Pareto-efficient coordination of the contract-based MTO supply chain under flexible cap-and-trade emission constraint

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Abstract: Low-carbon production is key to both economic and environmental sustainability. It is, however, inadequate to meet the low-carbon targets by the manufacturing industry alone. Current research on emission reduction targets mainly at individual optimality, with little consideration of the synergistic benefits achievable through coordination among supply chain players. This paper fills this gap by incorporating Pareto improvement to ensure that all members are likely to gain in emission reduction through coordination. It gives the emission-dependent manufacturers theoretical basis and managerial insights to go through the stringent emission-limited market, especially under a new proposed low-carbon policy of flexible cap-and-trade, which will soon be deployed for emissions trading in China. This flexible cap-and-trade policy aligns emission reduction with capacity adjustments, but its impact has rarely been investigated. Considering the complexity of the supply chain structure, this paper simplifies the problem to two stages: manufacturer and retailer. While the demand uncertainty is considered with Newsvendor models, Stackelberg game is exploited to solve this problem with three contracts, namely revenue sharing, cost sharing, and two-part tariff. Analytical and numerical studies show that the profitability and greenness of the supply chain are increased by coordination with revenue sharing and two-part tariff contracts. The Pareto improvement encourages cooperation between the supply chain members. Managerial insights are given to help emission-dependent manufacturers compete in the increasingly stringent low-carbon environment. The novelty of this paper lies in the investigation of synergistic benefits achievable through coordination under the new flexible cap-and-trade emission policy, and the Pareto-improving conditions with several contracts are analyzed by Newsvendor models.

Keywords: Supply Chain Coordination, Green Investment, Flexible Cap-and-Trade, Contracts, Pareto Improvement

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I. INTRODUCTION

Carbon emission from industrial processes is reportedly a dominant part of atmospheric pollution. Reducing the manufacturing carbon footprint is crucial to balancing economic development and environmental protection. The cap-and-trade policy is widely employed to mitigate emissions in manufacturing via economic incentives (Xu et al., 2017). Although the current cap-and-trade policy is deemed conducive to emission reduction, it is in practice not as successful as desirable. The world's first and largest cap-and-trade system, EU ETS, has reported disappointing results in the first two phases (European Commission, 2017a, 2017b). Moreover, it tends to stifle economic development, as it neglects a firm's need to adjust capacities, particularly for increased demands. To address the practical deficiency of the current cap-and-trade system, China, the world's largest emitter and a major party to the Paris Climate Accord, has recently proposed a flexible cap-and-trade scheme (China's NDRC, 2017). Seven pilots of this proposed flexible scheme in China have all demonstrated practicable results. Instead of endowing total fixed emission quotas that tend to choke production, it sets a permitted unitary emission (PUE) level for each unit of products below the average unitary emission level of the industry. The gap between UE and PUE is a kind of unitary cost/benefit for a product that encourages firms to adopt green production and adjust their cost structures before production. As such, firms with UE below PUE can produce more to generate and trade spare emission quotas for profit, while no firm can benefit from simply suspending production to sell quotas. This encourages production expansion of competitive firms in line with emission reduction. On the other hand, relatively high polluting firms that are sluggish in greenness improvement or cannot afford emission costs would be out-competed and subsequently obsoleted. This is good for the environment with minimal impact on economic development. Indeed, the proposed flexible cap-and-trade scheme encourages the survival of the fittest in the market which is crucial to the synergetic development of both society and the environment. In view of the significance, we believe that analyzing its impacts on the supply chain and the behaviors of the manufacturer is timely and academically worthwhile.

Apparently, the manufacturer tends to transfer its financial pressure from emission constraints to the downstream retailer via a higher wholesale price. Besides, green-sensitive customers are more inclined to green-labeled products, and thus the demand increases with emission reduction. For instance, H&M has adopted green technologies to reduce emissions in production and green-labeled its products to attract green-sensitivity customers (Dong et al., 2016). This demand increase inspires the manufacturer to invest more, but the resulted higher wholesale price shrinks the retailer's orders.

A supply chain is decentralized in general, where the members act separately to maximize their own profits, which would likely sacrifice the holistic benefit of the supply chain (Walsh & Wellman, 2003). Ideally, all the members act as one group with centrally concerted efforts for the whole supply chain. Such integrated supply chains are rare in real life, although some industries adopt partially integrated pattern. In order to reduce the profit discrepancy resulting from decentralized decision-making, it is imperative to coordinate the supply chain to cope with tightened emission regulations. Various kinds of contracts can help coordinate the supply chain, but only when Pareto improvement, which ensures that no member would be hurt but are all likely to gain, is satisfied will the contract come to fruition. Generally, the manufacturer dominates the market, whilst the retailer delivers the products to the end customers (Bai et al., 2017; Hosseini-Motlagh et al., 2018a; Hosseini-Motlagh et al., 2018b). Taking the motor industry for example, the dominance of the manufacturers like Volkswagen and General Motors is transparent. Their 4S retail stores perform as transfer stations, conveying cars to customers. This problem can be conveniently solved by the manufacturer-leader (M-leader) Stackelberg game, which is widely used for tackling the optimization problems in decentralized supply chains.

This paper investigates Pareto-efficient coordination of the make-to-order (MTO) supply chain by contracts under the flexible cap-and-trade emission constraint to bring about win-win benefits for all members. It is assumed that the MTO supply chain consists of one manufacturer and one retailer. The retailer decides the order quantity based on the customers' demand, while the manufacturer sets the wholesale price and emission abatement level. The manufacturer, as the Stackelberg leader, prepares production when receiving the retailer's orders, under a flexible cap-and-trade policy. Newsvendor models, a classical technique for considering demand uncertainty, are proposed to solve the coordination problem with uncertain green-driven demands using three contracts, namely revenue sharing, cost sharing, and two-part tariff.

This approach has rarely been used to deal with coordination problems due to its calculation difficulties. Moreover, Pareto improvement is explored to ensure that all members would increase profits after coordination. The contributions of our work can be summarized as follows: (1) It attempts to analyze the supply chain performance under the flexible cap-and-trade policy with the aim to overcome the weakness of the current ETS. Few previous works have discussed it in the context of supply chain coordination. The research work by Wang et al. (2018) discussed this issue but did not consider coordination. (2) It aligns carbon emissions with the capacity adjustment that encourages firms to invest in greenness improvement and consequently thrive in a low-carbon environment. (3) Synergistic benefits achievable through coordination by contracts are discussed and the Pareto-improving conditions are analyzed. (4) Newsvendor models considering demand uncertainty and green awareness make the results relatively more realistic. (5) The results provide guidance for the firms to compete under emission restrictions. The relatively high polluting firms that lack greenness upgrades or cannot afford emission costs would be obsoleted by the flexible cap-and-trade policy.

This paper first analyzes the supply chain coordination problem under the new proposed flexible cap-and-trade emission policy recently introduced in China. The novelty of this paper lies in the introduction of flexible cap-and-trade when achieving synergistic benefits through different contracts. It gives the emission-dependent manufacturing industry theoretical basis and managerial insights to go through the stringent emission environment due to the new flexible cap-and-trade emission policy.

The remainder of this paper is organized as follows: Section 2 provides a literature basis for this research. Section 3 explains the assumptions and notations and then formulates newsvendor models under cap-and-trade. Supply chain coordination by three types of contracts is elaborated and the Pareto improvement scenarios are analyzed. Section 4 conducts numerical studies to demonstrate and validate the proposed model, while Section 5 draws conclusions and highlights managerial insights. The proofs of the proposed model are presented in the Appendix.

II. LITERATURE REVIEW

This section briefly reviews some previous research works, and research gaps and motivations are correspondingly provided.

The cap-and-trade policy (also known as emission trading) for emission reduction has gained in popularity for environmental protection since the 1970s (Burton & Sanjour, 1970). The current cap-and-trade system was theoretically considered effective, but its practical performance was found far from satisfactory (European Commission, 2017a, 2017b). The erroneous estimates of emission allowance in the first EU ETS phase led to a collapse of the carbon price, dropping to zero in 2007. In China, the world's largest emitter and a major party to the Paris Climate Accord, attempts are being made to extract the essence of the EU ETS from its dross. Under the basic frame of EU ETS, a flexible cap-and-trade scheme has recently been proposed for implementation in China to overcome the price plunge and allowance surplus of the current cap-and-trade system. China's regulatory body sets a permitted unitary emission (PUE) level for each unit of products based on the emissions from all the key emission-dependent entities and its emission reduction target. This emission level is a baseline for producing one unit of products, and the company needs to pay for extra emission that exceeds PUE for any one unit of products. An emission trading platform is being built to regulate these emission trading behaviors. Non-complying companies would face severe financial penalties.

The Chinese government authorized in 2011 two provinces (Hubei and Guangdong) and five municipalities (Beijing, Shanghai, Tianjin, Chongqing, and Shenzhen) for a trial run of ETS under the proposed flexible cap-and-trade principle. These seven Chinese ETSs officially began operation between 2013 and 2014 (Cong & Lo, 2017). The Shenzhen ETS pilot succeeded in achieving the emission reduction target during the first compliance period with a decreasing rate of 11.5% (China Emission Exchange, 2014). In 2016, the Shanghai ETS pilot reduced carbon emissions by 9.35% than in 2013 (Shanghai Environment and Energy Exchange, 2016). The Beijing ETS has been in smooth operation for three years and has realized significant achievement in 2016 (China Beijing Environment Exchange, 2016). The compliance rate of the Guangdong ETS reached 100% for three consecutive years from 2014 and its total carbon emissions fell by 4% from 2013 (Research Centre for Climate Change of Guangdong, 2017). The Hubei ETS has not yet reported any result, but it has undertaken the construction and operation of the registration system of China's national ETS. In view of the success of these ETS pilots, the national carbon market in China was officially launched in December 2017.

Despite its significance and urgency, there is nevertheless a lack of academic study of the possible impacts of the proposed flexible cap-and-trade scheme on the supply chain and the manufacturing industry. Few previous works have ever discussed it in the context of supply chain coordination. The research work by Wang et al. (2018) discussed this issue without considering coordination. It is of great significance to explore whether the coordination methods fit with the flexible cap-and-trade scheme, which is proposed to overcome the weaknesses of the traditional ones.

Many research works have discussed the supply chain coordination problem under the traditional cap-and-trade system. Jeuland and Shugan (1983) argued that contracts possess desirable mechanistic features to facilitate supply chain cooperation. Many kinds of contracts, such as revenue sharing, cost sharing, two-part tariff, buyback, price discount, call option, commitment-option, risk-sharing, wholesale price, have been proposed for coordinating the supply chain. Hu and Feng (2017) adopted the revenue sharing contract to enhance the supply chain collaboration. Swami and Shah (2012) used a two-part tariff contract to raise the decentralized profit to the integrated level considering both the manufacturer and the retailer put efforts in green operation. Zhao et al. (2017) analyzed the decision behaviors of both members with green-sensitive demand and then coordinated this two-stage supply chain by a cost sharing contract. Dong et al. (2016) coordinated the supply chain with sustainability investment under the cap-and-trade system by three contracts mentioned above. However, previous research works on emission reduction in the green supply chain targeted mainly at individual optimality (Giri & Sarker, 2018). Heydari et al. (2017) highlighted the importance of Pareto improvement in supply chain coordination. Although some research works have taken Pareto improvement into consideration, analytical and numerical results for the Pareto conditions are hardly achieved due to its calculation complexity (Basiri & Heydari, 2017). This research attempts to enrich the literature by analytically achieving Pareto-improving conditions. Many researchers like Cheng et al. (2018) and Bai et al. (2018) have made great efforts on the coordination problem under the traditional emission regulations to prove that the coordinated contracts can raise the supply chain and members' profits and even green level of the products. Only one research work by Wang et al. (2018) was found to have discussed the purchasing decisions under the flexible cap-and-trade but without considering coordination. The literature on bilateral and further multilateral benefits in supply chain coordination under the flexible cap-and-trade system remains scarce. This is indeed the research gap that this paper aims to bridge with further discussion through different contracts.

In summary, few previous research works have achieved the analytical solutions of Pareto improvement together with green investment under emission regulation. The proposed flexible cap-and-trade scheme for addressing the practical deficiency of the current cap-and-trade system has yet to be academically analyzed in the context of supply chain coordination. Its significance and urgency motivate the research on bilateral and multilateral benefits in supply chain coordination under the flexible cap-and-trade system through different contracts, which is the research gap to be filled.

III. PROBLEM FORMULATION

The production problem and supply chain coordination under the flexible cap-and-trade constraint are modeled in this section. The related notations and assumptions are given and the analytical results for optimality are provided.

