A GREEN SUPPLY CHAIN COORDINATION CONTRACT CONSIDERING LOSS AVERSION AND CARBON EMISSIONS

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Abstract. Focusing on a two-echelon green supply chain in the context of carbon emissions, this paper sets up a Stackelberg game model of a loss-averse retailer and a risk-neutral manufacturer according to the prospect theory, solves the equilibrium ordering and green emission reduction strategies under decentralized decision-making by inverse induction, and then puts forward a cost sharing-revenue sharing contract to coordinate the supply chain. The results show that the positive/negative correlation between the retailer's optimal order quantity and the loss aversion coefficient depends on the distribution of random demand and the scale of unit shortage penalty cost; the green supply chain with loss aversion and carbon emissions can be coordinated if the retailer shares some of the manufacturer's green emission reduction cost and enjoys part of the manufacturer's profit; the parameters of the coordinate contract are constrained by the wholesale price of the manufacturer, but proper parameter values can ensure the Pareto optimization of the profits of both parties. Finally, numerical analysis shows that the proposed coordination contract can coordinate the target supply chain.
Keywords: *loss-averse, cap and trade, green emission reduction, cost sharing, revenue sharing*

Introduction

Since it was proposed by Michigan State University in 1996, green supply chain management has been emphasized and enforced by more and more governments and enterprises (Handfield et al., 1996). In China, many laws and regulations have been launched to encourage enterprises to develop clean energy and produce green products, enabling them to overcome green trade barriers in multilateral trade (Zhang, Zheng and Hu, 2019). For example, the Chinese State Council released the “Made in China 2025” strategy in May 2015, raising the concept of “green manufacturing”. In March 2016, the National Development and Reform Commission issued the *Guiding Opinions on Promoting Green Consumption*, calling enterprises to promote the construction of green supply chains. Nowadays, people are increasingly aware of the importance of resources and the environment, and holding a favorable attitude towards green and low-carbon concepts. With the continued expansion of green consumers, modern enterprises are obliged to enhance the positive externalities of their products, and introduce greener products to the market. Against this backdrop, the green supply chain becomes a new hotspot in the research of supply chains.

The green supply chain has been studied extensively from multiple angles at home and abroad. For instance, Zhang and Liu (2013) created three coordination mechanisms to discuss the coordination of three-echelon green supply chain system. Xie (2015) introduced government subsidy into the analysis on the greenness and price of green supply chain products, and coordinated the supply chain with wholesale price contract and revenue sharing contract. Sheu and Chen (2012) suggested that the government should

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take incentives to coordinate the green supply chain. Basiri and Heydari (2017) relied on a mathematical programming model to examine the channel coordination of two-echelon green supply chains. Zhang et al. (2018) established four green supply chain game models considering the participants' fairness preference, product greenness and government subsidy, and set up a coordination model based on cost and revenue sharing contract.

With the dawn of the low-carbon era, consumers are more willing to buy green products with carbon labels (Shuai and Zhang, 2013). Meanwhile, the carbon emission trading market has been unified by the government, allowing enterprises to buy or sell emission permits in a free manner. The trading mechanism encourages the enterprises to reduce carbon emission and improve product greenness (Jing et al., 2018). As a result, more and more scholars have turned their attention to supply chain problems in the context of carbon emission. For example, Hua et al. (2011) investigated the order quantity and inventory management of enterprises under the carbon cap and trading policy. Jaber et al. (2013) looked for the optimal inventory strategy under the same conditions. Du et al. (2013) analyzed the effect of carbon cap on the coordination of a two-echelon supply chain, in which the upstream manufacturer emits carbon in the production process. Zhang, Dong and Zhang (2019) discussed the selection of supply chain strategies under such factors as carbon quota and trading mechanism, emission reduction technology and the low-carbon preference of consumers.

To sum up, there are not many reports on green supply chain in the context of carbon emissions. Most of the existing studies assume that the decision-maker is purely rational, which goes against the reality. The actual market is full of uncertainties. Hence, the members of a supply chain face various risks of loss. If the supply chain is small, the participants are often loss-averse (Li et al., 2013). The loss aversion behavior was first discussed in the prospect theory (Kahneman and Tversky, 2013). Since then, many scholars have integrated the behavior with operation management. For example, He and Zhou (2011) studied the impact of loss aversion on the portfolio model. Liu and Shum (2013) explored the effect of loss-averse consumers on enterprise pricing. Liu and Fan (2017) probed into the coordination of two-echelon supply chain considering product quality and loss aversion. Du et al. (2018) investigated the effect of loss aversion behavior on the two-echelon supply chain with random supply and demand. Samatli-Pac et al. (2018) discussed the impact of consumer loss aversion on repurchase strategies and supply chain coordination.

