IMPACT OF RISK AVERSION ON TWO-ECHELON SUPPLY CHAIN SYSTEMS WITH CARBON EMISSION REDUCTION CONSTRAINTS

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Abstract. This study examines a two-echelon supply chain consisting of two competing manufacturers and one retailer that has the channel power, in which one manufacturer is engaged in sustainable technology to curb carbon emissions under the cap-and-trade regulation while the other one operates its business as usual in a traditional manner. Two different supply chain configurations concerning risk attributes of the agents are considered, that is, (i) two risk-neutral manufacturers with one risk-averse retailer; and (ii) two risk-averse manufacturers with one risk-neutral retailer. Under the mean-variance framework, we use a retailer-leader game optimization approach to study operational decisions of these two systems. Specifically, optimal operational decisions of the agents are established in closed-form expressions and the corresponding profits and carbon emissions are assessed. Numerical experiments are conducted to analyze the impact of risk aversion of the underlying supply chains. The results show that each risk-averse agent would benefit from a low scale risk aversion. Further, low carbon emissions could be attainable if risk aversion scale of the underlying manufacturer is small or moderate. In addition, the carbon emissions might increase when risk aversion of the traditional manufacturer or the retailer is of small or moderate scale.

1. Introduction. As public awareness and concerns about environmental protection continue to increase, consumer behavior has changed over time. In particular, products with lower carbon emissions are preferred by increasingly many customers. An European Commission poll conducted in 2008 indicated that 75% of the respondents were willing to buy environmentally friendly products at higher prices.
compared to their alternative products made from traditional manufacturers [14]. Similar results were reported in the studies by Bull [6] and Zhang et al. [42]. On the other hand, carbon emission reduction has received significant attention by policy makers because carbon emissions contribute to climate change including global warming, which can have serious consequences for humans and their environment. As the largest manufacturing country in the world, China set an aggressive target in 2015 to reduce 40% of CO$_2$ emissions in the manufacturing industry by 2050 [46]. To curb carbon emissions, many national governments and regional organizations have implemented various environmental protection mechanisms. Amongst, the cap-and-trade regulation has been recognized as one of the most effective market-based mechanisms for controlling carbon emissions [17]. Under the cap-and-trade regulation, a limited number of emission permits are allocated to the firms, which are allowed to trade the surplus emission permits in a carbon trading market when their carbon emissions are less than the cap. European Union first established a carbon trading system in 2005, which now has become the largest carbon trading scheme in the world [15].

Driven by both carbon emission regulations and consumer preferences for environmentally friendly products, many mainstream companies who have channel powers such as Wal-Mart and IBM require their suppliers to provide low-carbon label for their products. As such, to ensure supply chain sustainability and competitiveness, there have been increasing demands for the suppliers to invest in sustainable technologies to curb carbon emissions generated from production process in the supply chain. When an upstream supplier or manufacturer chooses to invest in sustainable technology to curb carbon emissions, some new and crucial challenges to the firm would arise accordingly. On the one hand, with consumers' increasing preferences to low-carbon-emission products, the manufacturers of interest should pay high cost to invest in sustainable technology and would develop sales strategies like higher selling prices of their products compared to their conventional alternative products in the market. However, it is unclear how these manufacturers could maintain their competitive advantages over the regular manufacturers without carbon emission constraints. On the other hand, under the circumstance of fierce market competition, the members involved in the supply chain would face many risks due to uncertain demand and other factors, which often leads to risk-averse behaviors of the agents in their supply chain management. Hence, it is necessary and important to study the effects of the risk-averse attitudes on operational decisions of the supply chain, such as the determination of the selling price, the wholesale price and the sustainable technology level.

Motivated by the above observations, in this paper we are interested to study a two-echelon supply chain consisting of two competing manufacturers and one retailer that has the channel power. We assume that manufacturer 1 invests in sustainable technology to curb carbon emissions generated during producing product 1 under the cap-and-trade regulation. Manufacturer 2 is a traditional firm to produce product 2. These two manufacturers produce and sell these two different types of products to the retailer, where product 1 and product 2 are assumed to be alternatives to the consumers. Based on the above arguments, the underlying sustainable technology level is assumed to have a positive effect on the demand of product 1 and a negative effect on the demand of product 2. In this paper, we use a retailer-leader game optimization method to model two supply chain structures, i.e., a system with two risk-neutral manufacturers and one risk-averse retailer; and
a system with two risk-averse manufacturers and one risk-neutral retailer. Under the mean-variance (MV) framework, we investigate optimal operational decisions of these two models and compare the profits and carbon emissions. We conduct numerical experiments to analyze the impact of risk aversion on these two supply chain models.

The main contributions of this paper are as follows. First, we incorporate risk aversion factor and carbon emission reduction into a two-echelon supply chain with two competing manufacturers and one retailer and apply a retailer-leader game optimization method to address two different supply chain structures of interest. Second, under the MV framework, we establish the closed-form expressions of optimal operational decisions concerning these two supply chain structures and analyze the impact of risk aversion on supply chain decisions numerically. Moreover, when the cap-and-trade regulation and investment in sustainable technology are adopted for carbon emission reduction, we analyze the tradeoffs between the carbon emissions and profits of these two supply chains and provide several managerial insights, which would be useful to the agents for supply chain management with carbon emission reduction constraints.

The remainder of this paper is organized as follows. In Section 2, we review the relevant literature. Section 3 details problem description and notations, model development of two supply chain structures under the MV framework, followed by operational decisions. Section 4 presents numerical examples to illustrate the obtained theoretical results and analyzes the impact of the risk aversion parameter involved. Section 5 concludes.

2. Literature review. This study is closely related to two important research streams in supply chain management, namely, supply chain models with risk-averse agents and supply chain models with carbon emission reduction constraints. In this section, we would like to review relevant research work in literature.

2.1. Supply chain models with risk-averse agents. In literature, a number of studies on supply chain management adopted the MV approach to analyze how risk attitudes affect the decision making of a supply chain consisting of risk-averse agents. In particular, Xiao and Choi [32] studied a system consisting of two manufacturers and two retailers where the manufacturers are risk averse with integrated retailing channels and the retailers are risk averse and independent. Under the MV decision framework, optimal decisions of all members for maximizing their respective utility profits were derived in different channel structures. Later, Xiao and Xu [33] developed a Stackelberg game model to study a two-echelon supply chain with a risk averse manufacturer and a risk averse retailer. The authors analyzed the impact of risk version on the system’s pricing and production decisions. Recently, Xie et al. [35] considered a green supply chain consisting of one manufacturer and one retailer associated with multiple cleaner products where both vertically integrated and decentralized structures were modeled for maximizing the corresponding profits using the MV approach when each member involved is risk averse. More recently, Li et al. [22] considered a dual-channel supply chain with a risk-neutral manufacturer and a risk-averse retailer under asymmetric demand information and analyzed the impact of the underlying risk aversion on operational decisions of the members in the chain based on the MV approach. Other recent studies in this regard include Shen et al. [27], Wang et al. [30], Xiao and Yang [34], Xue et al. [39], and Zhou et
Two comprehensive literature reviews on supply chain risk analysis with MV models can be found in Chiu and Choi [9] and Paul et al. [25].

The aforementioned research work analyzed the effect of risk aversion basically from the perspective of individual members using the MV approach. In literature, a lot of research has been carried out to analyze such effect from the perspective of supply chain coordination. For instance, Choi et al. [10] considered a supply chain consisting of one manufacturer and one retailer with different risk preferences and studies channel coordination using the MV method. Li et al. [21] considered a two-echelon fast fashion supply chain with one supplier and multiple risk-averse retailers and derived a return policy for supply chain coordination. In addition, motivated by the mobile application marketing, Avinadav et al. [1] developed a two-echelon supply chain with multiple competitive developers and one retailer under a consignment contract with revenue-sharing where all members involved were risk-averse, risk-neutral, or risk-seeking. They analyzed the impact of risk attitudes on supply chain coordination. Similarly, Ohmura and Matsuo [24] used a return policy to coordinate a two-echelon supply chain and investigated the effect of risk aversion factor on the preferences of the agents in supply chain coordination. Zhao et al. [44] conducted the mean-risk analysis for a wholesale price contract with one supplier and one retailer supply chain together with the effect of the retailer’s risk-averse degree on supply chain coordination. Other recent studies in this regard can be found in Chen et al. [8], Gan et al. [16], and Liu et al. [23].