3.1 Basic Model Description

This section solves the production problem by newsvendors in an MTO supply chain, in which a manufacturer schedules batch production upon receiving orders from a retailer. A flexible cap-and-trade policy imposes the firm to pay for extra emissions or to invest in green technology. We suppose the manufacturer invests in green production and then transfers the low-carbon cost to the retailer via the wholesale price. This model is suitable for the manufacturing industry with uncertain demand, similar to the works by Weng (2004), Koulamas (2006), Chen (2011), Azad Gholami et al. (2016).

An originality of this research lies in the incorporation of the flexible-cap ETS system since the traditional cap-and-trade system fails to achieve the desirable results in the implementation phase. This flexible cap addresses the weakness of the traditional ETS by capping the unitary emission level rather than the overall emission amounts, and it enables the synergetic development of both the economics and the environment. Moreover, its trial runs in China have shown good results.

The M-Stackelberg game is used to solve this problem. The manufacturer makes decisions at the first move assuming that the retailer makes orders based on its own interest. Firstly, the wholesale price is obtained according to the best decision-making of the production quantity by the retailer. Secondly, the results with the decision variable of wholesale price are inserted into the profit function of the manufacturer to obtain the best decision strategy possible, including the wholesale price and the emission abatement level. Finally, these decision results are inserted into the production quantity achieved in the first step to obtain the optimal production quantity.

This problem is addressed with Lagrange optimization (Lagrange mulitipilers with Karush- Kuhn-Tucker (KKT) conditions). Lagrange Multipliers can address the minimization/maximization problem facing one or some constrained equations, and KKT conditions are first-order necessary conditions for a solution in nonlinear programming to be optimal.

3.1.1 Notation and Assumptions

The following notations are employed throughout this research to develop the models, shown in table 1.

Table 1. Notations

Parameters	Description
a	The initial demand level of the product
b	The cap level set by China's government
c	The regular unit production cost
c_e	The carbon emission trading price
c_h	The unit inventory cost of the product
e_0	The initial emission level of the product
h	The cost factor of green investment
p	The unit retail price of the product
r	The rate of green level for green-sensitive demand
Decision Variables	Descriptions
e	The emission abatement level of the product
q	The production quantity
w	The wholesale price
ϕ	The sharing ratio of revenue sharing contract
φ	The sharing ratio of cost sharing contract
F	The lump sum of two-part tariff contract
Subscripts	Descriptions
M	Manufacturer
R	Retailer
D	Decentralized supply chain
I	Integrated supply chain
SC	Entire supply chain
o	Cost sharing contract
r	Revenue sharing contract
t	Two-part tariff contract

For the development of the proposed newsvendor model, some assumptions are made as follows:

Assumption 1: We consider a supply chain of a single product without the substitution effect in the market, where the information available is symmetric.

Assumption 2: The manufacturer has no capacity limit for meeting the orders.

Assumption 3: Non-negative profit and positive demand are assumed to ensure the survival of the firm.

This assumption requires the unitary selling price is larger than the total cost of one-unit product. This means:

$$p > c + he^2 + c_e \cdot \left(e_0 - e - b\right) \tag{1}$$

Assumption 4: It is assumed that the customers' demand is homogeneous in its preference for the product green level and follows the uniform distribution.

To reflect the real market, a uniform distribution is adopted to formulate the demand uncertainty. The demand at the retailer end is considered as follows:

$$\begin{aligned} &D = a + r \cdot \left(b + e - e_0\right) + U \\ &U \in \left[-a - r \cdot \left(b + e - e_0\right),\ a + r \cdot \left(b + e - e_0\right)\right] \end{aligned} \tag{2}$$

U is a continuous random variable following a uniform distribution between two bounding parameters as $[-a - r \cdot (b + e - e_0),\ a + r \cdot (b + e - e_0)]$. This uniform distribution is based on the work by Tsao et al. (2017).

Assumption 5: The green investment is burdened with an increasing marginal cost.

A quadratic function he^2 serves to develop a convex cost over the abatement level as Liu et al. (2012), Ghosh and Shah (2012), Xu et al. (2017), Basiri and Heydari (2017) did, where h is the greening investment coefficient. This is reasonable since the firm cannot infinitely reduce its emission level.

Assumption 6: The emission cap is a flexible cap in proportion to the order quantity.

The format of the emission cap is given by $K = bq$, where K is the emission cap which is related to the production quantity of a firm, and b is the emission cap level that is set by the government according to (usually less than) the average emission level of an industry.

3.1.2 Decentralized Supply Chain Scenario

In a decentralized (DSC) manner, both the manufacturer and the retailer act separately for their individual interests. On the M-Stackelberg assumption, the manufacturer dominates the market and makes its optimal decisions at the first move, while the retailer orders best out of the market demand and the wholesale price.

The profit of the manufacturer:

$$\begin{aligned} &\pi_M = w \cdot q - \left(c + he^2\right) \cdot q - c_e \cdot \left(e_0 - e - b\right) \cdot q \\ &s.t.\ \ q > 0; \\ &\qquad e_0 - b < e < e_0 \end{aligned} \tag{3}$$

This function is composed of the revenue, the production cost, the green investment cost, and the emission reduction cost. No shortage cost is considered in this MTO supply chain, where the manufacturer schedules its production upon receiving the retailer's orders.

The profit of the retailer:

$$\begin{aligned} &\pi_R = E\left[p \cdot \min\{D, q\} - wq - c_h\left(q - D\right)^+\right] \\ &s.t.\ D = a + r \cdot \left(b + e - e_0\right) + U, \\ &\quad U \in \left[-a - r \cdot \left(b + e - e_0\right),\ a + r \cdot \left(b + e - e_0\right)\right]; \\ &\quad q > 0; \\ &\quad e_0 - b < e < e_0 \end{aligned} \tag{4}$$

This function consists of the revenue, the wholesale cost, and the inventory cost. The expression of inventory cost $c_h\left(q - D\right)^+$ requires $q > D$. If $q \le D$, the retailer enjoys zero inventory cost, but suffers profit loss out of underestimating the demand.

The supply chain profit is the sum of the players' profits, that is:

$$\pi_D = \pi_M + \pi_R \tag{5}$$

From Assumption 4, the proposed demand function follows the uniform distribution in the interval [0, $2(a + r \cdot (b + e - e_0))$]. Therefore, the expected profit of the retailer is given as:

$$\begin{aligned} \pi_R = {} & p \cdot \left[\int_0^q \frac{x}{2\left[a + r \cdot \left(b + e - e_0\right)\right]} dx + \int_q^{2\left[a + r \cdot \left(b + e - e_0\right)\right]} \frac{q}{2\left[a + r \cdot \left(b + e - e_0\right)\right]} dx\right] \\ & - c_h \cdot \int_0^q \frac{q - x}{2\left[a + r \cdot \left(b + e - e_0\right)\right]} dx - wq \end{aligned} \tag{6}$$

Then the simplified expression is given below:

$$\pi_R = (p-w)\cdot q - \frac{p+c_h}{4(a+rb+re-re_0)}\cdot q^2 \tag{7}$$

The objective of the decentralized model is to determine the optimal solution of (e , w , q) to maximize the profits of both members. The retailer firstly decides the optimal order quantity. By derivation, we get:

$$\begin{aligned} \frac{\partial \pi_R}{\partial q} &= p - w - \frac{p+c_h}{2(a+rb+re-re_0)}\cdot q \\ \frac{\partial^2 \pi_R}{\partial q^2} &= -\frac{p+c_h}{2(a+rb+re-re_0)} \end{aligned} \tag{8}$$

It is obvious that the retailer's profit function is concave of the order quantity q , and we can get the expression of order quantity with a wholesale price w by:

$$\frac{\partial \pi_R}{\partial q} = 0 \tag{9}$$

Then we get:

$$q = \frac{2(a+rb+re-re_0)}{p+c_h}\cdot (p-w) \tag{10}$$

After receiving the order, the manufacturer prepares for production and decides the wholesale price and emission abatement level. By substituting equation (9) into equation (2), we have:

$$\begin{cases} \pi_M = \left[w - c - he^2 - c_e\cdot(e_0 - e - b)\right]\cdot \dfrac{2(a+rb+re-re_0)}{p+c_h}\cdot (p-w) \\ s.t. \quad e_0 - b < e < e_0 \end{cases} \tag{11}$$

Using Lagrange optimization, we get the following optimal solution:

$$\begin{aligned} & e^* \textit{ by solving } (c_e - 2he)\cdot(a+rb+re-re_0) + \frac{r\cdot\left[p - c - he - c_e\cdot(e_0 - e - b)\right]}{2} = 0, \textit{ and } e^* > \frac{c_e}{2h} \\ & w^* = \frac{p + c + he^{*2} + c_e\cdot\left(e_0 - e^* - b\right)}{2} \\ & q^* = \frac{a+rb+re^*-re_0}{p+c_h}\cdot\left[p - c - he^{*2} - c_e\left(e_0 - e^* - b\right)\right] \end{aligned} \tag{12}$$

Proof 1: please see the Appendix.

Based on the optimal values of (e , w , q), the optimal decentralized profits of both members are given:

$$\pi_M^* = w^* \cdot q^* - \left(c + he^{*2}\right) \cdot q^* - c_e \cdot \left(e_0 - e^* - b\right) \cdot q^*$$
$$\pi_R^* = \left(p - w^*\right) \cdot q^* - \frac{p + c_h}{4\left(a + rb + re^* - re_0\right)} \cdot q^{*2} \tag{13}$$

Then the optimal supply chain profit:

$$\pi_D^* = \pi_M^* + \pi_R^* \tag{14}$$

3.1.3 Integrated Supply Chain Scenario

In an integrated (ISC) manner, the manufacturer and the retailer act as one company. It eliminates the decision discrepancies between these two players to earn the optimality. Therefore, the integrated model can be regarded as an idealized benchmark for the following analysis.

The integrated profit function:

$$\begin{cases} \pi_I = E\left[p \cdot \min\{D, q\} - \left(c + he^2\right) \cdot q - c_h \cdot (q - D)^+ - c_e \cdot \left[(e_0 - e) \cdot q - bq\right]\right] \\ s.t.\ D = a + r \cdot \left(b + e - e_0\right) + U,\ U \in \left[-a - r \cdot \left(b + e - e_0\right),\ a + r \cdot \left(b + e - e_0\right)\right]; \\ \quad q > 0; \\ \quad e_0 - b < e < e_0 \end{cases} \tag{15}$$

From the demand assumption, we can transfer equation (14) to the following expression:

$$\begin{aligned} \pi_I &= p \cdot \left[\int_0^q \frac{x}{2\left[a + r \cdot \left(b + e - e_0\right)\right]} dx + \int_q^{2\left[a + r \cdot \left(b + e - e_0\right)\right]} \frac{q}{2\left[a + r \cdot \left(b + e - e_0\right)\right]} dx\right] \\ &\quad - c_h \cdot \int_0^q \frac{q - x}{2\left[a + r \cdot \left(b + e - e_0\right)\right]} dx - \left(c + he^2\right) \cdot q - c_e \cdot \left(e_0 - e - b\right) \cdot q \\ &= \left[p - c - he^2 - c_e \cdot \left(e_0 - e - b\right)\right] \cdot q - \frac{p + c_h}{4\left(a + rb + re - re_0\right)} \cdot q^2 \end{aligned} \tag{16}$$

Using Lagrange optimization, we can get the optimal solution as follows:

$$\begin{aligned} & e_I = e^*, \quad and\ e_I > \frac{c_e}{2h} \\ & q_I = 2 \cdot \frac{a + rb + re - re_0}{p + c_h} \cdot \left[p - c - he^2 - c_e\left(e_0 - e - b\right)\right] \end{aligned} \tag{17}$$

Proof 2: Please see the Appendix.

Based on the resulted optimal values of (e_I , q_I), the maximum profit of the ISC is:

$$\pi_I^* = \frac{1}{2} \cdot \left[p - c - he_I^2 - c_e \cdot \left(e_0 - e_I - b \right) \right] \cdot q_I \tag{18}$$

The integrated model eliminates the impact of the wholesale price, and the profit disposition is under the central decision maker's control. Suppose the central leader distributes the profit via a wholesale price $w_I, \left(w_I = w^* \right)$, we have:

$$\begin{aligned} \pi_M^I &= \pi_I^* \\ \pi_R^I &= 0 \end{aligned} \tag{19}$$

3.1.4 Basic Results Comparison

Comparing the results between the decentralized model and the integrated one, some corresponding propositions are proposed.