Obviously, the previous research has not tackled the decision-making and coordination of green supply chain that consider loss aversion behavior. To make up for this gap, this paper attempts to coordinate the green supply chain in the context of loss aversion and carbon emissions. Firstly, a Stackelberg game model was established based on the prospect theory, covering a loss-averse retailer and a risk-neutral manufacturer. Then, the equilibrium ordering and green emission reduction strategies were solved under the decentralized decision-making mode, and the effect of the retailer's loss aversion behavior on the optimal order quantity was analyzed in detail. Finally, a cost sharing-revenue sharing contract was designed to coordinate the said supply chain.

Materials and methods

Problem description

This paper targets a two-echelon green supply chain consisting of a risk-neutral manufacturer and a loss-averse retailer. The manufacturer is assumed as the leader in

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the market and the retailer, a follower. The two parties are in a Stackelberg game of complete information. The manufacturer first determines the green emission reduction level θ of a product, and then the retailer decides on the order quantity q of the product. Let w and c be the unit wholesale price and the unit production cost of the manufacturer, respectively, and p, v and g be the unit retail price, unit salvage value and unit shortage cost of the retailer, respectively. Here, it is assumed that $p > w > c > v$.

Hypothesis 1: The manufacturer, as the subject of carbon emissions, receives a free carbon quota E from the government. Under the carbon cap and trading policy, the enterprise needs to purchase emission permit in the carbon trading market if it emits more carbon than the quota; otherwise, the enterprise can sell the surplus permit. The unit transaction price p_t is exogenous. Without emission reduction technology, i.e. $\theta = 0$, the amount of carbon emitted by the manufacturer is denoted as e; after adopting the technology, that amount is reduced to $(1-\theta)e$. Here, θ $(0 \le \theta < 1)$ refers to the emission reduction efficiency of the manufacturer.

Hypothesis 2: In commodity trading, the greenness of a product is often described by the energy rating label, the carbon label, the content of harmful substances, and the recyclability of the parts. Thus, the product greenness can be observed and calculated. To make its products greener, the manufacturer should step up its R&D investment on green emission reduction. Inspired by the investment cost model, this paper depicts the emission reduction cost with the quadratic cost function: $H(\theta) = 0.5\alpha\theta^2$, where α is the green emission reduction cost.

Hypothesis 3: The market demand of a product is stochastic and depends on product greenness. The market demand function of a product is assumed as *Equation 1*.

$$D(\theta) = A + B\theta + \varepsilon = y(\theta) + \varepsilon \tag{Eq.1}$$

where A is the market demand, B is the green preference of consumers, and ε is a continuous random variable in the interval $[M, N]$. The cumulative distribution function and probability density function of the variable are denoted as $F(\varepsilon)$ and $f(\varepsilon)$, respectively.

Under the above hypotheses, the retailer's and manufacturer's profit functions for fulfilling any demand *x* can be respectively expressed as *Equations 2* and *3*.

$$\pi_r(q) = p\min(q, D) + v(q-D)^+ - g(D-q)^+ - wq = \begin{cases} (p-v)x + (v-w)q, & x < q \\ (p-w+g)q - gx, & x \ge q \end{cases} \tag{Eq.2}$$

$$\pi_m(\theta) = (w-c)q + p_t[E - (1-\theta)e] - \frac{1}{2}\alpha\theta^2 \tag{Eq.3}$$

Decision-making model based on loss aversion

Considering the loss aversion of the retailer, the simple piecewise linear function was introduced to describe the decision-maker (Kahneman and Tversky, 2013). Let π be the profit of the decision-maker. Then, the utility function of the decision-maker can be defined as *Equation 4*.

$$U(\pi) = \begin{cases} \pi, & \pi \ge 0, \\ \lambda\pi, & \pi < 0. \end{cases} \tag{Eq.4}$$

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The retailer's expected utility was discussed under two conditions.

Lemma 1 (i) If $x < q$ and $\pi_1 = (p - v)x + (v - w)q = 0$ is the retailer's profit function, then the breakeven point of the demand is $x_1 = \frac{(w-v)q}{p-v}$, i.e. the retailer makes no profit when the demand $x = \frac{(w-v)q}{p-v}$, makes profit when $x > \frac{(w-v)q}{p-v}$, and suffers losses when $x < \frac{(w-v)q}{p-v}$. In this case, the retailer's expected utility is $E[U(\pi_1)] = \lambda \int_M^{x_1-y(\theta)} \pi_1 f(\varepsilon)\, d\varepsilon + \int_{x_1-y(\theta)}^{q-y(\theta)} \pi_1 f(\varepsilon)\, d\varepsilon$.