The supply chain models discussed above did not consider product competition between the manufactures involving carbon emission reduction and without. Further, impact of the carbon emission reduction on operational decisions were not examined. In this paper, we would like to develop a two-echelon supply chain with two competing manufacturers and one retailer under the cap-and-trade regulation. With the members of the chain having different risk attitudes, we are interested to analyze the impact of risk aversion on the operational decisions of supply chain members under the constraint of carbon emission reduction.

2.2. Supply chain models with carbon emission reduction constraints.
Supply chain management with carbon emission reduction constraints is an important topic in operations management. In the past few years, researchers have become increasingly interested to study the impact of carbon emission reduction on operational decisions of supply chains. The first study in this regard was conducted by Bonney and Jaber [5] who incorporated carbon footprint into the classical economic order quantity model and showed the importance of inventory planning in reducing carbon emissions. A reader is referred to Bazan et al. [3] for a comprehensive review on inventory models with carbon footprint. Recently, Ji et al. [19] considered an online to offline supply chain with one manufacturer exerting efforts to curb carbon emissions and one retailer. They analyzed the pricing strategies and emission reduction decisions of the members under cap-and-trade regulation on the manufacturer. In addition, Xu et al. [38] analyzed the impact of cap-and-trade regulation on the production and pricing decisions of a supply chain consisting of one manufacturer and one retailer with two products. Yang et al. [41] considered two competing supply chains consisting of one manufacturer and one retailer and studied the equilibrium solutions and impacts of cap-and-trade regulation. Qi et al. [26] analyzed the pricing decisions of a make-to-order supply chain with one supplier and two retailers together with the effect of carbon cap on operational decisions. Xia et al. [31] incorporated the preferences and low-carbon awareness
of consumers into a supply chain. Under cap-and-trade regulation, they derived the pricing and emission reduction decisions of the supply chain members. The aforementioned models studied operational decisions of supply chains from the perspective of an individual firm. On the other hand, in literature there has been a number of research work focusing on impact analysis of carbon emission reduction on supply chain coordination, for instance, Bai et al. [2], Cao et al. [7], Jaber et al. [18], Xu, Chen and Bai [36], Xu et al. [37], and Yang and Chen [40], to name a few.

Note that the underlying supply chains in the above-mentioned literature were modeled and analyzed under the situation of the deterministic demand. While a few research publications considered the case of stochastic demand. Du et al. [12] used the Stackelberg game to model a supply chain with one emission-dependent manufacturer and one supplier under cap-and-trade regulation. In the context of the newsvendor model, the authors analyzed the impact of the carbon cap on operational decisions of these two members. Dong et al. [11] developed a one-manufacturer and one-retailer supply chain with carbon emission reduction constraint, where the manufacturer was imposed by the cap-and-trade regulation and invested in sustainable technology to curb carbon emissions. They discussed three different contracts to coordinate the supply chain, provided stochastic demand is affected by the sustainable technology level. Tao et al. [28] employed a multi-period stochastic dynamic programming method to analyze the impact of carbon transfer costs and carbon holding costs on supply chain coordination. The authors proposed a contract with a wholesale price, subsidies, and a fixed setup cost to coordinate the chain. Du et al. [13] considered the consumers’ low-carbon preferences in a two-echelon supply chain with one manufacturer and one retailer. When both parties of the supply chain are emitters and make low-carbon efforts to improve the products’ environmental performance, the authors suggested an effective contract to coordinate the supply chain. Wang et al. [29] incorporated government carbon tax decisions into a one-manufacturer and one-retailer supply chain under uncertain demand. They assessed supply chain performance and the government social welfare of three different dominance structures under consideration.

All the above studies were carried out under the assumption that the members involved are risk-neutral. In this paper, we like to develop a supply chain with two manufacturers and one retailer being the risk averse under the cap-and-trade regulation and stochastic demand. We investigate the impact of risk attitude on operational decisions of the supply chain under the mean-variance framework.

3. Problem formulation and model analysis.

3.1. Problem description and notations. We consider a two-echelon supply chain consisting of two competing manufacturers and one retailer that has the channel power, where the three members have different risk attitudes. Let $\lambda_{m1}, \lambda_{m2}$ and $\lambda_r$ denote the risk aversion parameters of manufacturer 1, manufacturer 2, and the retailer, respectively, where $\lambda_{m1}, \lambda_{m2}, \lambda_r \in (0, 1)$. In the supply chain system, the manufacturers order raw materials at the ordering prices of $c_1$ and $c_2$ per unit from their suppliers, then produce and sell the associated products to the retailer at the wholesale prices of $w_1(> 0)$ and $w_2(> 0)$ per unit, respectively. The retailer then sells the products to the consumers. Following studies [32] and [33], we assume that there is no production and order capacity limits and the lead time is zero such that all the demands of the consumers can be served by the supply chain. Suppose
manufacturer 1 is engaged in sustainable technology to curb carbon emissions generated from production process at a technology level denoted by \( s \), where \( s > 0 \). In general, improving the sustainable technology level could result in a diminishing return on sustainable technology expenditures. By studies [2] and [11], we define the investment cost regarding sustainable technology by \( \frac{1}{2} \eta s^2 \) and the carbon emission in terms of the technology level \( s \) by \( a - bs \), where \( \eta \) denotes the sustainable investment coefficient, \( a \) is the base carbon emission without technology implementation (i.e., \( s = 0 \)), and \( b \) is the coefficient of the technology level on reducing carbon emissions. Here, \( \eta, a, b > 0 \). Evidently, \( 0 \leq s < \frac{a}{b} \) since it is impossible to completely cut carbon emissions in practice. The carbon cap-and-trade regulation imposed on manufacturer 1 is by a cap \( C(> 0) \) with the trading price \( c_p(> 0) \) of emission permits. By assumption, manufacturer 2 is a traditional and there is no impact of carbon emissions involved in operational decisions. Let \( p_1(> w_1), p_2(> w_2) \) be the selling prices of product 1 and product 2 from the retailer to the customers, respectively. Suppose the product demands are stochastic, denoted by \( D_i, i = 1, 2 \). Recent studies [4] and [20] indicated that consumers were willing to pay more money to buy food products with low carbon emission labels, compared to the alternatives.

In view of the channel power of the retailer, we formulate the problem as retailer-leader game optimization models as follows, that is, decentralized model 1 (DM1); the supply chain with two risk-neutral manufacturers and one risk-averse retailer;
and decentralized model 2 (DM2): the supply chain with two risk-averse manufacturers and one risk-neutral retailer. The sequential activities in each model are as follows: (i) the retailer first sets the selling prices of these two products; (ii) observing the retailer’s decisions, manufacturer 1 determines the optimal wholesale price of product 1 and the sustainable technology level, manufacturer 2 determines the optimal wholesale price of product 2. We note that when manufacturer 2 makes the wholesale price decision, manufacturer 2 can infer manufacturer 1’s optimal sustainable technology level since all the information is common knowledge.

In this paper, we need the following assumptions to ensure the feasibility of the underlying models regarding the non-negativity of optimal values of decision variables and the associated objective functions of interest. For ease of reading and the completeness, we move necessary mathematical expositions in the Appendix. Throughout, we make the following assumptions.

**Assumption 1.** $d_2 - \beta_2 c_2 > d_1 - \beta_1 (c_1 + a c_p) > 0$.

This assumption means that basic demands of the two products will be of certain sizes. Also, if manufacturer 1 does not invest in the sustainable technology to curb emissions generated in the production process, the market demand of product 2 will be higher than that of product 1 under the zero gross profit margin. In reality, a high investment cost is usually paid to improve the technology level ([11] and [36]), we assume the coefficient $\eta$ of sustainable technology investment is of certain large quantity with a lower bound as below.