Proposition 1: $q^* = \frac{1}{2} q_I$, $\pi_M^* = \frac{1}{2} \pi_I^*$, $\pi_R^* = \frac{1}{4} \pi_I^*$, then $\pi_D^* = \frac{3}{4} \pi_I^*$. The DSC sacrifices ¼ of the maximum profit for individual decision-making. It loses half of the integrated order quantity.

$$q^* = \frac{a + rb + re - re_0}{p + c_h} \cdot \left[p - c - he^2 - c_e \left(e_0 - e - b \right) \right] = \frac{1}{2} q_I \tag{20}$$

From $q^* = \frac{1}{2} q_I$, we get:

$$\begin{aligned} \pi_I^* &= \frac{1}{2} \cdot \left[p - c - he_I^2 - c_e \cdot \left(e_0 - e_I - b \right) \right] \cdot q_I \\ &= \left[p - c - he_I^2 - c_e \cdot \left(e_0 - e_I - b \right) \right] \cdot q^* \end{aligned} \tag{21}$$

Transferring the expressions in equation (13) and equation (14) by eliminating w^*, we have:

$$\begin{aligned} \pi_M^* &= \frac{1}{2} \cdot \left[p - c - he^{*2} - c_e \cdot \left(e_0 - e^* - b \right) \right] \cdot q^* = \frac{1}{2} \pi_I^* \\ \pi_R^* &= \frac{1}{4} \cdot \left[p - c - he^{*2} - c_e \cdot \left(e_0 - e^* - b \right) \right] \cdot q^* = \frac{1}{4} \pi_I^* \\ \pi_D^* &= \pi_M^* + \pi_R^* = \frac{3}{4} \cdot \left[p - c - he^{*2} - c_e \cdot \left(e_0 - e^* - b \right) \right] \cdot q^* = \frac{3}{4} \pi_I^* \end{aligned} \tag{22}$$

Proposition 2: $e_I = e^* > \frac{c_e}{2h}$, due to the green awareness, the firm is likely to invest more even if the marginal cost of green upgrades is larger than the carbon price.

A quadratic function is employed to develop a convex cost function as:

$$G = he^2 \tag{23}$$

Then the marginal cost function of green investment is given:

$$\frac{\partial G}{\partial e} = 2he \tag{24}$$

The expression of the optimal abatement level $e_I = e^* > \frac{c_e}{2h}$ shows $2he^* = 2he_I > c_e$, meaning that the upper boundary of marginal investment cost is larger than the carbon price.

Proposition 3: The wholesale price w^* will squeeze the retailer's profit to zero if the order quantity remains the same as that of ISC.

$$\pi_M^{w*} = \pi_I^*; \ \pi_R^{w*} = 0; \ \pi^{w*} = \pi_I^* \tag{25}$$

This is the reason why the decentralized order quantity is less than the integrated one.

3.2 Supply Chain Coordination Model Description

It has been proved that a supply chain performs better in the integrated system. While coordination bridges decision discrepancies, the concept of Pareto improvement fosters cooperation among supply chain members by assuring that no one would lose out but all are likely to gain through collaboration.

3.2.1 Coordination Model with Revenue Sharing Contract

Coordination by a revenue sharing contract (RSC) implies that the retailer pays the wholesale price for the product and shares a proportion $1-\phi$ of its earning with the manufacturer.

The profits of both the manufacturer and the retailer:

$$\begin{aligned} \pi_M^r &= E\left[(1-\phi)\cdot p \cdot \min\{D,q\}\right] + \left[w - c - he^2 - c_e \cdot \left(e_0 - e - b\right)\right]\cdot q \\ \pi_R^r &= E\left[\phi p \cdot \min\{D,q\} - c_h \cdot (q-D)^+ - wq\right] \end{aligned} \tag{26}$$

The profit of the entire supply chain:

$$\pi_r = \pi_M^r + \pi_R^r \tag{27}$$

To bear off the integrated profit, the optimal solution is calculated:

$$
\begin{aligned}
& e_r = e_I \\
& \phi = \frac{2c_h S + pS - pc_h}{(3p+2c_h)(p-S)} \\
& w_r = \phi p - \frac{\phi p + c_h}{p + c_h} \cdot (p-S) \\
& q_r = \frac{2(a + rb + re_r - re_0)}{(\phi p + c_h)} \cdot (\phi p - w_r) \\
& where \;\; S = c + he_r^2 + c_e \cdot (e_0 - e_r - b)
\end{aligned} \tag{28}
$$

Proof 3: please see the Appendix.

According to the optimal values of (e_r , ϕ , w_r , q_r), the profits of both members and the supply chain are respectively given:

$$
\begin{aligned}
& \pi_M^r = \frac{(3p-4S)\cdot p}{(3p+2c_h)(p-S)} \cdot \pi_I^* \\
& \pi_R^r = \frac{2pc_h - 2Sc_h + pS}{(3p+2c_h)(p-S)} \cdot \pi_I^* \\
& \pi_r^* = \pi_I^*
\end{aligned} \tag{29}
$$

Proof 4: please see the Appendix.

Proposition 4: $q_r = q_I = 2q^*$, $\pi_r^* = \pi_I^*$, when $\phi = \frac{2c_h S + pS - pc_h}{(3p+2c_h)(p-S)}$. If the retailer shares a proportion ϕ of its revenue, this contract enables the DSC to achieve superb performance like a fully coordinated supply chain by doubling the optimal quantity.

$$
q_r = q_I = 2q^* = 2 \cdot \frac{a + rb + re - re_0}{p + c_h} \cdot \left[p - c - he^2 - c_e (e_0 - e - b) \right] \tag{30}
$$

Proposition 5: $e_r = e_I$, $q_r = q_I = 2q^*$, the total emission reduction doubles, as it is presented by the expression $e_r \cdot q_r = 2e^* \cdot q^*$.

Proposition 6: $w_r < w^*$. If the manufacturer’s earning only depends on the wholesale price without any revenue sharing, he has to levy a higher wholesale price for positive profit.

$$
w_r - w^* = \frac{1(\phi - 1)\cdot p \cdot (c_h + S) + (S - p)\cdot(p + c_h)}{2(p + c_h)} < 0 \tag{31}
$$

From $0 \le \phi \le 1$, $S < p$, $w_r - w^* < 0$. That is $w_r < w^*$.

Proposition 7: If the condition $\frac{(3p-4S)\cdot p}{(3p+2c_h)(p-S)} \ge \frac{1}{2}, \frac{2pc_h - 2Sc_h + pS}{(3p+2c_h)(p-S)} \ge \frac{1}{4}$ can be satisfied, the RSC is able to achieve Pareto improvement, which assures that the coordinated profits of both members are no less than the initial DSC profits.

$$\begin{aligned} \pi_M^r &= \frac{(3p-4S)\cdot p}{(3p+2c_h)(p-S)} \cdot \pi_I^* \ge \pi_M^* = \frac{1}{2}\pi_I^* \\ \pi_R^r &= \frac{2pc_h - 2Sc_h + pS}{(3p+2c_h)(p-S)} \cdot \pi_I^* \ge \pi_R^* = \frac{1}{4}\pi_I^* \end{aligned} \tag{32}$$

3.2.2 Coordination Model with Cost Sharing Contract

Under this cost sharing contract (CSC) scenario, the retailer bears a certain proportion φ of the production cost but enjoys a reduced wholesale price enough for the manufacturer to gain profit.

The members' profit functions:

$$\begin{aligned} \pi_M^o &= wq - (1-\varphi)\cdot(c + he^2)\cdot q - c_e \cdot (e_0 - e - b)\cdot q \\ \pi_R^o &= E\left[p \cdot \min\{D, q\} - wq - c_h \cdot (q-D)^+ - \varphi \cdot (c + he^2)\cdot q \right] \end{aligned} \tag{33}$$

The supply chain profit function:

$$\pi_o = \pi_M^o + \pi_R^o \tag{34}$$

When using the cost sharing contract to achieve the integrated profit, the optimal solutions need to reach the same level as the integrated solutions, with the help of the cost proportion φ. This means the solutions are:

$$\begin{aligned} e_o &= e_I \\ q_o &= \frac{2(a + rb + re_o - re_0)}{p + c_h} \cdot \left[p - w - \varphi \cdot (c + he_o^2) \right] \\ w_o &= \frac{p + (1-2\varphi)\cdot(c + he_o^2) + c_e \cdot (e_0 - e_o - b)}{2} \end{aligned} \tag{35}$$

The key is to address the cost proportion φ. However, a solution of this scenario requires that the unit retail price just offsets the total unit cost of the product, that is $p = c + he^2 + c_e \cdot (e_0 - e - b)$, and it rejects the prerequisite that the retail price is larger than the total cost for positive profit as $p > c + he^2 + c_e \cdot (e_0 - e - b)$. Thus, there exists no cost proportion φ to raise the profit to the integrated level. The cost sharing contract cannot coordinate the supply chain under this assumption set.

Proof 5: please see the Appendix.

Result 1: The cost sharing contract cannot coordinate the decentralized supply chain.

The analytical solution makes the supply chain enjoy no net profit and just produce for public welfare. It runs against the hypothesis of economic man.

3.2.3 Coordination Model with Two-part Tariff Contract

The two-part tariff contract (TPT) allows the manufacturer to charge a wholesale price and a lump sum fee F from the retailer.

The profit functions of both members:

$$\begin{aligned} \pi_M^t &= w \cdot q - \left(c + he^2\right) \cdot q - c_e \cdot \left(e_0 - e - b\right) \cdot q + F \\ \pi_R^t &= E\left[p \cdot \min\{D, q\} - wq - c_h \left(q - D\right)^+ \right] - F \end{aligned} \tag{36}$$

The profit function of the supply chain:

$$\pi_t = \pi_M^t + \pi_R^t \tag{37}$$

To achieve the integrated profit, we obtain the optimal solution values as:

$$\begin{aligned} e_t &= e_I \\ w_t &= c + he_t^2 + c_e \cdot \left(e_0 - e_t - b\right) \\ q_t &= 2 \cdot \frac{a + rb + re_t - re_0}{p + c_h} \cdot \left[p - c - he^2 - c_e \left(e_0 - e_t - b\right) \right] \end{aligned} \tag{38}$$

Proof 6: please see the Appendix.

According to the optimal values of (e_t, w_t, q_t), the profits of both members and the supply chain are shown, respectively:

$$\begin{aligned} \pi_M^t &= F \\ \pi_R^t &= \pi_I^* - F \\ \pi_t^* &= \pi_I^* \end{aligned} \tag{39}$$

Proof 7: please see the Appendix.

Proposition 8: $q_t = q_I = 2q^*$, $\pi_t^* = \pi_I^*$, $\pi_M^t = F$, $\pi_R^t = \pi_I^* - F$. This contract enables a company to capture the maximum consumer surplus as it otherwise would in an integrated environment. The optimal quantity doubles.

From the solution process shown in the Appendix, we know that:

$$q_t = q_I = 2 \cdot \frac{a + rb + re - re_0}{p + c_h} \cdot \left[p - c - he^2 - c_e \left(e_0 - e - b \right) \right] \tag{40}$$

Proposition 9: $e_t = e_I$, $q_t = q_I = 2q^*$, the total emission reduction doubles, as it is presented by the expression $e_t \cdot q_t = 2e^* \cdot q^*$.

Proposition 10: $w_t = c + he_t^2 + c_e \cdot \left(e_0 - e_t - b \right)$, $w_t < w^*$. In the two-part tariff contract case, the bloom of the wholesale price fades. It just covers the total unit cost, consisting of the costs of production and emissions.

Proposition 11: When the lump sum F satisfies the condition $\frac{1}{2} \cdot \pi_I^* \le F \le \frac{3}{4} \cdot \pi_I^*$, the supply chain under TPT can achieve Pareto improvement to fully coordinate the supply chain.

The Pareto improvement needs to satisfy the following conditions:

$$\begin{aligned} \pi_M^t &= F \ge \pi_M^* = \frac{1}{2} \pi_I^* \\ \pi_R^t &= \pi_I^* - F \ge \pi_R^* = \frac{1}{4} \pi_I^* \end{aligned} \tag{41}$$

Then we have:

$$\frac{1}{2} \cdot \pi_I^* \le F \le \frac{3}{4} \cdot \pi_I^* \tag{42}$$

From $\pi_t^* = \pi_M^t + \pi_R^t = \pi_I^*$, the supply chain can be fully coordinated while ignoring the profit allocation by F .

IV. NUMERICAL ANALYSIS

The Chinese cement industry has been the largest globally for many years in terms of gross output, but it is among the most energy and emission intensive. Emission reduction is indeed a pressing issue to be addressed by the cement supply chain in China.

We therefore conduct numerical analyzes using the following data collected from a Chinese cement company, whose average monthly production is about 29,500 tons of cement at a retail price of 50USD per ton. The impacts of the decision variables on the resulting profits of the supply chain and its individual members are revealed. Pareto improvement is demonstrated to highlight its motivation for the contract coordination of the supply chain.

The data used in the DSC, ISC, RSC, and TPT scenarios are shown in Table 2 below:

Table 2. Data Set

p	c	c_h	c_e	h	e_0	b	a	r
$US\$50$	$US\$30$	$US\$5$	$US\$10$	100	0.88	0.85	$200kton$	10

The green investment here can be deemed to purchase greener raw materials or upgrade the production lines by high-tech manufacture equipment, procedure, and process.