(ii) If $x \geq q$ and $\pi_2 = (p - w + g)q - gx = 0$ is the retailer's profit function, then the breakeven point of the demand is $x_2 = \frac{(p-w+g)q}{g}$, i.e. the retailer makes no profit when the demand $x = \frac{(p-w+g)q}{g}$, makes profit when $x > \frac{(p-w+g)q}{g}$, and suffers losses when $x < \frac{(p-w+g)q}{g}$. In this case, the retailer's expected utility is $E[U(\pi_2)] = \int_{q-y(\theta)}^{x_2-y(\theta)} \pi_2 f(\varepsilon)\, d\varepsilon + \lambda \int_{x_2-y(\theta)}^{N} \pi_2 f(\varepsilon)\, d\varepsilon$.

According to Lemma 1, the retailer's expected utility can be described as *Equation 5*.

$$E\left[U\left(\pi_r(q)\right)\right] = E\left[U\left(\pi_1\right)\right] + E\left[U\left(\pi_2\right)\right] = \lambda \int_{M}^{x_1-y(\theta)} \pi_1 f(\varepsilon) d\varepsilon + \int_{x_1-y(\theta)}^{q-y(\theta)} \pi_1 f(\varepsilon) d\varepsilon + \int_{q-y(\theta)}^{x_2-y(\theta)} \pi_2 f(\varepsilon) d\varepsilon + \lambda \int_{x_2-y(\theta)}^{N} \pi_2 f(\varepsilon) d\varepsilon = E\left(\pi_r(q)\right) + (\lambda - 1)\left[\int_{M}^{x_1-y(\theta)} \pi_1 f(\varepsilon) d\varepsilon + \int_{x_{2-y(\theta)}}^{N} \pi_2 f(\varepsilon) d\varepsilon\right] \quad \text{(Eq.5)}$$

where $E\left(\pi_r(q)\right) = \int_M^{q-y(\theta)} \pi_1 f(\varepsilon)\, d\varepsilon + \int_{q-y(\theta)}^{N} \pi_2 f(\varepsilon)\, d\varepsilon$ is the expected utility of risk-neutral retailer.

Equation 5 means the expected utility of loss-averse retailer equals the expected profit plus the total expected underage and overage losses, biased by a factor of $\lambda - 1$. Note that $\lambda - 1$ is the loss aversion factor. In particular, when $\lambda = 1$, the second term on the right side of the equation disappears. In this case, the retailer's expected utility equals the expected profit, that is, the retailer is risk-neutral.

The decision-making problem of a loss-averse retailer and a risk-neutral manufacturer can be respectively expressed as *Equations 6* and *7*.

$$max_{q>0}\, E\left[U\left(\pi_r(q)\right)\right] \quad \text{(Eq.6)}$$

$$max_{0\leq\theta<1}\, \pi_m(\theta) \quad \text{(Eq.7)}$$

Optimal strategy in decentralized mode

Under decentralized decision-making, the manufacturer and the retailer only consider their own profits (utilities) and make decisions independently. As the leader of the Stackelberg game, the manufacturer first determines the green emission reduction level

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θ of a product, and then the retailer, as the follower, decides on the order quantity q of the product. By inverse induction, the author calculated the optimal order quantity q_λ^* of the loss-averse retailer before deriving the optimal green input level θ^* of the manufacturer.

Theorem 1: $E\left[U\left(\pi_r(q)\right)\right]$ is a strict concave function with respect to *q*, and $\max_{q>0} E\left[U\left(\pi_r(q)\right)\right]$has a unique optimal solution q_λ^* that satisfies *Equation 8*.

$$\int_{\frac{(w-v)q}{p-v}-y(\theta)}^{q-y(\theta)} (v-w) f(\varepsilon) d\varepsilon + \int_{q-y(\theta)}^{\frac{(p-w+g)q}{g}-y(\theta)} (p-w+g) f(\varepsilon) d\varepsilon + \lambda\left[\int_{M}^{\frac{(w-v)q}{p-v}-y(\theta)} (v-w) f(\varepsilon) d\varepsilon + \int_{\frac{(p-w+g)q}{g}-y(\theta)}^{N} (p-w+g) f(\varepsilon) d\varepsilon\right] = 0 \quad \text{(Eq.8)}$$