**Assumption 2.**

$$ \eta > \Omega = \max\{\Omega_1, \Omega_2, \Omega_3, \Omega_4\}, $$

where

$$\Omega_1 = \frac{(\beta_1 + 2 \lambda_1 \sigma_1^2 + \lambda_2 \sigma_1^2)}{2 \beta_1 (\beta_1 + \lambda_1 \sigma_1^2)} + \frac{\alpha_1 + b c_p \beta_1}{2 \beta_1} \left[ \frac{(\beta_2 + \lambda_2 \sigma_2^2 + \lambda_3 \sigma_2^2)}{(\beta_2 + \lambda_2 \sigma_2^2 + \lambda_3 \sigma_2^2)} \right],$$

$$\Omega_2 = \frac{\alpha_2 \beta_1 (\alpha_1 + b c_p \beta_1)}{2(\beta_1 + \lambda_1 \sigma_1^2)} \frac{\lambda_4 \sigma_2^2 - \lambda_3 \sigma_2^2}{2(\beta_1 + \lambda_1 \sigma_1^2)} \frac{\lambda_2 \sigma_1^2}{(\beta_2 + \lambda_2 \sigma_2^2 + \lambda_3 \sigma_2^2)} [(d_1 - \beta_1 (c_1 + a c_p))^{-1}],$$

$$\Omega_3 = \frac{\alpha_2 \beta_1 (\alpha_1 + b c_p \beta_1)}{2(\beta_1 + \lambda_1 \sigma_1^2)} \frac{\lambda_4 \sigma_2^2 - \lambda_3 \sigma_2^2}{2(\beta_1 + \lambda_1 \sigma_1^2)} \frac{\lambda_2 \sigma_1^2}{(\beta_2 + \lambda_2 \sigma_2^2 + \lambda_3 \sigma_2^2)} [(d_1 - \beta_1 (c_1 + a c_p))^{-1}].$$

In the following, when the notation could be confusing superscripts "\*" and "\**" will be added to variables or objective functions of interest to distinguish from the DM1 model of the DM2 model.

**3.2. Model analysis.** In this subsection, we study optimal operational decisions of the members involved in the two models under consideration, including their existence, uniqueness together with their explicit solution expressions. According to (7) and (8), we have the following results concerning the the technology level $s$ and the whole prices $w_1$ and $w_2$.

**Lemma 3.1.** For any given $p_1$ and $p_2$, the following statement hold.

(i) There exists a unique optimal sustainable technology level $s^*$ and the wholesale price $w_1^*$ of product 1 such that the expected profit of manufacturer 1 is maximized, where

$$s^* = \frac{(\alpha_1 + b c_p \beta_1)(d_1 - \beta_1 p_1)}{\beta_1 \eta - \alpha_1 (\alpha_1 + b c_p \beta_1)},$$

$$w_1^* = c_1 + a c_p + \frac{[\eta - b c_p (\alpha_1 + b c_p \beta_1)](d_1 - \beta_1 p_1)}{\beta_1 \eta - \alpha_1 (\alpha_1 + b c_p \beta_1)}.$$


(ii) There exists a unique optimal wholesale price of product 2, \( w^*_2 \), such that the expected profit of manufacturer 2 is maximized, where

\[
w^*_2 = c_2 + \frac{[\beta_1 \eta - \alpha_1 (a_1 + bc_p \beta_1)](d_2 - \beta_2 p_2) - \alpha_2 (a_1 + bc_p \beta_1)(d_1 - \beta_1 p_1)}{\beta_2 [\beta_1 \eta - \alpha_1 (a_1 + bc_p \beta_1)]}.
\]

Proof. Please see Appendix A.

Lemma 3.1 shows the existence and uniqueness of the two manufacturers’ operational decisions. The lemma also implies that when the retailer makes his/her operational decisions, the manufacturers as followers will respond by maximizing their respective expected profits.

3.2.1. Case 1: DM model. We incorporate the factor of risk aversion of the retailer in analysis and apply the mean-variance method to determine optimal operational decisions of the retailer, from which we derive optimal operational decisions of the manufacturers accordingly. With similar arguments in [10, 16, 33, 35], the utility function, denoted by \( U(\pi_r) \), concerning the retailer’s profit is as below.

\[
U(\pi_r) = E(\pi_r) - \frac{1}{2} \lambda_r Var(\pi_r)
\]

\[= (p_1 - w_1)(d_1 + \alpha_1 s - \beta_1 p_1) + (p_2 - w_2)(d_2 - \alpha_2 s - \beta_2 p_2) \]
\[-\frac{1}{2} \lambda_r \sum_{i=1}^{2} (p_i - w_i)^2 \sigma_i^2,
\]

where \( E(\pi_r) \) and \( Var(\pi_r) \) represent the mean and variance of the retailer’s random profit, respectively. From equation (13), we have the following result.

**Theorem 3.2.** There exists the unique optimal selling prices \( p^*_1 \) and \( p^*_2 \) associated with the two products, at which the utility profit function of the retailer is maximized and the optimal prices are in form of

\[
p^*_1 = \frac{d_1 A_1 - [\beta_1 \eta - \alpha_1 (a_1 + bc_p \beta_1)]A_2}{\beta_1 A_1},
\]

\[
p^*_2 = \frac{[(3 \beta_2 + 2 \lambda_r \sigma_2^2)d_2 + \beta_2 c_2(\beta_2 + 2 \lambda_r \sigma_2^2)]A_1 - \alpha_2 (3 \beta_2 + 2 \lambda_r \sigma_2^2)(a_1 + bc_p \beta_1)A_2}{4 \beta_2 (\beta_2 + \lambda_r \sigma_2^2) A_1},
\]

where

\[
A_1 = 4 \lambda_r \sigma_1^2 (\beta_2 + \lambda_r \sigma_2^2)[2 \beta_1 \eta - (a_1 + bc_p \beta_1)^2] + 8 \beta_1^2 \eta (\beta_2 + \lambda_r \sigma_2^2) [2 \beta_1 \eta - (a_1 + bc_p \beta_1)^2] - \alpha_2 ^2 \beta_1^2 (a_1 + bc_p \beta_1)^2,
\]

\[
A_2 = 4(\beta_2 + \lambda_r \sigma_2^2)[d_1 - \beta_1 (c_1 + ac_p)] [\beta_1 \eta (\beta_1 + 2 \lambda_r \sigma_1^2) - \lambda_r \sigma_1^2 (a_1 + bc_p \beta_1)^2] - \beta_2^2 \alpha_2 (a_1 + bc_p \beta_1)(d_2 - \beta_2 c_2).
\]

Proof. Please see Appendix B.
Theorem 3.3. When the utility profit of the retailer is maximized, the expected profits of the two manufacturers are maximized as well. In particular, the optimal wholesale prices of the two products and the sustainable technology level can be expressed explicitly as follows.

$$s^* = \frac{(\alpha_1 + bc_p\beta_1)A_2}{A_1}, \quad \text{(16)}$$

$$w_1^* = \frac{(c_1 + ac_p)A_1 + [\eta - bc_p(\alpha_1 + bc_p\beta_1)]A_2}{A_1}, \quad \text{(17)}$$

$$w_2^* = \frac{(\beta_2 + 2\lambda_2\sigma_2^2)[d_2A_1 - \alpha_2(\alpha_1 + bc_p\beta_1)A_2] + \beta_2sc_2(3\beta_2 + 2\lambda_2\sigma_2^2)A_1}{4\beta_2^2(\beta_2 + \lambda_2\sigma_2^2)A_1} \quad \text{(18)}$$

Proof. Please see Appendix C.

Theorem 3.3 shows that, as a follower in the game, each manufacturer makes its own optimal decisions separately when the retailer determines the optimal selling prices of these two products. According to (16), (17) and (18), we can see that the sustainable technology level is positively related to the wholesale price of product 1 while is negatively related to the wholesale price of product 2. This result implies that manufacturer 1 will increase the wholesale price of product 1 while manufacturer 2 would reduce the wholesale price of product 2 when manufacturer 1 chooses a higher level of sustainable technology.

Let $A_3 = [d_1 - \beta_1(c_1 + ac_p)]A_1 - [2\beta_1\eta - (\alpha_1 + bc_p\beta_1)^2]A_2$. From Theorems 3.2 and 3.3, we have the following results.