4.1 The Performance of the Revenue Sharing Contract

A. Results Comparison

Table 3 and Figure 1 elaborate that the DSC suffers 25% value loss with 50% smaller order quantity, but this profit gap could be filled via the RSC. Along with the order quantity, the total emission abatement amount doubles after coordination. The wholesale price in the RSC is much less than that in the DSC due to the revenue sharing ratio. Moreover, the retailer may earn nothing in the ISC if the integrated decision-maker distributes the profit by the decentralized wholesale price. This is the reason why the retailer orders less quantity in the decentralized model.

Table 4 shows that the profit increases to the integrated level by the revenue sharing contract, along with huge growth in the retailer's earning to about 113% increment. Yet the manufacturer experiences a 6.6% profit decrease. This makes the coordination hard to realize under the hypothesis of economic man that believes the entities are rational for their subjectively-defined ends optimally. This revenue sharing ratio cannot bring about Pareto improvement, and thus it is essential to take an adjustment for ϕ into account.

Table 3. Results Comparison of Three Models

	DSC		ISC		RSC	
	Members	Total	Members	Total	Members	Total

	M	R	SC	M	R	SC	M	R	SC
Order Quantity (Ton)		72.6248			145.2496			145.2496	
		50% q_I			q_I			q_I	
Emission Abatement Level		0.0525			0.0525			0.0525	
Emission Abatement Amount (Ton)		3.8128			7.6256			7.6256	
Wholesale Price (USD)		40.0253		40.0253		---		13.6901	
Revenue Sharing Ratio		---			---			0.4866	
Profit (1000USD)	724.4096	362.2048	1086.6144	1448.8192	0	1448.8192	676.2616	772.5576	1448.8192
	50% π_I	25% π_I	75% π_I	π_I	0	π_I	46.68% π_I	53.32% π_I	100% π_I

Table 4. Comparison between decentralized and RSC coordinated supply chain

	DSC	RSC	Increment
Manufacturer	724.4096	676.2616	-6.6%
Retailer	362.2048	772.5576	113%
Supply Chain	1086.6144	1448.8192	33%

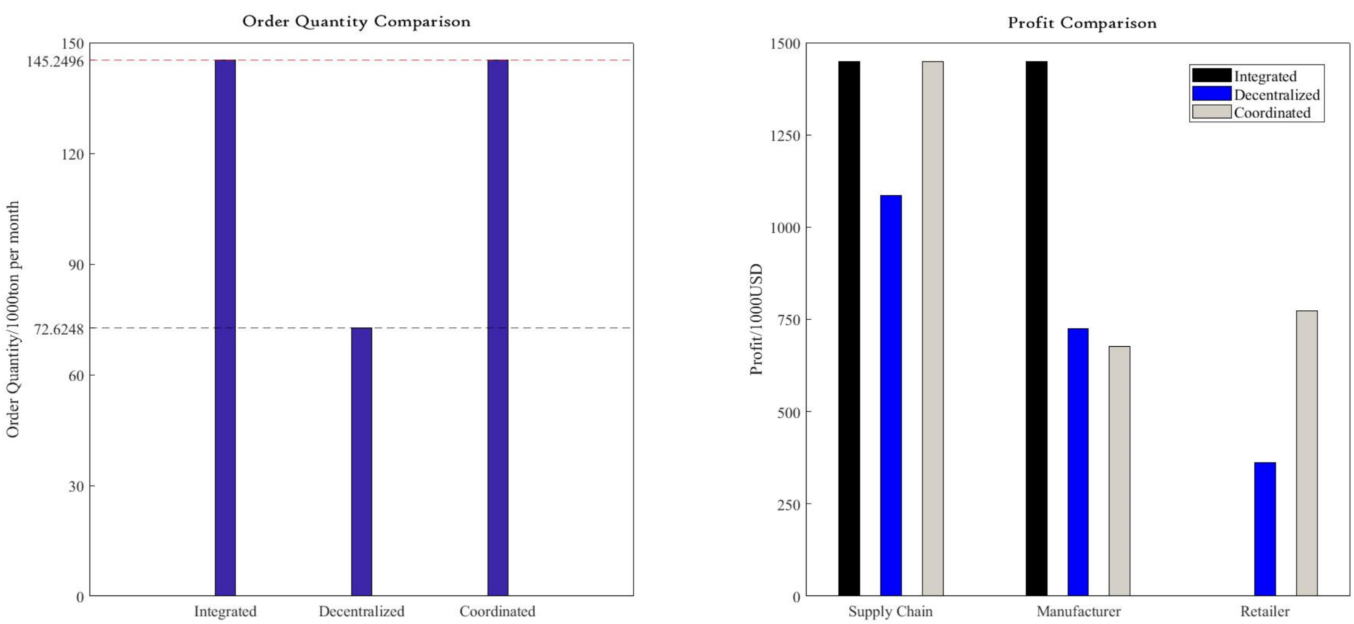

Figure 1. Results Comparison of Three Models

B. Sensitivity Analysis

This subsection analyzes how the profits and decision variables alter under various market environments and firm settings.

Figure 2 shows that both the profits and the order quantity increase when the retailing price goes up no matter under which supply chain. The line for the RSC coordinated profit coincides with that for the integrated profit, so does the order quantity. The profit gap between the integrated & coordinated and the decentralized supply chain widens as the order quantity gap is enlarged with the price rise.

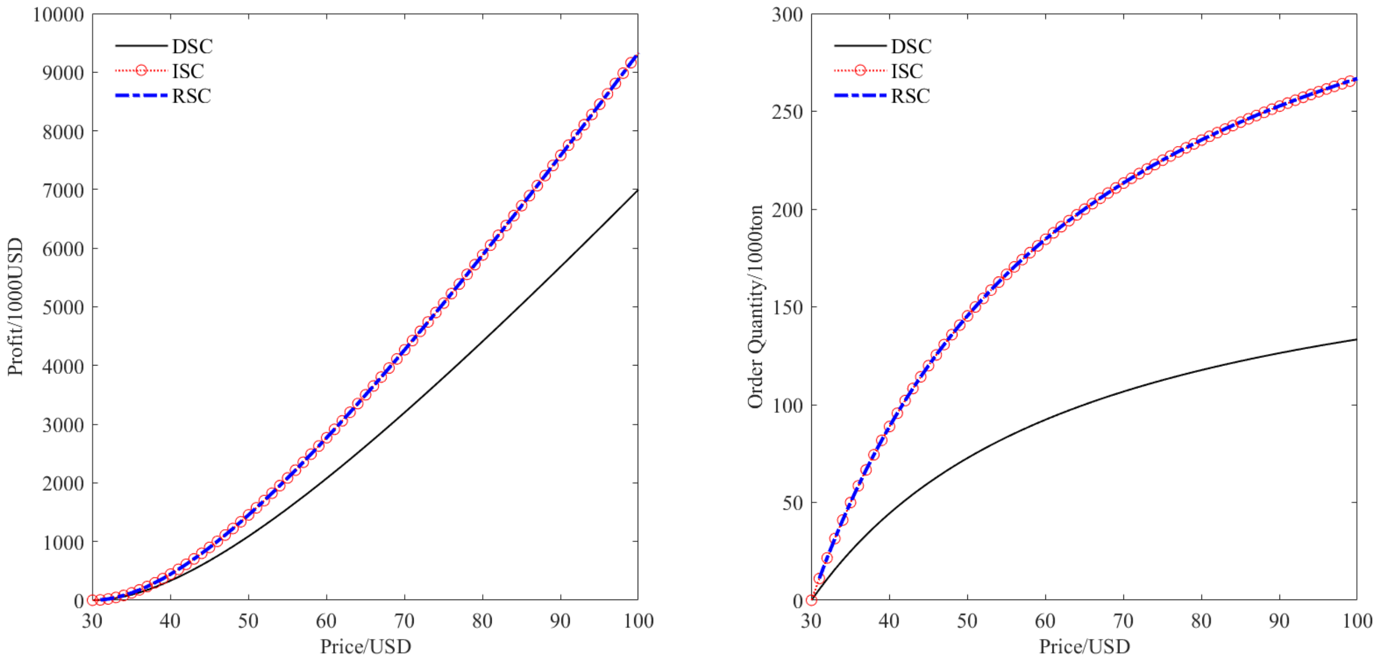

Figure 2. Profit & Order Quantity Trends with Retailing Price

Managerial Insight 1: The performance discrepancies widen with the price rise.

A higher selling price charges more for individual decision-making. When the supply chain members tend to drive up the selling price for more profit, the coordination mechanism becomes more important to fill these enlarged performance discrepancies.

Figure 3 shows that the wholesale price of the RSC is much less than that of the DSC. The resulted optimal wholesale price in the DSC decreases its profit by 25% less than the maximum. The reason is explained in Figure 4, focusing on the decentralized model, all the supply chain profit goes into the retailer's pocket and the manufacturer shares nothing when the decentralized profit hits the integrated line. This is impossible especially when the manufacturer is the leader. To earn more, the manufacturer will charge a higher wholesale price, and therefore a profit hemorrhage exists.

Managerial Insight 2: The revenue sharing contract raises the supply chain profit to the maximum where both members gain positive earning.

However, Table 4 shows that the manufacturer suffers 6.6% profit loss compared with the decentralized earning, which means the RSC cannot achieve Pareto improvement when the supply chain tries to reach the integrated profit.

Furthermore, the carbon emission price affects not only the firm's profitability but also its green production. From Figure 5, the profit initially increases and then drops to zero when the carbon emission price is about \$98, so does the order quantity. This denotes that the firm can hardly survive where the market charges \$98/ton (emission). Narrowing the variation range, from \$0 to \$50, the profit peaks next to \$10, so does the order quantity. It is a healthy and profitable market with a carbon emission price at about \$10. Besides, Figure 6 shows that a higher carbon price urges the firm to invest more in reducing its emissions.

