the production process. However, contract D is difficult to increase the total profit of the supply chain, so enterprises may not choose this contract. In order to better achieve the purpose of environmental protection, the government can choose to give enterprises certain preferential or subsidies to stimulate enterprises to choose contract D.

(2) Considering the environmental and economic performance, the contract should not only increase profits but also reduce carbon emissions. The results show that contract C meets the above conditions to a certain extent. Therefore, without considering government subsidies, both parties should choose contract C.
(3) The research laid a foundation for further improving environmental performance. According to our research, trade credit functions well in encouraging enterprises to generate greener products, thereby contributing to carbon emission reduction. Enterprises can make better use of trade credit to improve environmental performance and establish a good brand image.

(4) Relevant organizations can also achieve the goal of reducing carbon emissions by regulating the carbon trading market and increasing the carbon trading price. The increase of carbon trading price will restrict the carbon emission of enterprises.

7. Conclusions. Decision makers have been encountering many new challenges in a low-carbon environment. The production and sale of products will produce carbon emissions. The countermeasures that the supply chain takes to reduce carbon emissions have become a hot topic recently. The paper mainly investigates the supply chain contract selection based on trade credit and cap-and-trade mechanism. The decentralized and centralized scenarios are analysed, after that four propose composite contracts that have been compared by various examples.

The results are presented as follows: (1) the total profit and emission reduction effort under centralized decision are higher; (2) four compound contracts can increase the profits of both parties and facilitate a win-win scenario; (3) the members prefer the composite Contract A, which can significantly increase the members’ profits; (4) from an environmental perspective, the composite Contract D can bring in significant reduction in carbon emissions generated by manufacturing and sales. (5) trade credit works well in protecting the environment and plays a vital role in achieving coordination.

There is much room for us to conduct further analysis in terms of research directions. Further research can analyse the coordination of supply chain for multiple competing retailers or suppliers. In addition, the coordination of supply chain with multiple products are also worth studying. The case of random demand can also be further considered, which is more in line with the reality.

Acknowledgments. The authors greatly appreciate the editor and the anonymous referees for their insightful comments and suggestions that have significantly improved the paper.

Appendix.

Proof of Proposition 1. We assume that there is a Nash equilibrium between the manufacturer and the retailer, and both sides make their own decision variables at the same time. By solving the derivative of Eqs. (1) and (2) to variable \( \theta, P, s \) and \( M \). We can get:

\[
\frac{d\pi_m}{dM} = W (\beta + (b_p - y_2 s - y_2 \theta - a) I) + \beta_c (v \theta W_c - W_c \varepsilon - c) - 2 W I \beta M;
\]

\[
\frac{d^2 \pi_m}{dM^2} = -2 W I \beta < 0;
\]

\[
\frac{d\pi_m}{d\theta} = (W - C - W M T - \varepsilon W_c) y_1 + v W_c (a - b_p + y_2 s + \beta M) - (n_1 - 2 v y_1 W_c) \theta;
\]

\[
\frac{d^2 \pi_m}{d\theta^2} = 2 v y_1 W_c - n_1 < 0;
\]

\[
\frac{d^2 \pi_m}{dM d\theta} = v W_c \beta - W I y_1.
\]
Proof of Proposition 2. By solving the derivative of Eqs. (3) to variable $\theta, P, s$ and $M$. We can get:

\[
|H| = \left| \begin{array}{cc}
\frac{d^2\pi_m}{dM^2} & \frac{d^2\pi_m}{dP dM} \\
\frac{d^2\pi_m}{dP dM} & \frac{d^2\pi_m}{dM^2}
\end{array} \right| = -(\beta v W_{e})^2 + 2WI\beta (\eta_1 - W_{e}v_{y_1}) - (IW_{y_1})^2
\]

\[
\frac{d\pi_r}{dP} = (a + y_1 \theta + y_2 s + \beta M) (1 + MI) + bW - 2b(1 + MI)P
\]

\[
\frac{d^2\pi_r}{dP^2} = -2b(1 + MI) < 0
\]

\[
\frac{d\pi_{sc}}{ds} = (P - W + PMI)y_2 - n_2 s
\]

\[
\frac{d^2\pi_{sc}}{ds^2} = -\eta_2 < 0; \quad \frac{d^2\pi_r}{ds dP} = (1 + MI)y_2 \text{ and}
\]

\[
|H| = \left| \begin{array}{cc}
\frac{d^2\pi_r}{dP^2} & \frac{d^2\pi_r}{dP dM} \\
\frac{d^2\pi_r}{dP dM} & \frac{d^2\pi_r}{dM^2}
\end{array} \right| = (1 + MI) \left[ 2b\eta_2 - (1 + MI)y_2^2 \right].
\]

Let \((\beta v W_{e})^2 + 2WI\beta (\eta_1 - W_{e}v_{y_1}) - (IW_{y_1})^2 \geq 0 \) and \(2b\eta_2 - (1 + MI)y_2^2 \geq 0\).
It proves that taking the first derivative to be 0 is the optimal solutions.

Proof of Corollary 1. Based on the optimal solutions for $M^{d^*}, P^{d^*}, \theta^{d^*}$ and $s^{d^*}$, Corollary 1 can be supported by the derivation of the correlation coefficient.
\[ |H| = \begin{vmatrix} d^2 \pi_{sc} & d^2 \pi_{sc} & d^2 \pi_{sc} & d^2 \pi_{sc} \\ \frac{dM^2}{d^2 \pi_{sc}} & \frac{dPdM}{d^2 \pi_{sc}} & \frac{dMd\theta}{d^2 \pi_{sc}} & \frac{dMd\theta}{d^2 \pi_{sc}} \\ \frac{dMdP}{d^2 \pi_{sc}} & \frac{dP^2}{d^2 \pi_{sc}} & \frac{dPd\theta}{d^2 \pi_{sc}} & \frac{dPd\theta}{d^2 \pi_{sc}} \\ \frac{dsdM}{d^2 \pi_{sc}} & \frac{dsdP}{d^2 \pi_{sc}} & \frac{dsd\theta}{d^2 \pi_{sc}} & \frac{dsd\theta}{d^2 \pi_{sc}} \\ \frac{\theta dM}{d^2 \pi_{sc}} & \frac{\theta dP}{d^2 \pi_{sc}} & \frac{\theta ds}{d^2 \pi_{sc}} & \frac{\theta ds}{d^2 \pi_{sc}} \end{vmatrix} \]

Let \(|H| \geq 0\) and \(2vy_1W_e - n_1 < 0\), which implies that \(\pi_{sc}\) is concave in \(\theta, M, P\) and \(s\).

**Proof of Corollary 2.** Based on the solutions for \(M^*_d, P^*_d, \theta^*_d\) and \(s^*_d\), Corollary 2 can be proved by derivation of the correlation coefficient.

**Proof of Proposition 3.** Proposition 3 is proved the same way as before, so it can be omitted.

**Proof of Proposition 4.** Proposition 4 is proved the same way as before, so it can be omitted.

**Proof of Proposition 5.** Proposition 5 is proved the same way as before, so it can be omitted.

**Proof of Proposition 6.** Proposition 6 is proved the same way as before, so it can be omitted.

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Received March 2021; revised May 2021; early access August 2021.

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