Theorem 3.4. The optimal utility profit of the retailer and the expected profits of the two manufacturers are as follows.

$$U^*(\pi_r) = \frac{4A_3(\beta_2 + \lambda_2\sigma_2^2)(2\beta_2^2\eta A_2 - \lambda_2\sigma_2^2 A_1) + \beta_2^2[(d_2 - \beta_2c_2)A_1 - \alpha_2(\alpha_1 + bc_p\beta_1)A_2]^2}{8\beta_2^2(\beta_2 + \lambda_2\sigma_2^2)A_1^2}, \quad \text{(19)}$$

$$E^*(\pi_{m_1}) = \frac{\eta A_2^2[2\beta_1\eta - (\alpha_1 + bc_p\beta_1)^2]}{2A_1^2} + c_pC, \quad \text{(20)}$$

$$E^*(\pi_{m_2}) = \frac{(\beta_2 + 2\lambda_2\sigma_2^2)^2[(d_2 - \beta_2c_2)A_1 - \alpha_2(\alpha_1 + bc_p\beta_1)A_2]^2}{16\beta_2^2(\beta_2 + \lambda_2\sigma_2^2)^2A_1^2}. \quad \text{(21)}$$

Moreover, the corresponding carbon emissions of manufacturer 1 are equal to

$$J(s^*) = \frac{\beta_1\eta A_2[aA_1 - b(\alpha_1 + bc_p\beta_1)A_2]}{A_1^2}. \quad \text{(22)}$$

Proof. Please see Appendix D.
Corollary 3.5. There exists a threshold $C_0$ in form of $C_0 = CA^2 - \beta_1\eta A_1 - b(\alpha_1 + bc_p\beta_1)A_2$. Manufacturer 1 will buy $\frac{C_0}{B_1}$ quantity of emission permits if $C_0$ is positive; and sell $\frac{C_0}{B_1}$ quantity of emission permits, otherwise.

3.2.2. Case 2: DM$_2$ model. We now study the situation of model DM$_2$, where the supply chain system consists of two risk-averse manufacturers and one risk-neutral retailer. Similarly, we formulate the utility functions of these two manufacturers’ random profits as below.

$$U(\pi_{m_1}) = [w_1 - c_1 - c_p(a - bs)](d_1 + \alpha_1s - \beta_1p_1) - \frac{1}{2}\eta s^2 + c_pC$$
$$-\frac{1}{2}\lambda_{m_1}\sigma_1^2[w_1 - c_1 - c_p(a - bs)]^2,$$  

(23)

$$U(\pi_{m_2}) = (w_2 - c_2)(d_2 - \alpha_2s - \beta_2p_2) - \frac{1}{2}\lambda_{m_2}\sigma_2^2(w_2 - c_2)^2.$$  

(24)

For brevity in description in the subsequent analysis, we define

$$B_1 = 4\beta_2(2\beta_2 + \lambda_m\sigma_2^2)(\beta_1 + \lambda_m\sigma_1^2)\eta[(2\beta_1 + \lambda_m\sigma_1^2)\eta - (\alpha_1 + bc_p\beta_1)^2]$$
$$-\alpha_2^2\beta_1(\alpha_1 + bc_p\beta_1)^2(\beta_2 + \lambda_m\sigma_2^2),$$

$$B_2 = 2\beta_2(2\beta_2 + \lambda_m\sigma_2^2)(\beta_1 + \lambda_m\sigma_1^2),\eta[d_1 - \beta_1(c_1 + ac_p)]$$
$$-\alpha_2\beta_1(\alpha_1 + bc_p\beta_1)(\beta_2 + \lambda_m\sigma_2^2)(d_2 - \beta_2c_2),$$

$$B_3 = [d_1 - \beta_1(c_1 + ac_p)]B_1 - [(2\beta_1 + \lambda_m\sigma_1^2)\eta - (\alpha_1 + bc_p\beta_1)^2]B_2.$$

With similar arguments above on model DM$_1$, we derive the following results.

Theorem 3.6. The following statements holds.

(i) When the expected profit of the retailer and the utility profits of two manufacturers are maximized, respectively, the corresponding optimal operational decisions of three members are as follows.

$$s^{**} = \frac{(\alpha_1 + bc_p\beta_1)B_2}{B_1},$$  

(25)

$$w_1^{**} = \frac{(c_1 + ac_p)B_1 + \eta - bc_p(\alpha_1 + bc_p\beta_1)]B_2}{B_1},$$  

(26)

$$w_2^{**} = \frac{[d_2 + (3\beta_2 + 2\lambda_m\sigma_2^2)c_2]B_1 - \alpha_2(\alpha_1 + bc_p\beta_1)B_2}{2(2\beta_2 + \lambda_m\sigma_2^2)B_1},$$  

(27)

$$p_1^{**} = \frac{d_1B_1 - [(\beta_1 + \lambda_m\sigma_1^2)\eta - \alpha_1(\alpha_1 + bc_p\beta_1)]B_2}{\beta_1B_1},$$  

(28)

$$p_2^{**} = \frac{[(3\beta_2 + \lambda_m\sigma_2^2)d_2 + \beta_2c_2(\beta_2 + \lambda_m\sigma_2^2)]B_1 - \alpha_2(3\beta_2 + \lambda_m\sigma_2^2)(\alpha_1 + bc_p\beta_1)B_2}{2\beta_2(2\beta_2 + \lambda_m\sigma_2^2)B_1}.$$

(ii) The optimal expected profit of the retailer and the utility profits of two manufacturers are as follows.

$$E^{**}(\pi_r) = \frac{(\beta_2 + \lambda_m\sigma_2^2)[(d_2 - \beta_2c_2)B_1 - \alpha_2(\alpha_1 + bc_p\beta_1)B_2]^2}{4\beta_2(2\beta_2 + \lambda_m\sigma_2^2)B_1^2}$$
$$+ \frac{(\beta_1 + \lambda_m\sigma_1^2)\eta B_2 B_3}{\beta_1B_1},$$  

(29)
\[ U^{**}(\pi_{m_1}) = \frac{\eta B_2^2 [2(\beta_1 + \lambda_m, \sigma_x^2)\eta - (\alpha_1 + bc_p, \beta_1)]^2}{2B_1^2} + c_p C, \quad (30) \]

\[ U^{**}(\pi_{m_2}) = \frac{[(d_2 - \beta_2, c_2)B_1 - \alpha_2(\alpha_1 + bc_p, \beta_1)B_2]^2}{8(2\beta_2 + \lambda_m, \sigma_x^2)B_1^2}. \quad (31) \]

(iii) Accordingly, the carbon emissions of manufacturer 1 are as below.

\[ J(s^{**}) = \frac{(\beta_1 + \lambda_m, \sigma_x^2)\eta B_2[aB_1 - b(\alpha_1 + bc_p, \beta_1)B_2]}{B_1^2}. \quad (32) \]

By Theorem 3.6, we can see that the operational decisions and the expected profit of the risk-neutral retailer are affected by the risk aversion parameters of the manufacturers. This implies that the retailer as the game leader takes into account risk attitudes of the manufacturers when he/she determines the optimal selling prices of the two products.

By Theorems 3.4 and 3.6, we derive the following results in comparison with model DM\(_1\) and model DM\(_2\).

**Theorem 3.7.** For DM\(_1\) and DM\(_2\), we have

(i) \( E^{**}(\pi_r) > U^{**}(\pi_r), \ E^{*}(\pi_{m_1}) > U^{**}(\pi_{m_1}) \) and \( E^{*}(\pi_{m_2}) > U^{**}(\pi_{m_2}) \);

(ii) \( J(s^{**}) = \frac{\beta_1, A_2, B_2[A_1 - b(\alpha_1 + bc_p, \beta_1)A_2]}{(\beta_1 + \lambda_m, \sigma_x^2)B_2A_1[A_2 - b(\alpha_1 + bc_p, \beta_1)A_2]} \).

*Proof.* Please see Appendix E. \( \square \)

According to Theorem 3.7, it follows that risk aversion could lead to a reduction in the profit of each supply chain member in general. In addition, a quantitative comparison is provided in terms of carbon emissions between risk-aversion and risk-neutral of manufacturer 1.