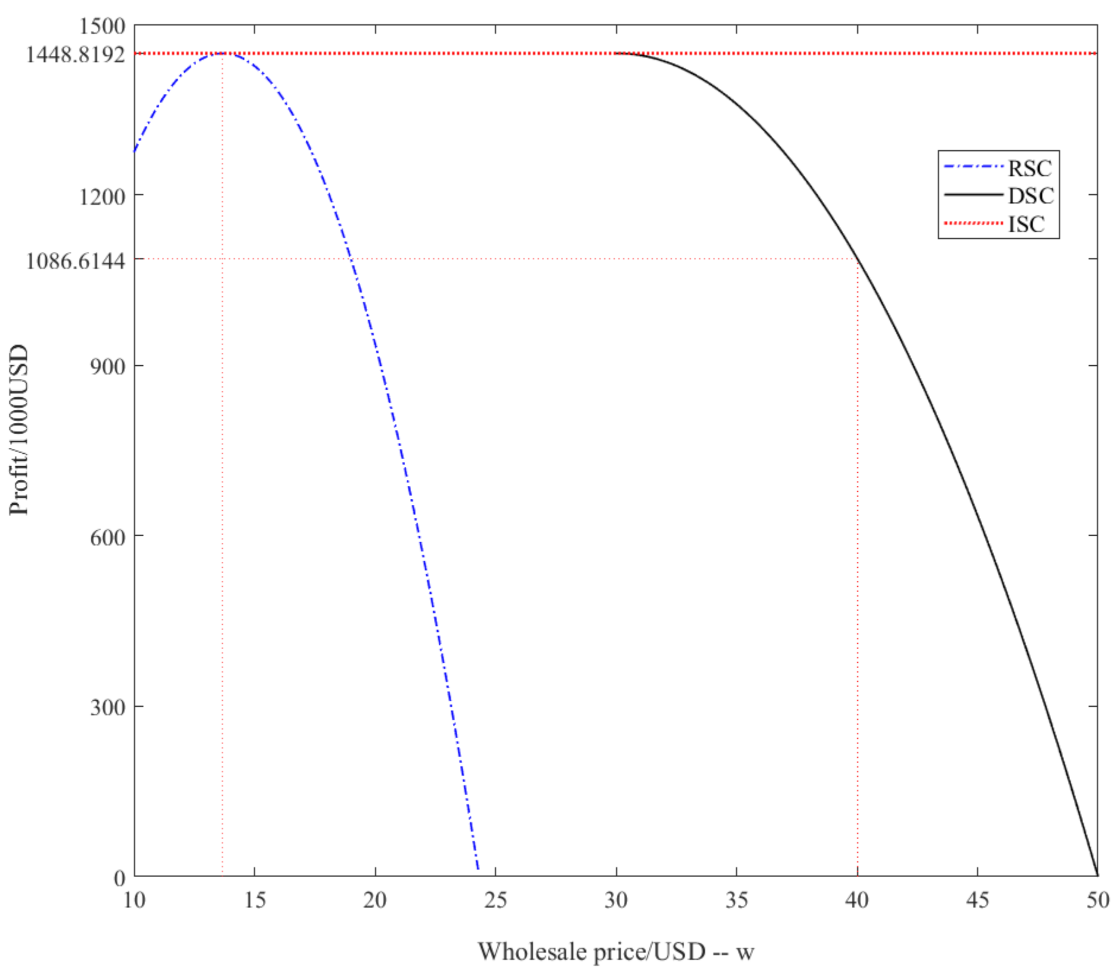

Figure 3. Profit Trend with Wholesale Price

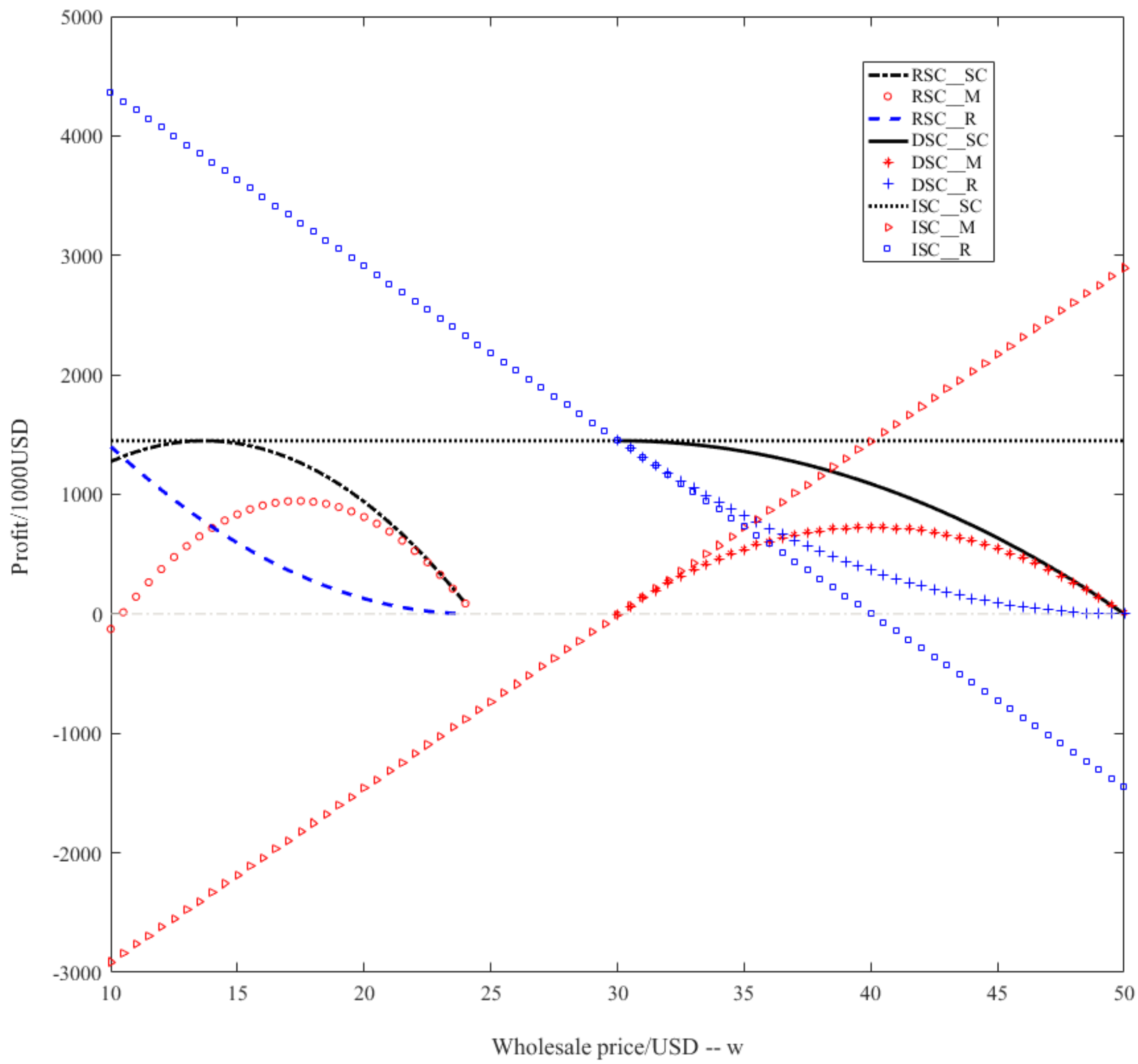

Figure 4. Profit Trends for SC Members when Wholesale Price Varies

The carbon price significantly affects the supply chain profit. A proper carbon price increases both the profit and the emission reduction. For the policymakers, it should be noticed that some policies and regulations are needed to adjust the carbon market for the win-win conditions.

We now turn to the non-price factors. From Figure 7, the supply chain bears more financial loss in a stringent market. Above 0.88, the firm is under the non-cap situation but can benefit from selling the spare quotas to the market.

From Figure 8, the profit decreases when the green investment cost factor increases. The increase in green investment cost factor means the firm bears more cost for one-unit green investment. It is consistent with the economic theory that the firm pays more at a higher cost. Moreover, as shown in Figure 9, the emission abatement level tends to vary inversely with the green investment cost factor. These results prove that lowering the cost factor of green investment contributes to both economic and environmental development. It is imperative to upgrade the green technologies for lower cost factor of green investment.

Managerial Insight 3: The supply chain can benefit more from the lower carbon price and lower green investment cost factor, economically and environmentally.

The increase in supply chain profit means the rise in the sum of the manufacturer's and retailer's profits. Hence, there exists a chance that both members' profits increase with green investment via the revenue sharing contract.

The policymakers need to strike a balance between the carbon reduction level and economic prosperity when setting a carbon price.

According to Figure 10, the profit of the supply chain experiences an upward trend till the top (at 0.4866) and then goes down with the revenue sharing ratio increasing. From 0.3 to 0.5, the manufacturer's profit meets its summit and then misses it, while the retailer takes an increasing profit. The optimal value of the revenue sharing ratio is at the top point of the supply chain profit line, where the members possibly earn more. Nevertheless, the manufacturer loses some profits for achieving supply chain coordination under this data set. If the contract damages the interest of either member, it has no chance to be conducted. Only by achieving Pareto improvement will the revenue sharing contract be enforced.

The revenue sharing contract is required to achieve Pareto improvement for closing a bargain, and it is distinguished by the revenue sharing ratio ϕ. Achieving Pareto improvement requires that the revenue sharing ratio does not harm any but benefits at least one economic entity. From Figure 11, we can get the lower boundary by the retailer's profit line at 0.4096, and the upper boundary by the manufacturer's profit line at 0.4782. In this range $\phi \in (0.4096, 0.4782)$, the supply chain is more profitable than the decentralized system but earns less than the integrated one; however, both members' profits rise for a win-win condition. Table 5 correspondingly shows the profit changes of the supply chain and members for different values of ϕ. Between the range $\phi \in (0.4096, 0.4782)$, both members increase their profitability compared to the decentralized levels, as well as the supply chain.

Managerial Insight 4: The revenue sharing contract drives the supply chain profit closer to the integrated earning with consideration of the Pareto improvement.

The RSC helps increase the supply chain profit. However, it cannot reach the maximum for full coordination due to the Pareto-improving conditions, which charge some financial costs to enforce this contract under this dataset.

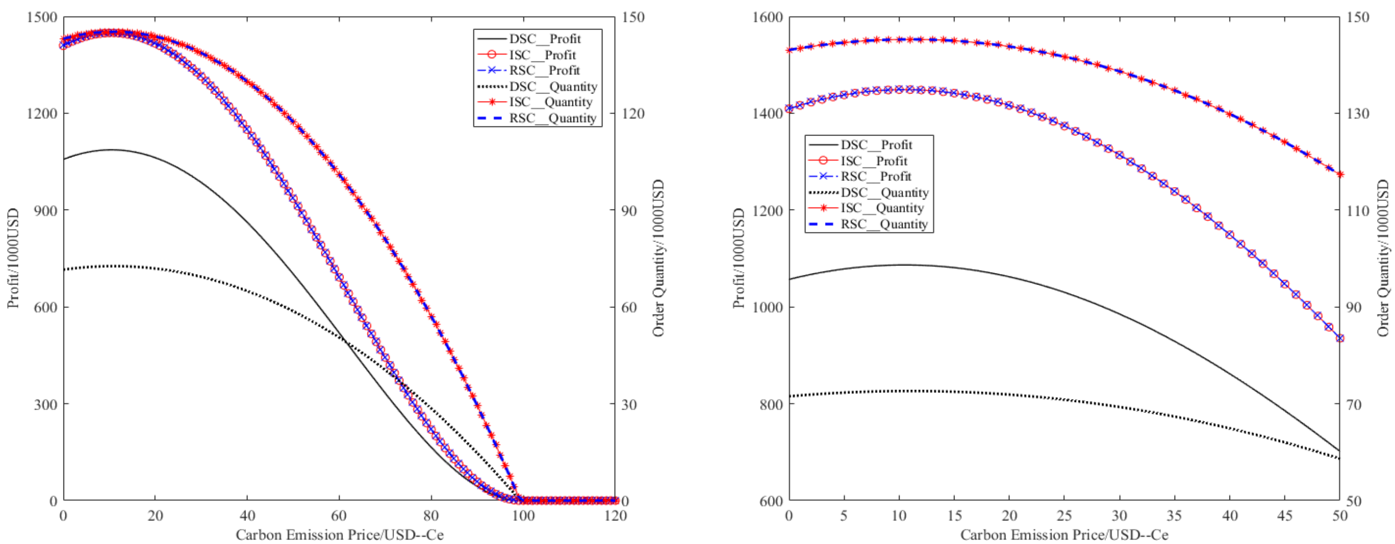

Figure 5. Profit & Order Quantity with Carbon Emission Price

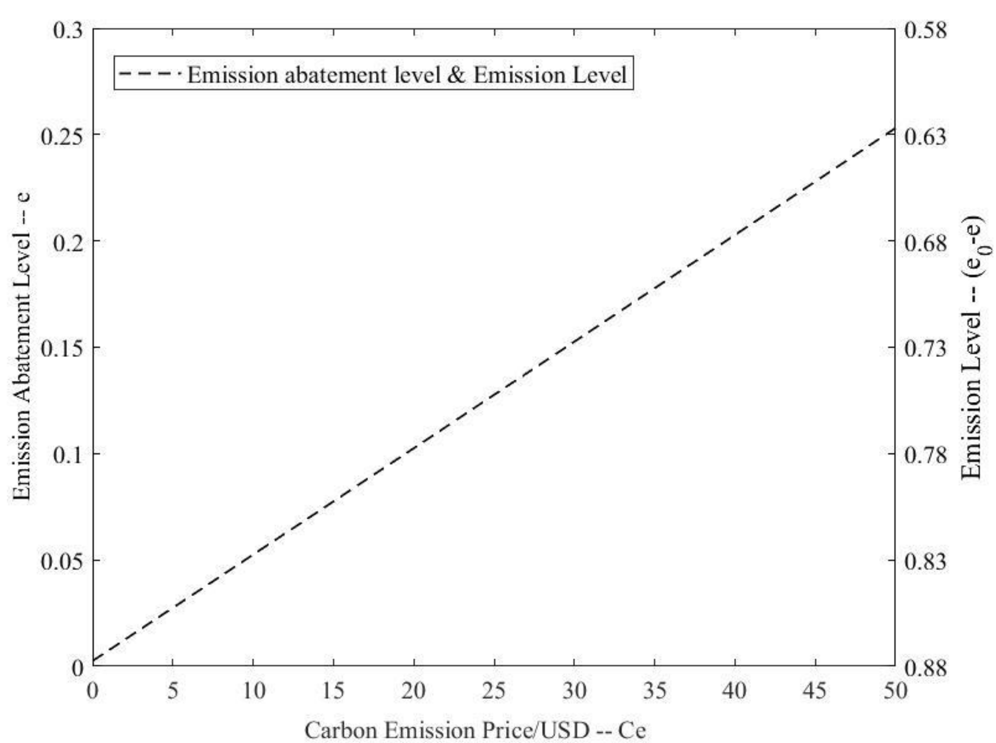

Figure 6. Emission Abatement Level & Emission Level Trends with Carbon Emission Price