4. **Numerical study.** In this section, we conduct numerical experiments to illustrate the obtained results concerning the two underlying models and study the impact of the risk attributes on profits and carbon emissions of the supply chain. In numerical experiments, the values of the underlying parameters are set as follows.

\[ d_1 = 600, d_2 = 400, \alpha_1 = 0.8, \alpha_2 = 0.5, \beta_1 = 0.9, \beta_2 = 0.8, c_1 = 12, c_2 = 10, \sigma_1 = 1.96, \sigma_2 = 1.5, c_p = 3, a = 90, b = 0.8 \text{ and } \eta = 70. \]

We choose \( \lambda_r = 0.6 \) and solve the optimal operational decisions for DM\(_1\) with various values of carbon cap, i.e., 9000, 12,569 and 15,000. Computational results are reported in Tables 1 and 2. Similarly, for \( \lambda_{m_1} = 0.5 \) and \( \lambda_{m_2} = 0.8 \), we solve optimal operational decisions for model DM\(_2\) and the values of carbon cap are 9000, 11,416, and 15,000. We report computational results in Tables 3 and 4.

**Table 1.** The optimal solutions for DM\(_1\)

| Decentralized Model 1 | \( w_1^* \) | \( w_2^* \) | \( s^* \) | \( p_1^* \) | \( p_2^* \) |
|-----------------------|------------|------------|---------|---------|---------|
| \( C = 9000 \)       | 422.5471  | 207.3770   | 8.0263  | 483.9910| 297.6065|
| \( C = 12569 \)      | 422.5471  | 207.3770   | 8.0263  | 483.9910| 297.6065|
| \( C = 15000 \)      | 422.5471  | 207.3770   | 8.0263  | 483.9910| 297.6065|

From Tables 1 and 2, we can see that in model DM\(_1\), as the carbon cap increases, optimal operational decisions of the three members, the utility profit of the retailer, the expected profit of manufacturer 2 and carbon emissions remain unchanged. However, the expected profit of manufacturer 1 increases. Tables 3 and 4 show a similar phenomenon for model DM\(_2\). This indicates that under the cap-and-trade...
regulation, manufacturer 1 benefits from a higher carbon cap while carbon emissions remain unchanged with an increase in the carbon cap. This implies that the cap-and-trade regulation is a market-based approach that could be used to manage carbon emissions by providing different economic incentives.

Furthermore, we investigate the effects of the risk aversion parameters on the supply chain performance. For the numerical example with $C = 9000$ for model DM$_1$, we vary the value of $\lambda_r$ from 0.1 to 0.9. The corresponding results are shown in Figure 1. On the other hand, in the numerical example with $C = 9000$ for model DM$_2$, we vary the values of $\lambda_{m_1}$ and $\lambda_{m_2}$ from 0.1 to 0.9. The corresponding results are shown in Figures 2 and 3.

According to Figures 1-3, we have the following observations and findings.

1. When the risk aversion parameter of retailer $\lambda_r$ increases, the wholesale prices of the two products, the sustainable technology level, the profits of the two manufacturers and the carbon emissions will increase accordingly. However, the selling prices of the two products and the profit of the retailer appear to decrease. A high value of $\lambda_r$ urges the retailer to decrease the selling prices of the two products so as to increase their demands as much as possible. Increasing the demand of product 1 will lead to an increase in carbon emissions and manufacturer 1 will invest in a higher level of sustainable technology. A decrease in the selling price of product 1 and an increase in the sustainable technology investment cost will cause manufacturer 1 to increase the wholesale price in order to improve its revenue, which eventually leads to an increase in the profit of manufacturer 1. On the other hand, when manufacturer 1 invests in a higher level of sustainable technology, the demand of product 2 might decrease. However, the demand of product 2 still increases due to a decrease in the selling price of product 2. Manufacturer 2 will increase the wholesale price of product 2, which increases its revenue in the end. In this scenario, the increase in the demand and the wholesale price of product 2 would lead to an increase in the profit of the manufacturer. Although increases in the demand of the two products resulting in that the revenues increase, the profit of the retailer will decrease because of the increases in the product wholesale prices and the decreases in the selling prices.
When the risk aversion parameter of manufacturer 1 increases, the wholesale price and selling price of product 2, the profits of the retailer and manufacturer 2, and the carbon emissions will increase, while the wholesale price and selling price of product 1, the sustainable technology level and the profit of manufacturer 1 will decrease. Increasing the risk aversion parameter $\lambda_{m_1}$ could cause manufacturer 1 to invest in a lower level of sustainable technology to reduce the investment cost. A decrease in the sustainable technology level may lead to a decrease in the demand of product 1. As the leader, the retailer has to decrease the selling price of product 1 to attract the customers of product 1, which eventually leads to an increase in the demand of product 1. In this scenario, with an increase in the risk aversion parameter and a decrease in the selling price of product 1, manufacturer 1 will decrease the wholesale price and its profit will decrease as well. Both a decrease in the sustainable technology level and an increase in the demand of product 1 could lead to an increase in carbon emissions. On the other hand, when manufacturer 1 invests in a lower level of sustainable technology, the demand of product 2 may increase. The retailer increases the selling price of product 2 to increase revenue and reduce the revenue from product 1. Facing an increase in the selling price of product 2, manufacturer 2 increases the wholesale price, which would increase its revenue. When $\lambda_{m_1}$ increases, the profit of the retailer also increases because both the demand of product 2 and the selling price of product 2 increase.

When the risk aversion parameter of manufacturer 2 $\lambda_{m_2}$ increases, the selling price of product 1 and the profit of the retailer increase while the wholesale prices of the two products, the selling price of product 2, the sustainable technology level, the profits of the two manufacturers and carbon emissions decrease. Increasing the risk aversion parameter $\lambda_{m_2}$ causes manufacturer 2 to decrease the wholesale price of product 2 using a more conservative strategy. The retailer usually reduces the selling price of product 2 to attract the customers. A decrease selling price of product 2 causes the retailer to increase the selling price of product 1 to increase revenues. With a decrease in the wholesale price of product 2 and an increase in the selling price of product 1, manufacturer 1 has to reduce the wholesale price of product 1 because of the competition between the two manufacturers. Manufacturer 2 will also invest in a lower level of sustainable technology to reduce investment costs. Both investing in a lower level of sustainable technology and increasing the selling price of product 1 lead to a decrease in the demand of product 1. In this scenario, carbon emissions will decrease, and the profit of manufacturer 1 eventually decreases because of the decreases in the demand and the wholesale price of product 1. Although increasing the selling price of product 2 and investing in a lower level of sustainable technology lead to an increase in the demand of product 2, the profit of manufacturer 2 still decreases because of a decrease in the wholesale price of product 2 and an increase in the risk aversion parameter of manufacturer 2. On the other hand, when $\lambda_{m_2}$ increases, increases in the selling price of product 1 and the demand of product 2 eventually lead to an increase in the profit of the retailer.

5. Conclusion. In this paper, we incorporate risk aversion and carbon emission reduction into a two-echelon supply chain with two competing manufacturers and one retailer that has channel power. The two manufacturers produce and sell two different types of products to the retailer. The cap-and-trade regulation and sustainable technology are involved in curbing carbon emissions generated from the production process of manufacturer 1 while manufacturer 2 acts as a traditional enterprise in the study. We assume that the sustainable technology level has positive
and negative effects on stochastic demands of product 1 and product 2, respectively. Two supply chain structures of interest are considered, that is, a system with two risk-neutral manufacturers and one risk-averse retailer; and a system with two risk-averse manufacturers and one risk-neutral retailer. A retailer-leader game optimization method has been applied to address these two supply chain models. Under the mean-variance framework, we derive optimal operational decisions of each member in closed form. Numerical examples are presented to illustrate the theoretical results and analyze the impact of risk aversion on the profits and carbon emissions. The results show that (i) under the cap-and-trade regulation, a change in the carbon cap does not affect the sustainable technology investment decisions of manufacturer 1 which would benefit from a high carbon cap; (ii) each risk-averse member of the supply chain can benefit from a low risk aversion parameter; (iii) low carbon emissions are emitted when the risk aversion parameter of manufacturer 1 is moderate; and (iv) carbon emissions might increase when the risk aversion parameter of either manufacturer 2 or the retailer is small or moderate.