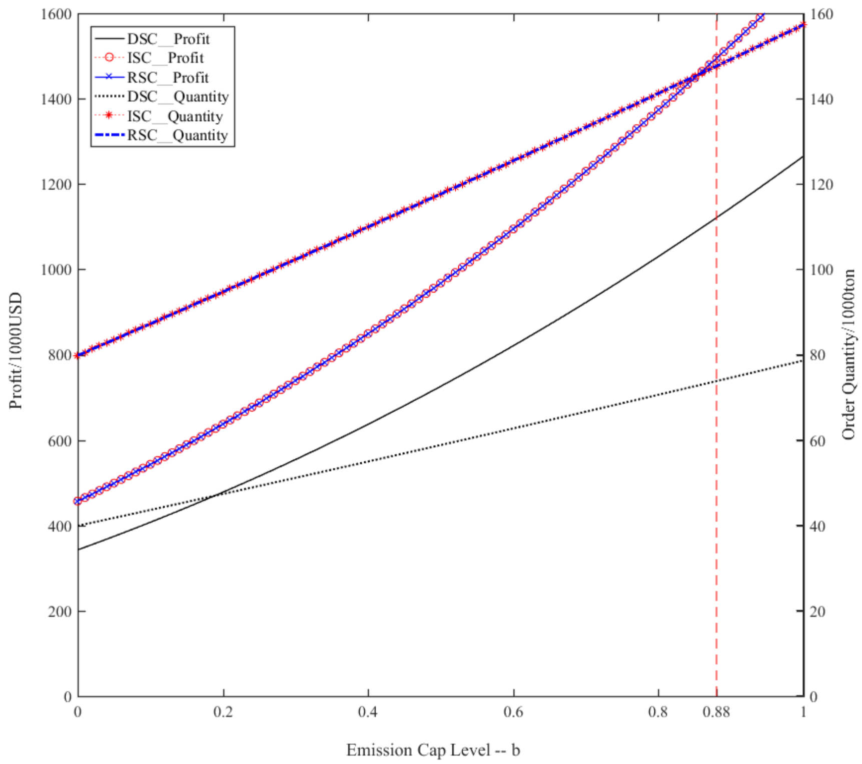

Figure 7. The Profit & Order Quantity Trends with Emission Cap Level

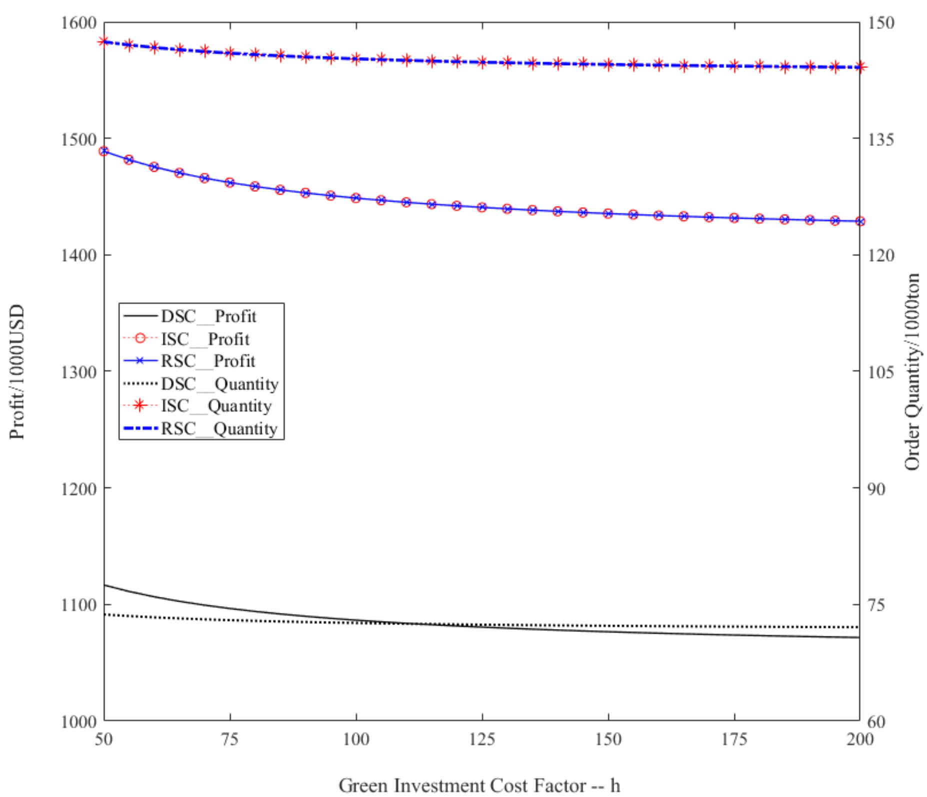

Figure 8. The Profit & Order Quantity Trends

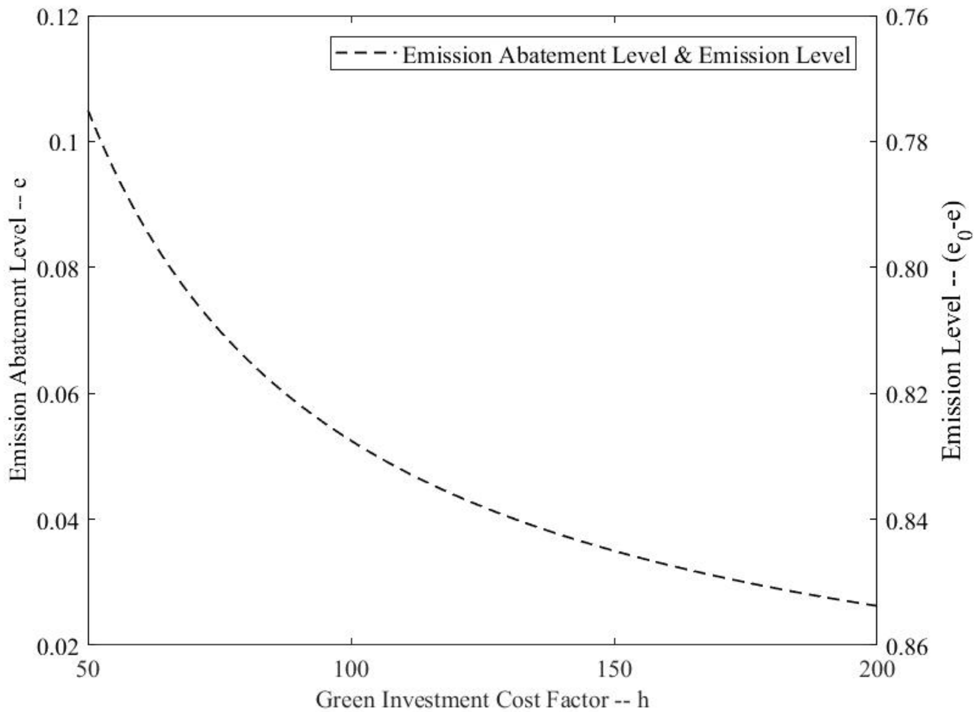

Figure 9. The Emission Reduction Capacity Trends

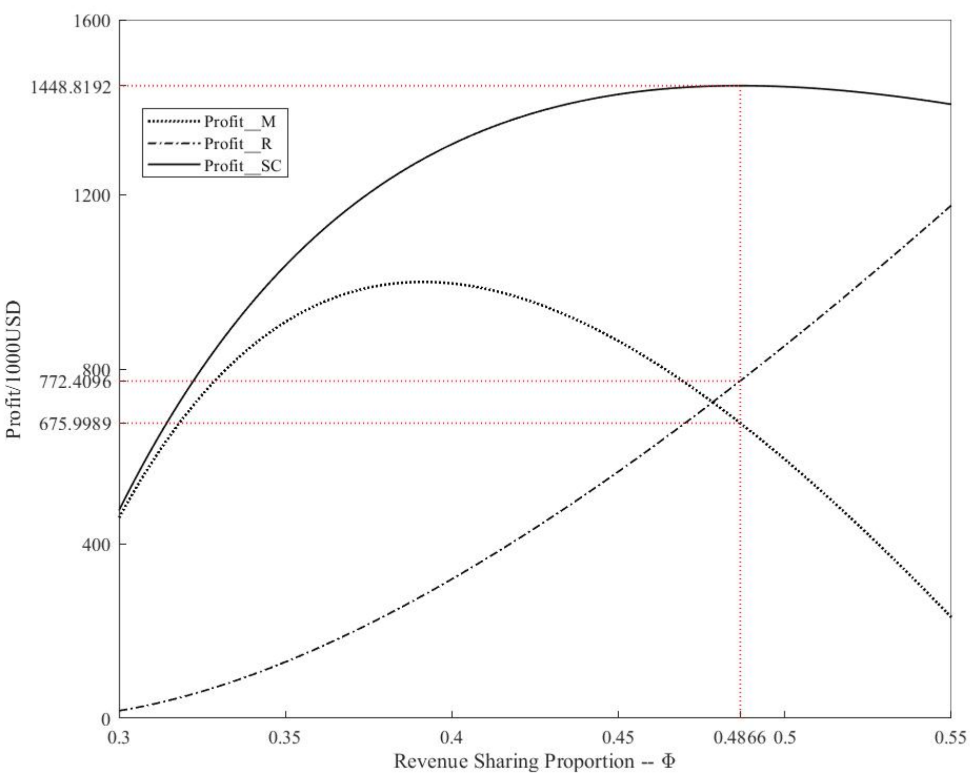

Figure 10. Profit Trends of SC & Members with Revenue Sharing Ratio

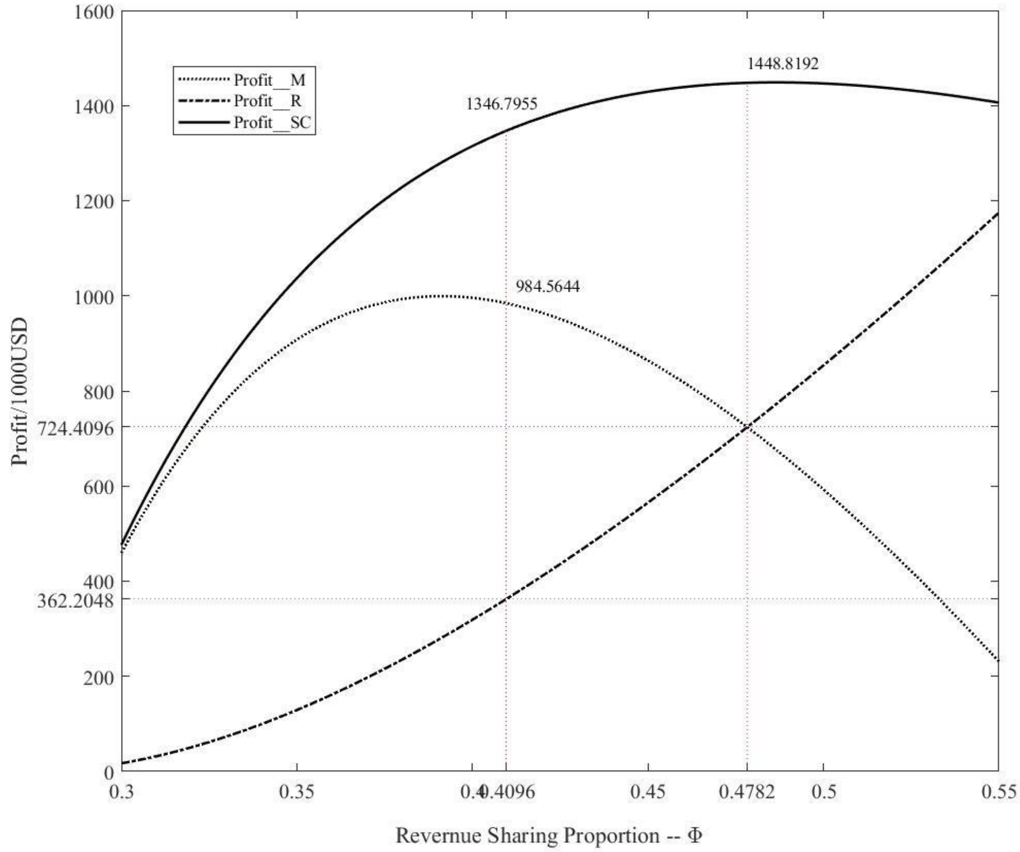

Figure 11. Pareto Improvement Analysis

Table 5. Profit Changes for Different Values of ϕ

Values	Profit/1000USD		
ϕ	Manufacturer	Retailer	Supply Chain
0.4096	984.5486	362.2774	1346.8260
0.4233	955.8502	427.6652	1383.5154
0.4370	914.0682	496.7302	1410.7984
0.4508	860.7294	569.1974	1429.9268
0.4645	797.1599	644.8189	1441.9788

0.4782	724.5150	723.3701	1447.8851

4.2 The Performance of the Two-Part Tariff Contract

A. Results Comparison

From Table 6, the order quantity with a two-part tariff contract (TPT) catches up with the integrated level, and the total emission abatement amount correspondingly doubles. Also, the profit loss from decentralized decision-making is compensated by TPT. It further validates that the wholesale price in the TPT model equals the unitary total cost and is smaller than that in the decentralized model.

Table 7 limits the range of the lump sum fee to make the contract valid. Only when the inequality shown in Table 7 is satisfied can the supply chain achieve the Pareto improvement, with which the TPT is enforced.