In this study, we use the classical mean-variance framework to analyze the effect of risk attributes. In the future, we are interested to use other risk measures such as conditional value-at-risk and entropic risk measure to study the underlying utility and the impact of risk aversion on supply chains involved with carbon footprint reduction. We also leave the extension of current study to supply chain coordination as a future research topic.
Figure 2. Effects of $\lambda_{m1}$ on DM2

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**Appendix.**

**Proof of Lemma 3.1.** (i) Without loss of generality, let $p_1 = w_1 + \Delta_1$, where $\Delta_1 \geq 0$. In addition, the expected profit of manufacturer 2 in (7) can be rewritten as

$$E(\pi_{m1}) = [w_1 - c_1 - c_p(a - bs)][d_1 + \alpha_1 s - \beta_1(w_1 + \Delta_1)] - \frac{1}{2}\eta s^2 + c_p C. \quad (33)$$

Taking the first order partial derivative of $E(\pi_{m1})$ in (33) with respect to $s$ and $w_1$, it gives that

$$\frac{\partial E(\pi_{m1})}{\partial s} = bc_p[d_1 + \alpha_1 s - \beta_1(w_1 + \Delta_1)] + \alpha_1[w_1 - c_1 - c_p(a - bs)] - \eta s, \quad (34)$$

and

$$\frac{\partial E(\pi_{m1})}{\partial w_1} = d_1 + \alpha_1 s - \beta_1(w_1 + \Delta_1) - \beta_1[w_1 - c_1 - c_p(a - bs)]. \quad (35)$$
Taking the second order partial derivatives of \( E(\pi_{m_1}) \) with respect to \( s \) and \( w_1 \), it follows that
\[
\frac{\partial^2 E(\pi_{m_1})}{\partial s^2} = 2bc_p\alpha_1 - \eta, \quad \frac{\partial^2 E(\pi_{m_1})}{\partial w_1^2} = -2\beta_1, \quad \frac{\partial^2 E(\pi_{m_1})}{\partial s \partial w_1} = \alpha_1 - bc_p \beta_1.
\]
According to condition (9) on \( \eta \), it is not hard to derive that
\[
\eta > \frac{(\alpha_1 + bc_p \beta_1)^2}{2\beta_1}, \quad \frac{\partial^2 E(\pi_{m_1})}{\partial s^2} < 0, \quad \frac{\partial^2 E(\pi_{m_1})}{\partial s^2} \cdot \frac{\partial^2 E(\pi_{m_1})}{\partial w_1^2} - \left( \frac{\partial^2 E(\pi_{m_1})}{\partial s \partial w_1} \right)^2 > 0.
\]
Thus, \( E(\pi_{m_1}) \) is jointly concave in \( s \) and \( w_1 \). Thereby, there exist the unique optimal values of \( s \) and \( w_1 \) at which the maximum expected profit of manufacturer 1 is attained. Next, solving \( \frac{\partial E(\pi_{m_1})}{\partial s} = 0 \) and \( \frac{\partial E(\pi_{m_1})}{\partial w_1} = 0 \), we have
\[
s^* = \frac{(\alpha_1 + bc_p \beta_1)[d_1 - \beta_1(w_1 + \Delta_1)]}{\beta_1 \eta - \alpha_1(\alpha_1 + bc_p \beta_1)} = \frac{(\alpha_1 + bc_p \beta_1)(d_1 - \beta_1 p_1)}{\beta_1 \eta - \alpha_1(\alpha_1 + bc_p \beta_1)}, \quad (36)
\]
\[
w_1^* = c_1 + ac_p + \frac{[\eta - bc_p(\alpha_1 + bc_p \beta_1)](d_1 - \beta_1 p_1)}{\beta_1 \eta - \alpha_1(\alpha_1 + bc_p \beta_1)}.
\]

**Figure 3.** Effects of \( \lambda_{m_2} \) on DM2
(ii) Let \( p_2 = w_2 + \Delta_2 \), where \( \Delta_2 \geq 0 \). Rewrite the expected profit of manufacturer 1 in (8) as follows

\[
\mathbb{E}(\pi_{m_2}) = (w_2 - c_2)[d_2 - \alpha_2 s - \beta_2(w_2 + \Delta_2)].
\]

Similarly, taking the first order partial derivative of \( \mathbb{E}(\pi_{m_2}) \) in (38) with respect to \( w_2 \), we have

\[
\frac{\partial \mathbb{E}(\pi_{m_2})}{\partial w_2} = d_2 - \alpha_2 s - \beta_2(w_2 + \Delta_2) - \beta_2(w_2 - c_2).
\]

Further, it is not hard to see that \( \frac{\partial^2 \mathbb{E}(\pi_{m_2})}{\partial w_2^2} = -2\beta_2 < 0 \). Thereby, function \( \mathbb{E}(\pi_{m_2}) \) is concave in \( w_2 \). Then, there exists a unique optimal value of \( w_2 \) such that the expected profit of manufacturer 2 is maximized. On the other hand, solving the equation \( \frac{\partial \mathbb{E}(\pi_{m_2})}{\partial w_2} = 0 \), it then follows from (36) and (39) that

\[
\begin{align*}
 w_2^* &= c_2 + \frac{d_2 - \beta_2 p_2 - \alpha_2 s^*}{\beta_2} \\
 &= c_2 + \frac{[\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)](d_2 - \beta_2 p_2) - \alpha_2 (\alpha_1 + bc_p \beta_1)(d_1 - \beta_1 p_1)}{\beta_2 \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)}.
\end{align*}
\]

**Proof of Theorem 3.2.** By (10), (11) and (12), we have

\[
\begin{align*}
p_1 - w_1^* &= p_1 - (c_1 + ac_p) - \frac{[\eta - bc_p (\alpha_1 + bc_p \beta_1)](d_1 - \beta_1 p_1)}{\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)}, \\
d_1 + \alpha_1 s^* - \beta_1 p_1 &= \frac{\beta_1 \eta (d_1 - \beta_1 p_1)}{\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)}, \\
p_2 - w_2^* &= \frac{2\beta_2 p_2 - (d_2 + \beta_2 c_2)}{\beta_2} + \frac{\alpha_2 (\alpha_1 + bc_p \beta_1)(d_1 - \beta_1 p_1)}{\beta_2 \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)},
\end{align*}
\]

and

\[
d_2 - \alpha_2 s^* - \beta_2 p_2 = d_2 - \beta_2 p_2 - \frac{\alpha_2 (\alpha_1 + bc_p \beta_1)(d_1 - \beta_1 p_1)}{\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)}.
\]

Substituting equations (41) – (44) into equation (14) and taking the first order partial derivative of \( U(\pi_r) \) with respect to \( p_1 \) and \( p_2 \), we have

\[
\begin{align*}
\frac{\partial U(\pi_r)}{\partial p_1} &= \frac{\beta_1 (d_1 - \beta_1 p_1) \{ \beta_2 [3 \beta_1 \eta (\alpha_1 + bc_p \beta_1)(\alpha_1 + 2bc_p \beta_1)] + 2 \alpha_2^2 (\alpha_1 + bc_p \beta_1)^2 \} \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)}{\beta_2 \beta_2 \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)} \\
&\quad+ \frac{\alpha_2 \beta_1 (\alpha_1 + bc_p \beta_1)(3 \beta_2 p_2 - 2d_2 - \beta_2 c_2) - \beta_2^2 \beta_2 \eta (p_1 - c_1 - ac_p)}{\beta_2 \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)} \\
&\quad+ \frac{\lambda r \{ (p_1 - w_1^*) \sigma_1^2 \beta_2^2 [2 \beta_2 \eta - (\alpha_1 + bc_p \beta_1)^2] - (p_2 - w_2^*) \sigma_2^2 \alpha_2 \beta_1 (\alpha_1 + bc_p \beta_1) \} \beta_2 \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)}{\beta_2 \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)},
\end{align*}
\]

and

\[
\begin{align*}
\frac{\partial U(\pi_r)}{\partial p_2} &= 2(d_2 - \beta_2 p_2) - \frac{(\beta_2 + 2\lambda r \sigma_2^2)(2\beta_2 p_2 - d_2 - \beta_2 c_2)}{\beta_2} \\
&\quad- \frac{\alpha_2 (\alpha_1 + bc_p \beta_1)(3 \beta_2 + 2\lambda r \sigma_2^2)(d_1 - \beta_1 p_1)}{\beta_2 \beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)}.
\end{align*}
\]
Further, taking the second order partial derivatives of $U(\pi_r)$ with respect to $p_1$ and $p_2$, we have

$$
\frac{\partial^2 U(\pi_r)}{\partial p_1^2} = \frac{-2\beta_2^2 \{2\beta_2 \eta [2\beta_1 \eta - (\alpha_1 + bc_p \beta_1)^2] + \alpha_2^2 (\alpha_1 + bc_p \beta_1)^2 \}}{\beta_2 [\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)^2]}
- \lambda_r \{\beta_2^2 \sigma_1^2 [2\beta_1 \eta - (\alpha_1 + bc_p \beta_1)^2] + \sigma_2^2 (\alpha_2 \beta_2)^2 (\alpha_1 + bc_p \beta_1)^2 \}
\frac{\partial^2 U(\pi_r)}{\partial p_1 \partial p_2} = \frac{\alpha_2 \beta_2 (\alpha_1 + bc_p \beta_1) (3\beta_2 + 2\lambda_r \sigma_2^2)}{\beta_2 [\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)]}
\frac{\partial^2 U(\pi_r)}{\partial p_2^2} = -4(\beta_2 + \lambda_r \sigma_2^2).
\tag{47}
\tag{48}
\tag{49}

From equation (47), (48) and (49), we have

$$
\frac{\partial^2 U(\pi_r)}{\partial p_1^2} \cdot \frac{\partial^2 U(\pi_r)}{\partial p_2^2} - \left( \frac{\partial^2 U(\pi_r)}{\partial p_1 \partial p_2} \right)^2 = f(\eta) \frac{[\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)]^2}{[\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)]^2},
\tag{50}
$$

where $f(\eta) = 16(\beta_2 + \lambda_r \sigma_2^2)(\beta_1 + \lambda_r \sigma_2^2)(\beta_1 \eta)^2 - 8(\beta_2 + \lambda_r \sigma_2^2)(\beta_1 + 2\lambda_r \sigma_2^2) + (\alpha_1 + bc_p \beta_1)^2 \beta_1 \eta + (\alpha_1 + bc_p \beta_1)^2 [4\lambda_r \sigma_2^2 (\beta_2 + \lambda_r \sigma_2^2) (\alpha_1 + bc_p \beta_1)^2 - \alpha_2^2 (\beta_2 + \lambda_r \sigma_2^2)]$.

Noticing the lower bound requirement on $\eta$, we have $f(\eta) > 0$, \(\frac{\partial^2 U(\pi_r)}{\partial p_1^2} \cdot \frac{\partial^2 U(\pi_r)}{\partial p_2^2} > 0\), which implies that $U(\pi_r)$ is jointly concave in $p_1$ and $p_2$. Hence, there exist the unique optimal values of $p_1$ and $p_2$ such that the utility profit function of the retailer is maximized. Similarly, by solving \(\frac{\partial U(\pi_r)}{\partial p_1} = 0\) and \(\frac{\partial U(\pi_r)}{\partial p_2} = 0\), we derive the optimal selling prices of two products as follows.

$$
p_1^* = \frac{d_1 A_1 - [\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)]A_2}{\beta_2 A_1},
\tag{51}
$$

$$
p_2^* = \frac{[(3\beta_2 + 2\lambda_r \sigma_2^2) d_2 + \beta_2 c_2 (\beta_2 + 2\lambda_r \sigma_2^2)] A_1 - \alpha_2 (3\beta_2 + 2\lambda_r \sigma_2^2) (\alpha_1 + bc_p \beta_1) A_2}{4\beta_2 (\beta_2 + \lambda_r \sigma_2^2) A_1}.
\tag{52}
$$

**Proof of Theorem 3.3.** From equations (14) and (15), we have

$$
d_1 - \beta_1 p_1^* = \frac{[\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)]A_2}{A_1},
\tag{53}
$$

$$
d_2 - \beta_2 p_2^* = \frac{(\beta_2 + 2\lambda_r \sigma_2^2) (d_2 - \beta_2 c_2) + \alpha_2 (\alpha_1 + bc_p \beta_1) (3\beta_2 + 2\lambda_r \sigma_2^2)(d_1 - \beta_1 p_1^*)}{4(\beta_2 + \lambda_r \sigma_2^2)[\beta_1 \eta - \alpha_1 (\alpha_1 + bc_p \beta_1)]}
= \frac{(\beta_2 + 2\lambda_r \sigma_2^2)(d_2 - \beta_2 c_2) A_1 + \alpha_2 (3\beta_2 + 2\lambda_r \sigma_2^2)(\alpha_1 + bc_p \beta_1) A_2}{4(\beta_2 + \lambda_r \sigma_2^2) A_1}.
\tag{54}
$$

Substituting (53) and (54) into equations (10), (11) and (12), we have

$$
s^* = \frac{(\alpha_1 + bc_p \beta_1) A_2}{A_1},
\tag{55}
$$

$$
w_1^* = \frac{(c_1 + ac_p) A_1 + [\eta - \beta_p (\alpha_1 + bc_p \beta_1)]A_2}{A_1},
\tag{56}
$$

$$
w_2^* = \frac{(\beta_2 + 2\lambda_r \sigma_2^2)(d_2 A_1 - \alpha_2 (\alpha_1 + bc_p \beta_1) A_2) + \beta_2 c_2 (3\beta_2 + 2\lambda_r \sigma_2^2) A_1}{4\beta_2 (\beta_2 + \lambda_r \sigma_2^2) A_1}.
\tag{57}
$$
Proof of Theorem 3.4. By equations (41)-(44) together with (53) and (54), it follows that

\[
(p_1^* - w_1^*)(d_1 + a_1 s^* - \beta_1 p_1^*) + (p_2^* - w_2^*)(d_2 - \alpha_2 s^* - \beta_2 p_2^*) = \eta A_2 \{[d_1 - \beta_1 (c_1 + ac_p)]A_1 - [2\beta_1 \eta - (a_1 + bc_p \beta_1)^2]A_2\}
\]

\[
+ \frac{\beta_2 + 2\lambda_r \sigma_2^2}{8(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2} \left[(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2\right]^2
\]

\[
= \frac{\eta A_2 A_1}{A_1^2} + \frac{\beta_2 + 2\lambda_r \sigma_2^2}{8(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2} \left[(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2\right]^2,
\]

and

\[
(p_1^* - w_1^*)^2 \sigma_1^2 + (p_2^* - w_2^*)^2 \sigma_2^2 = \frac{\beta_2 + 2\lambda_r \sigma_2^2}{4(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2} \left[(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2\right]^2 \sigma_1^2
\]

\[
+ \frac{\beta_2 + 2\lambda_r \sigma_2^2}{8(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2} \left[(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2\right]^2 \sigma_2^2
\]

\[
= \frac{A_3^2 \sigma_1^2}{2\beta_2^2 A_1^4} + \frac{[(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2]^2 \sigma_1^2}{8(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2}.
\]

Substituting (58) and (59) into equation (14), we derive the optimal utility function of the retailer’s random profit as below.

\[
U^*(\pi_r) = \eta A_2 A_3 \frac{\lambda_r A_3^2 \sigma_1^2}{2\beta_2^2 A_1^4} + \frac{[(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2]^2 \sigma_1^2}{8(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2}
\]

\[
= \frac{A_3(2\beta_2^2 \eta A_2 - \lambda_r \sigma_1^2 A_3)}{2\beta_2^2 A_1^4} + \frac{[(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2]^2 \sigma_1^2}{8(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2}.
\]

In addition, it follows from (37) and (53) that

\[
w_1^* - c_1 - c_p(a - bs^*) = \frac{\eta A_2}{A_1}.
\]

Substituting (42), (55) and (61) into equation (7), we have the optimal expected profit of manufacturer 1 as follows.

\[
\mathbb{E}^*(\pi_{m_1}) = \frac{\eta A_2^2 [2\beta_1 \eta - (a_1 + bc_p \beta_1)^2]}{2A_1^2} + c_p C.
\]

Similarly, substituting (44) and (57) into (8), we derive the optimal expected profit of manufacturer 2.

\[
\mathbb{E}^*(\pi_{m_2}) = \frac{(\beta_2 + 2\lambda_r \sigma_2^2)^2 [(d_2 - \beta_2 c_2)A_1 - \alpha_2(a_1 + bc_p \beta_1)A_2]^2}{16\beta_2(\beta_2 + \lambda_r \sigma_2^2)^2 A_1^2}.
\]

With help of (42) and (55), it is not hard to simplify the carbon emissions of manufacturer 1 as below.

\[
J(s^*) = \frac{(a - bs^*) \beta_1 \eta A_2}{A_1} = \frac{\beta_1 \eta A_2 [a A_2 - b(a_1 + bc_p \beta_1)A_2]}{A_1^2}.
\]
Proof of Theorem 3.7. (i) Note that \((p_1^*, p_2^*)\) and \((p_1, p_2)\) are respectively the optimal and feasible solutions of maximizing the retailer’s expected profit in decentralized model 2. Then, we have

\[ E^*(\pi_r) \geq E[\pi_r(p_1, p_2)] > U^*(\pi_r). \]

The second strict inequality above holds because \((p_1^*, p_2^*)\) is the optimal solution of maximizing the utility profit of the retailer in decentralized model 1 and \(U(\pi_r(p_1^*, p_2^*)) = E[\pi_r(p_1^*, p_2^*)] - \frac{1}{2} \lambda_r Var[\pi_r(p_1^*, p_2^*)]. \)

Similarly, we obtain \(E^*(\pi_m_1) > U^*(\pi_m_1)\) and \(E^*(\pi_m_2) > U^*(\pi_m_2)\).