Table 6. Results Comparison of Three Models

	DSC			ISC			TPT		
	Members		Total	Members		Total	Members		Total
	M	R	SC	M	R	SC	M	R	SC
Order Quantity (Ton)	72.6248			145.2496			145.2496		
	50% q_I			q_I			q_I		
Emission Abatement Level	0.0525			0.0525			0.0525		
Emission Abatement Amount (Ton)	3.8128			7.6256			7.6256		
Wholesale Price (USD)	40.0253			40.0253		---	30.0506		
Lump Sum Fee	---			---			F		
Profit (1000USD)	724.4096	362.2048	1086.6144	1448.8192	0	1448.8192	F	$\pi_I - F$	1448.8192
	50% π_I	25% π_I	75% π_I	π_I	0	π_I	---	---	π_I

Table 7. Comparison between Decentralized and TPT coordinated models

	DSC	TPT	The relationship for Pareto Improvement	
Manufacturer	$\frac{1}{2} \cdot \pi_I^*$	$\pi_M^t = F$	$F \geq \frac{1}{2} \cdot \pi_I^*$	$\frac{1}{2} \cdot \pi_I^* \leq F \leq \frac{3}{4} \cdot \pi_I^*$

Retailer	$\frac{1}{4}\cdot\pi_I^*$	$\pi_R^t=\pi_I^*-F$	$F\le\frac{3}{4}\cdot\pi_I^*$	
Supply Chain	$\frac{3}{4}\pi_I^*$	π_I^*	π_I^*	π_I^*

Managerial Insight 5: Only when the lump sum fee F varies within a certain scope can the contract take effect with full coordination.

B. Sensitivity Analysis

As the profit function in the TPT owns the same mathematical expression as that in the ISC, its sensitivity analysis is similar to that discussed before. What needs to be specifically discussed are the profit trends with the lump sum fee and the possibility of achieving Pareto improvement.

In Figure 12, the lump sum fee F does not affect the supply chain profit. However, the profits of the manufacturer and the retailer respectively increases and decreases linearly with the increase of F. According to the results of the decentralized model, the profit boundaries of Pareto improvement is clearly limited, from 724.4096 to 1086.6144. Within this range, at least one player earns more and it is of great possibility that both the members benefit from the two-part tariff contract. Table 8 correspondingly shows the profit changes of the supply chain and members for different values of F. Between the range $F\in(724.4096, 1086.6144)$, both members increase their profitability compared to the decentralized levels and the supply chain reaches the integrated profit.

Managerial Insight 6: The two-part tariff contract charges nothing to come into force, but it is short of flexibility compared to the RSC.

A higher demand risk and lower flexibility may cause greater profit hemorrhage.

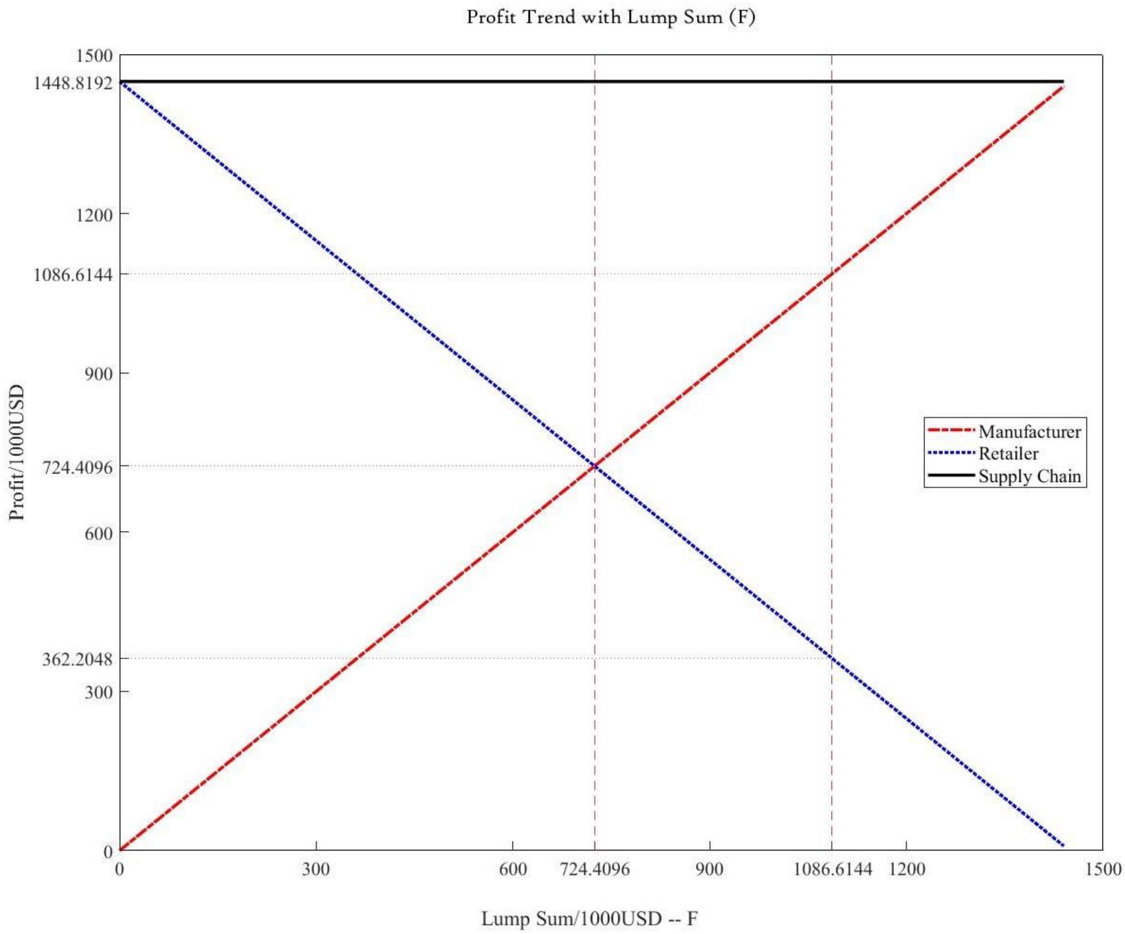

Figure 12. Pareto Improvement Analysis

Table 8. Profit Changes for Different Values of F

Values	Profit/1000USD		
F	Manufacturer	Retailer	Supply Chain
724.4096	724.4096	724.4096	1448.8192
814.9608	814.9608	633.8584	1448.8192
905.5120	905.5120	543.3072	1448.8192
996.0632	996.0632	452.7560	1448.8192

1086.6144	1086.6144	362.2048	1448.8192

V. CONCLUSION

Reducing the manufacturing carbon footprint is key to both economic and environmental sustainability. Supply chain coordination alleviates the burden of emission on the manufacturer and improves the profitability and sustainability of all the supply chain members. This paper investigates the Pareto-efficient coordination problem under the flexible cap-and-trade emission constraints. Three kinds of contracts are explored to fill the huge profit and greenness gaps between the decentralized and integrated supply chain. Both analytical and numerical results for Pareto-improving conditions are given to achieve coordination contract enforcement.

The results provide several managerial insights for manufacturing decision-making under China's flexible cap-and-trade. Both the revenue sharing and two-part tariff contracts help increase profitability and greenness. Unlike other researches, the cost sharing contract does not work under this model setting. Besides, the Pareto conditions decide whether the contract can be enforced. The revenue sharing contract better copes with the demand risk but may sacrifice some profits for Pareto improvement, whereas the two-part tariff is easy to conduct without profit loss but suffers higher profit deviation. Moreover, lower green cost and emission limitations contribute to green production, but extravagant carbon prices hamper economic development. This requires the policymakers to set reasonable policies and then to carefully regulate the market operation. These findings call for the supply chain members to make better decisions for achieving both the individual and the whole optimality, as well as for the policymakers to limit the carbon price within a reasonable range for the health of the carbon market.

There are several opportunities for further research. First, this paper only considers the manufacturer's effort on the green investment. In reality, carbon emission generates throughout the supply chain, and therefore all the members should pay more attention to and put some efforts into the emission abatement project. Second, a wider supply chain scheme and a more practical newsvendor model suitable for any demand distribution can be considered. Third, a multi-period production problem is worthwhile to be discussed in a more practical market, where the carbon price varies across periods. Finally, this paper assumes one product without the substitution effect in the proposed market. The multi-product problem and the substitution effect deserves further study.

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Pareto-efficient coordination of the contract-based MTO supply chain under flexible cap-and-trade emission constraint

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APPENDIX

***Proof 1*: optimal solutions for the decentralized case**

$$\begin{cases} \pi_M = \left[w - c - he^2 - c_e \cdot (e_0 - e - b)\right] \cdot \dfrac{2(a + rb + re - re_0)}{p + c_h} \cdot (p - w) \\ s.t. \quad e_0 - b < e < e_0 \\ \qquad p > c + he^2 + c_e \cdot (e_0 - e - b) \end{cases} \tag{1}$$

By using Lagrange optimization with the multipliers λ_1, λ_2 and λ_3 and slack variables η_1^2, η_2^2 and η_3^2, we can have:

$$\begin{cases} L_D = -\left[w - c - he^2 - c_e \cdot (e_0 - e - b)\right] \cdot \dfrac{2(a + rb + re - re_0)}{p + c_h} \cdot (p - w) \\ \quad + \lambda_1 \cdot (e_0 - b - e + \eta_1^2) + \lambda_2 \cdot (e - e_0 + \eta_2^2) + \lambda_3 \cdot \left(p - c - he^2 - c_e \cdot (e_0 - e - b) - \eta_3^2\right) \\ s.t. \ \lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_3 \geq 0, \eta_1 \neq 0, \eta_2 \neq 0, \eta_3 \neq 0 \end{cases} \tag{2}$$

Then the KKT conditions can be:

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$$
\begin{cases}
\dfrac{\partial L_D}{\partial e} = -\dfrac{2(p-w)}{p+c_h}\cdot\left[(c_e-2he)\cdot(a+rb+re-re_0)+r\cdot\left(w-c-he^2-c_e\cdot(e_0-e-b)\right)\right] \\
\qquad -\lambda_1+\lambda_2+\lambda_3\cdot(c_e-2he)=0 \\
\dfrac{\partial L_D}{\partial w} = -\dfrac{2(a+rb+re-re_0)}{p+c_h}\left[p-2w+c+he^2+c_e\cdot(e_0-e-b)\right]=0 \\
\dfrac{\partial L_D}{\partial \lambda_1} = e_0-b-e+\eta_1^2=0 \\
\dfrac{\partial L_D}{\partial \lambda_2} = e-e_0+\eta_2^2=0 \\
\dfrac{\partial L_D}{\partial \lambda_3} = p-c-he^2-c_e\cdot(e_0-e-b)-\eta_3^2=0 \\
\dfrac{\partial L_D}{\partial \eta_1} = 2\lambda_1\cdot\eta_1=0 \\
\dfrac{\partial L_D}{\partial \eta_2} = 2\lambda_2\cdot\eta_2=0 \\
\dfrac{\partial L_D}{\partial \eta_3} = -2\lambda_3\cdot\eta_3=0
\end{cases} \tag{3}
$$

From $\eta_1 \neq 0$, $\eta_2 \neq 0$ and $\eta_3 \neq 0$, together with $\frac{\partial L_D}{\partial \eta_1} = 2\lambda_1\cdot\eta_1=0$, $\frac{\partial L_D}{\partial \eta_2} = 2\lambda_2\cdot\eta_2=0$ and $\frac{\partial L_D}{\partial \eta_3} = -2\lambda_3\cdot\eta_3=0$, we have $\lambda_1=0$, $\lambda_2=0$ and $\lambda_3=0$. From $\frac{\partial L}{\partial w}=0$, we have $w=\frac{p+c+he^2+c_e\cdot(e_0-e-b)}{2}$. By inserting it into $\frac{\partial L_D}{\partial e}=0$, we have $(c_e-2he)\cdot(a+rb+re-re_0)+\frac{r\cdot\left[p-c-he^2-c_e\cdot(e_0-e-b)\right]}{2}=0$. Then we can have the optimal e^* by solving $(c_e-2he)\cdot(a+rb+re-re_0)+\frac{r\cdot\left[p-c-he^2-c_e\cdot(e_0-e-b)\right]}{2}=0$, and the optimal w^* as $w^*=\frac{p+c+he^{*2}+c_e\cdot(e_0-e^*-b)}{2}$.

Then we can have:

$$
q^* = \frac{a+rb+re^*-re_0}{p+c_h}\cdot\left[p-c-he^{*2}-c_e\left(e_0-e^*-b\right)\right] \tag{4}
$$

As $\left(c_e-2he\right)\cdot\left(a+rb+re-re_0\right)+\dfrac{r\cdot\left[p-c-he-c_e\cdot\left(e_0-e-b\right)\right]}{2}=0$, we have $\left(c_e-2he\right)\cdot\left(a+rb+re-re_0\right)=-\dfrac{r\cdot\left[p-c-he-c_e\cdot\left(e_0-e-b\right)\right]}{2}$.

As $r>0,\ p-c-he-c_e\cdot\left(e_0-e-b\right)>0$, we have $\left(c_e-2he\right)\cdot\left(a+rb+re-re_0\right)<0$. As $\left(a+rb+re-re_0\right)>0$, we have $c_e-2he<0$. Then we have $e^*>\dfrac{c_e}{2h}$.

The KKT sufficient condition is the concavity of the objective function, which cannot be proven due to the unknown values of the parameters. However, after giving values to the parameters, we can know whether the profit function is concave or not. If it is concave, the KKT conditions are sufficient and necessary, and there exists a unique optimal solution. Otherwise there may exist more than one maxima point, which can be chosen by the decision maker when the problem is solved.

***Proof 2*: optimal solutions for the integrated case**

$$\pi_I=\left[p-c-he^2-c_e\cdot\left(e_0-e-b\right)\right]\cdot q-\frac{p+c_h}{4\left(a+rb+re-re_0\right)}\cdot q^2 \qquad (5)$$

Same as Proof 1, by using Lagrange optimization with the multipliers λ_4, λ_5 and λ_6 and slack variables η_4^2, η_5^2 and η_6^2, we can have:

$$\begin{cases} L=-\left[p-c-he^2-c_e\cdot\left(e_0-e-b\right)\right]\cdot q+\dfrac{p+c_h}{4\left(a+rb+re-re_0\right)}\cdot q^2 \\ \qquad +\lambda_4\cdot\left(e_0-b-e+\eta_4^2\right)+\lambda_5\cdot\left(e-e_0+\eta_5^2\right)+\lambda_6\cdot\left(p-c-he^2-c_e\cdot\left(e_0-e-b\right)-\eta_6^2\right) \\ s.t.\ \ \lambda_4\geq 0,\lambda_5\geq 0,\lambda_6\geq 0,\eta_4\neq 0,\eta_5\neq 0,\eta_6\neq 0 \end{cases} \qquad (6)$$

Then the KKT conditions can be:

$$\begin{cases} \frac{\partial L}{\partial e} = -\left(c_e - 2he\right)\cdot q - \frac{\left(p + c_h\right)\cdot r \cdot q^2}{4\left(a + rb + re - re_0\right)^2} \\ \qquad -\lambda_3 + \lambda_4 + \lambda_6 \cdot \left(c_e - 2he\right) = 0 \\ \frac{\partial L}{\partial q} = -\left[p - c - he^2 - c_e \cdot \left(e_0 - e - b\right)\right] + \frac{p + c_h}{2\left(a + rb + re - re_0\right)} \cdot q = 0 \\ \frac{\partial L}{\partial \lambda_4} = e_0 - b - e + \eta_4^2 = 0 \\ \frac{\partial L}{\partial \lambda_5} = e - e_0 + \eta_5^2 = 0 \\ \frac{\partial L}{\partial \lambda_3} = p - c - he^2 - c_e \cdot \left(e_0 - e - b\right) - \eta_6^2 = 0 \\ \frac{\partial L}{\partial \eta_4} = 2\lambda_4 \cdot \eta_4 = 0 \\ \frac{\partial L}{\partial \eta_5} = 2\lambda_5 \cdot \eta_5 = 0 \\ \frac{\partial L}{\partial \eta_6} = -2\lambda_6 \cdot \eta_6 = 0 \end{cases} \tag{7}$$

From $\eta_4 \neq 0$, $\eta_5 \neq 0$, and $\eta_6 \neq 0$, together with $\frac{\partial L}{\partial \eta_4} = 2\lambda_4 \cdot \eta_4 = 0$, $\frac{\partial L}{\partial \eta_5} = 2\lambda_5 \cdot \eta_5 = 0$ and $\frac{\partial L}{\partial \eta_6} = 2\lambda_6 \cdot \eta_6 = 0$, we have $\lambda_4 = 0$, $\lambda_5 = 0$ and $\lambda_6 = 0$. From $\frac{\partial L}{\partial q} = 0$, we have $q = 2 \cdot \frac{a + rb + re - re_0}{p + c_h} \cdot \left[p - c - he^2 - c_e\left(e_0 - e - b\right)\right]$. By inserting it into $\frac{\partial L}{\partial e} = 0$, we have $\left(c_e - 2he\right)\left(a + rb + re - re_0\right) + \frac{r \cdot \left[p - c - he^2 - c_e \cdot \left(e_0 - e - b\right)\right]}{2} = 0$, which is the same as that in Proof 1. Then we can know that the optimal $e_I = e^*$, and $e > \frac{c_e}{2h}$.

$$\begin{cases} e_I = e^* \\ q_I = 2 \cdot \frac{a + rb + re_I - re_0}{p + c_h} \cdot \left[p - c - he_I^2 - c_e\left(e_0 - e_I - b\right)\right] \end{cases} \tag{8}$$

***Proof 3*: optimal solutions for the revenue sharing case**

After some integral calculation, we can have the resulted profit functions of both the manufacturer and the retailer, as shown:

$$\begin{aligned}\pi_M^r &= (1-\phi)\cdot p\cdot\left[\int_0^q \frac{x}{2\left[a+r\cdot(b+e-e_0)\right]}dx+\int_q^{2\left[a+r\cdot(b+e-e_0)\right]}\frac{q}{2\left[a+r\cdot(b+e-e_0)\right]}dx\right]\\ &\quad+\left[w-c-he^2-c_e\cdot(e_0-e-b)\right]\cdot q\\ &=(1-\phi)\cdot p\cdot\left[q-\frac{q^2}{4(a+rb+re-re_0)}\right]+\left[w-c-he^2-c_e\cdot(e_0-e-b)\right]\cdot q\end{aligned} \tag{9}$$

$$\begin{aligned}\pi_R^r &= \phi p\cdot\left[\int_0^q \frac{x}{2\left[a+r\cdot(b+e-e_0)\right]}dx+\int_q^{2\left[a+r\cdot(b+e-e_0)\right]}\frac{q}{2\left[a+r\cdot(b+e-e_0)\right]}dx\right]\\ &\quad-c_h\cdot\int_0^q\frac{q-x}{2\left[a+r\cdot(b+e-e_0)\right]}dx-wq\\ &=(\phi p-w)\cdot q-\frac{\phi p+c_h}{4(a+rb+re-re_0)}\cdot q^2\end{aligned} \tag{10}$$

For easy to calculate, let $S=c+he^2+c_e\cdot(e_0-e-b)$, $d=a+rb+re-re_0$. Then we can get the expression of the optimal order quantity by deviation.

$$\begin{aligned}\frac{\partial\pi_R^r}{\partial q}&=(\phi p-w)-\frac{\phi p+c_h}{2d}\cdot q\\ \frac{\partial^2\pi_R^r}{\partial q^2}&=-\frac{\phi p+c_h}{2d}\end{aligned} \tag{11}$$

From $\frac{\partial\pi_R^r}{\partial q}=0$ and $q_c=q_I$, we can know:

$$w_r=\phi p-\frac{\phi p+c_h}{p+c_h}\cdot(p-S) \tag{12}$$

By substituting w_r into $\frac{\partial\pi_M^r}{\partial w}=0$, we can get:

$$\phi=\frac{2c_hS+pS-pc_h}{(3p+2c_h)(p-S)} \tag{13}$$

From the solution process above, we can get the optimal value of each variable:

$$
\begin{aligned}
& e_r = e^* \\
& \phi = \frac{2c_h S + pS - pc_h}{(3p+2c_h)(p-S)} \\
& w_r = \phi p - \frac{\phi p + c_h}{p + c_h} \cdot (p - S) \\
& q_r = \frac{2(a + rb + re_r - re_0)}{(\phi p + c_h)} \cdot (\phi p - w_r) \\
& where \;\; S = c + he_r^2 + c_e \cdot (e_0 - e_r - b)
\end{aligned} \tag{14}
$$

***Proof 4*: profit comparison between the revenue sharing case and the integrated case**

According to Proof 3, we can have:

$$
\begin{aligned}
& \pi_M^r = \frac{(3p-4S)\cdot p}{(3p+2c_h)(p-S)} \cdot \frac{1}{2} \cdot \left[p - c - he_r^2 - c_e \cdot (e_0 - e_r - b) \right] \cdot q_r \\
& \pi_R^r = \frac{2pc_h - 2Sc_h + pS}{(3p+2c_h)(p-S)} \cdot \frac{1}{2} \cdot \left[p - c - he_r^2 - c_e \cdot (e_0 - e_r - b) \right] \cdot q_r \\
& \pi_r^* = \frac{1}{2} \cdot \left[p - c - he_r^2 - c_e \cdot (e_0 - e_r - b) \right] \cdot q_r
\end{aligned} \tag{15}
$$

It is clear that $e_r = e_I$ and $q_r = q_I$, so that:

$$
\frac{1}{2} \cdot \left[p - c - he_r^2 - c_e \cdot (e_0 - e_r - b) \right] \cdot q_r = \frac{1}{2} \cdot \left[p - c - he_I^2 - c_e \cdot (e_0 - e_I - b) \right] \cdot q_I = \pi_I^* \tag{16}
$$

Thus, we know the relationship between the revenue sharing case and the integrated case, as shown below:

$$
\begin{aligned}
& \pi_M^r = \frac{(3p-4S)\cdot p}{(3p+2c_h)(p-S)} \cdot \pi_I^* \\
& \pi_R^r = \frac{2pc_h - 2Sc_h + pS}{(3p+2c_h)(p-S)} \cdot \pi_I^* \\
& \pi_r^* = \pi_I^*
\end{aligned} \tag{17}
$$

***Proof 5*: solution process for the cost sharing case**

The transformed profit functions with cost sharing ratio φ:

$$\pi_M^o = \left[w - (1-\varphi)\cdot\left(c+he^2\right) - c_e\cdot\left(e_0 - e - b\right)\right]\cdot q$$
$$\pi_R^o = \left[p - w - \varphi\cdot\left(c+he^2\right)\right]\cdot q - \frac{p+c_h}{4\left(a+rb+re-re_0\right)}\cdot q^2 \tag{18}$$

From $\frac{\partial \pi_R^o}{\partial q} = 0$ and $\frac{\partial \pi_M^o}{\partial w} = 0$, we can have:

$$q_o = \frac{2\left(a+rb+re-re_0\right)}{p+c_h}\cdot\left[p - w - \varphi\cdot\left(c+he^2\right)\right]$$
$$w_o = \frac{p + (1-2\varphi)\cdot\left(c+he^2\right) + c_e\cdot\left(e_0-e-b\right)}{2} \tag{19}$$

By substituting w_c into q_c, then let $q_o = q_I$, we can see that:

$$p = c + he^2 + c_e\cdot\left(e_0 - e - b\right) \tag{20}$$

The expression (25) contradicts the prerequisite as $p > c + he^2 + c_e\cdot\left(e_0 - e - b\right)$, thus the cost sharing contract lacks the capability for the supply chain coordination.

***Proof 6*: optimal solutions for the two-part tariff case**

The transformed profit functions with a lump sum fee F:

$$\pi_M^t = \left[w - c - he^2 - c_e\cdot\left(e_0 - e - b\right)\right]\cdot q + F$$
$$\pi_R^t = \left(p - w\right)\cdot q - \frac{p+c_h}{4\left(a+rb+re-re_0\right)}\cdot q^2 - F \tag{21}$$

It is obvious that $e_t = e_I$ and $q_t = q_I$, and then insert e_t and q_t into $\frac{\partial \pi_R^t}{\partial q} = 0$, we can have $w_t = c + he_t^2 + c_e\cdot\left(e_0 - e_t - b\right)$.

Consequently, the optimal solutions for the two-part tariff case are shown as follows:

$$e_t = e^*$$
$$w_t = c + he_t^2 + c_e\cdot\left(e_0 - e - b\right) \tag{22}$$
$$q_t = 2\cdot\frac{a+rb+re-re_0}{p+c_h}\cdot\left[p - c - he^2 - c_e\left(e_0 - e - b\right)\right]$$

***Proof 7*: profit comparison between the two-part tariff case and the integrated case**

From Proof 6, by inserting e_t, w_t, and q_t into the profit functions in the two-part tariff case, we can have:

$$\begin{aligned}&\pi_M^t = F\\&\pi_R^t = \frac{1}{2}\cdot\left[p - c - he_t^2 - c_e\cdot\left(e_0 - e_t - b\right)\right]\cdot q_t - F\\&\pi_t^* = \pi_I^*\end{aligned} \tag{23}$$

It is clear that $e_t = e_I$ and $q_t = q_I$, we can see that:

$$\frac{1}{2}\cdot\left[p - c - he_t^2 - c_e\cdot\left(e_0 - e_t - b\right)\right]\cdot q_t = \frac{1}{2}\cdot\left[p - c - he_I^2 - c_e\cdot\left(e_0 - e_I - b\right)\right]\cdot q_I = \pi_I^* \tag{24}$$

Thus, we know the relationship between the two-part tariff case and the integrated case, as shown below:

$$\pi_M^t = F;\ \pi_R^t = \pi_I^* - F;\ \pi_t^* = \pi_I^* \tag{25}$$