(ii) Comparing equations (22) and (32), it follows immediately that

\[ J(s^*) = \frac{\beta_1 A_2 B_1^2[a A_1 - b(\alpha_1 + bc_p \beta_1) A_2]}{(\beta_1 + \lambda_m \sigma_f^2) B_2 A_1^2[a B_1 - b(\alpha_1 + bc_p \beta_1) A_2]} \]

Proof of non-negativity of optimal values of decision variables and objective functions. First, we prove that parameters \(A_i, B_i, i = 1, 2, 3\), are positive under the assumption. It is easy to verify that \(A_1 = 0\) when

\[ \eta = \frac{(\beta_1 + 2\lambda_r \sigma_f^2)(\alpha_1 + bc_p \beta_1^2) + 4\beta_1(\beta_1 + \lambda_r \sigma_f^2)}{4(\beta_1 + \lambda_r \sigma_f^2)} \]

Further, by the first order derivative of \(A_1\) with respect to \(\eta\), we have \(A_1\) is increasing in \(\eta\) if \(\eta > \frac{(\beta_1 + 2\lambda_r \sigma_f^2)(\alpha_1 + bc_p \beta_1^2)}{4\beta_1(\beta_1 + \lambda_r \sigma_f^2)}\). Since \(\eta > \Omega \geq \Omega_1\) by assumption, thereby, \(A_1 > 0\).

Again, by assumption, \(d_1 - \beta_1(c_1 + ac_p) > 0\) and \(\eta > \Omega \geq \Omega_1\), it follows that \(A_2 > 0\).

Since \(\Omega_1 > \frac{(\beta_1 + 2\lambda_r \sigma_f^2)(\alpha_1 + bc_p \beta_1^2)}{2\beta_1(\beta_1 + \lambda_r \sigma_f^2)} > \frac{(\alpha_1 + bc_p \beta_1)^2}{2\beta_1}\) and noticing \(\eta > \Omega_1\), it follows that \(2\beta_1 \eta - (\alpha_1 + bc_p \beta_1)^2 > 0\). By notions of \(A_1, A_2, A_3\) and since \(d_2 - \beta_2 c_2 > 0\), we have

\[ A_3 = [d_1 - \beta_1(c_1 + ac_p)] A_1 - [2\beta_1 \eta - (\alpha_1 + bc_p \beta_1)^2] A_2 > \beta_1^2(d_1 - \beta_1(c_1 + ac_p)) \times F, \]

where \(F = 8(\beta_2 + \lambda_r \sigma_f^2) \eta^2 - 4(\beta_2 + \lambda_r \sigma_f^2)(\alpha_1 + bc_p \beta_1)^2 \eta - \alpha_2^2(\alpha_1 + bc_p \beta_1)^2\). Because of \(\eta > \Omega \geq \Omega_1\), we have \(F > 0\), thereby, \(A_3 > 0\). With similar arguments, we can show that \(B_i > 0\) for \(i = 1, 2, 3\).

Next, we show the positiveness of optimal values of decision variables under consideration and the corresponding objective functions. (i), By equation (16), it is evident that \(s^* > 0\). (ii), since

\[ \Omega_1 > \frac{(\beta_1 + 2\lambda_r \sigma_f^2)(\alpha_1 + bc_p \beta_1)^2}{2\beta_1(\beta_1 + \lambda_r \sigma_f^2)} + \frac{(\alpha_1 + bc_p \beta_1)^2}{2\beta_1} \]

and \(\alpha_1 + bc_p \beta_1 > bc_p \beta_1\), we have \(\frac{(\alpha_1 + bc_p \beta_1)^2}{\beta_1^2} > bc_p (\alpha_1 + bc_p \beta_1)\) which implies that \(\eta > bc_p (\alpha_1 + bc_p \beta_1)\) in view of \(\eta > \Omega_1\) by assumption. Then, it follows from (17) that \(w_1^* > 0\). (iii), we simplify the optimal wholesale price \(w_2^*\) of product 2 as below.

\[ w_2^* = c_2 + \frac{(\beta_2 + 2\lambda_r \sigma_f^2)(d_2 - \beta c_2)(\alpha_1 + bc_p \beta_1) A_1}{4\beta_1(\beta_2 + \lambda_r \sigma_f^2) A_1} \]
Since \( \eta > \Omega_1 > \frac{(\alpha_1 + bc_p \beta_1)(\alpha_1 + \sigma_1^2 \beta_1)}{2 \beta_1} \) and \( \eta > \Omega_2 > \frac{\lambda_r \sigma_1^2 (\alpha_1 + 2bc_p \beta_1)^2}{\beta_1 (\beta_1 + 2 \lambda_r \sigma_1^2)} \), recalling the definitions of \( A_1 \) and \( A_2 \) and applying basic mathematical manipulations, we derive that \( (d_2 - \beta_2 c_2)A_1 - \alpha_2 (\alpha_1 + bc_p \beta_1)A_2 > 0 \). Thus, \( w^*_2 > 0 \). (iv), according to (17) and (18), the optimal selling prices of the two products can be rewritten as

\[
p_1^* = w^*_1 + \frac{A_1}{\beta_1 A_1}, \quad p_2^* = w^*_2 + \frac{(d_2 - \beta_2 c_2)A_1 - \alpha_2 (\alpha_1 + bc_p \beta_1)A_2}{2(\beta_2 + \lambda_r \sigma_1^2)A_1}.
\]

Since \( w^*_1 > 0, w^*_2 > 0, A_1 > 0, A_2 > 0 \) and \( (d_2 - \beta_2 c_2)A_1 - \alpha_2 (\alpha_1 + bc_p \beta_1)A_2 > 0 \), we have \( p_1^* = w^*_1 > 0 \) and \( p_2^* = w^*_2 > 0 \). With similar arguments, we can show that \( w^*_1 > 0, w^*_2 > 0, p^*_1 > 0, \) and \( p^*_2 > 0 \).

At last, we prove the non-negativity of \( E^*(\pi_{m_1}), E^*(\pi_{m_2}), U^{**}(\pi_{m_1}), U^{**}(\pi_{m_2}) \).

By assumption,

\[
\eta > \Omega_1 > \frac{(\beta_1 + 2 \lambda_r \sigma_1^2)(\alpha_1 + bc_p \beta_1)}{2 \beta_1} > \frac{(\alpha_1 + bc_p \beta_1)^2}{2 \beta_1} > \frac{(\alpha_1 + bc_p \beta_1)^2}{2 \beta_1 + \lambda_m \sigma_1^2}.
\]

Hence, \( 2 \beta_1 \eta - (\alpha_1 + bc_p \beta_1)^2 > 0 \) and \( (2 \beta_1 + \lambda_m \sigma_1^2) \eta - (\alpha_1 + bc_p \beta_1)^2 > 0 \). By equations (20) and (31), we have \( E^*(\pi_{m_1}) > 0 \) and \( U^{**}(\pi_{m_1}) > 0 \). On the other hand, according to (21) and (32), it is straightforward to obtain that \( E^*(\pi_{m_2}) > 0 \) and \( U^{**}(\pi_{m_2}) > 0 \).

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