Proof: Substituting π_1, π_2, x_1 and x_2 into *Equation 5*, we have:

$$E\left[U\left(\pi_r(q)\right)\right] = \lambda \int_{M}^{\frac{(w-v)q}{p-v}-y(\theta)} \left\{(p-v)\left[y(\theta)+\varepsilon\right]+(v-w)q\right\} f(\varepsilon) d\varepsilon + \int_{\frac{(w-v)q}{p-v}-y(\theta)}^{q-y(\theta)} \left\{(p-v)\left[y(\theta)+\varepsilon\right]+(v-w)q\right\} f(\varepsilon) d\varepsilon + \int_{q-y(\theta)}^{\frac{(p-w+g)q}{g}-y(\theta)} \left\{(p-w+g)q-g\left[y(\theta)+\varepsilon\right]\right\} f(\varepsilon) d\varepsilon + \lambda \int_{\frac{(p-w+g)q}{g}-y(\theta)}^{N} \left\{(p-w+g)q-g\left[y(\theta)+\varepsilon\right]\right\} f(\varepsilon) d\varepsilon \quad \text{(Eq.9)}$$

Then, the first- and second-order derivatives of *Equation 9* relative to *q* can be obtained as *Equations 10* and *11*.

$$\frac{dE\left[U\left(\pi_r(q)\right)\right]}{dq} = \int_{\frac{(w-v)q}{p-v}-y(\theta)}^{q-y(\theta)} (v-w)f(\varepsilon)\,d\varepsilon + \int_{q-y(\theta)}^{\frac{(p-w+g)q}{g}-y(\theta)} (p-w+g)f(\varepsilon)\,d\varepsilon + \lambda\left[\int_{M}^{\frac{(w-v)q}{p-v}-y(\theta)} (v-w)f(\varepsilon)\,d\varepsilon + \int_{\frac{(p-w+g)q}{g}-y(\theta)}^{N} (p-w+g)f(\varepsilon)\,d\varepsilon\right] \quad \text{(Eq.10)}$$

$$\frac{d^2E[U(\pi_r)]}{dq^2} = -(p-v+g)f\left(q-y(\theta)\right) - \frac{\lambda-1}{(p-v)g} \left[g(w-v)^2 f\left(\frac{(w-v)q}{p-v}-y(\theta)\right) + (p-v)(p-w+g)^2 f\left(\frac{(p-w+g)q}{g}-y(\theta)\right)\right] \quad \text{(Eq.11)}$$

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Since $p > v$ and $\lambda \geq 1$, we have $\frac{d^2 E[U(\pi_r)]}{dq^2} < 0$, indicating that $E\left[U\left(\pi_r(q)\right)\right]$ is a strict concave function with respect to *q*. Considering the first-order condition $\frac{dE\left[U\left(\pi_r(q)\right)\right]}{dq} = 0$, it can be seen that the unique optimal solution q_λ^* of loss-averse retailer satisfies *Equation 8*.

If the retailer is risk-neutral, i.e. $\lambda = 1$, then *Equation 8* can be rewritten as *Equation 12*.

$$\int_M^{q-y(\theta)} f(\varepsilon)\, d\varepsilon = \frac{p-w+g}{p-v+g} \tag{Eq.12}$$

Therefore, the optimal order quantity of risk-neutral retailer $q_1^* = F^{-1}\left(\frac{p-w+g}{p-v+g}\right) + y(\theta)$.

The effect of loss aversion of the retailer on the optimal order quantity can be summed up as Property 1 below.

Property 1: If $(w-v)F\big(x_1 - y(\theta)\big) + (p-w+g)F\big(x_2 - y(\theta)\big) < (p-w+g)$, then $\frac{dq_\lambda^*}{d\lambda} > 0$; if $(w-v)F\big(x_1 - y(\theta)\big) + (p-w+g)F\big(x_2 - y(\theta)\big) = (p-w+g)$, then $\frac{dq_\lambda^*}{d\lambda} = 0$; if $(w-v)F\big(x_1 - y(\theta)\big) + (p-w+g)F\big(x_2 - y(\theta)\big) > (p-w+g)$, then $\frac{dq_\lambda^*}{d\lambda} < 0$.

Proof: The following *Equation 13* can be derived from the implicit function theorem:

$$\frac{dq_\lambda^*}{d\lambda} = \frac{\frac{\partial^2 E[U(\pi_r)]}{\partial q \partial \lambda}}{\frac{\partial^2 E[U(\pi_r)]}{\partial q^2}} = \frac{(p-w+g)-(w-v)F\big(x_1-y(\theta)\big)-(p-w+g)F\big(x_2-y(\theta)\big)}{\frac{\partial^2 E[U(\pi_r)]}{\partial q^2}} \tag{Eq.13}$$

Besides, *Equation 11* shows that $\frac{\partial^2 E[U(\pi_r)]}{\partial q^2} < 0$. Thus, the sign of $\frac{dq_\lambda^*}{d\lambda}$ is opposite to the positivity/negativity of $(p-w+g) - (w-v)F\big(x_1 - y(\theta)\big) - (p-w+g)F\big(x_2 - y(\theta)\big)$. Q.E.D.

Property 1 indicates that the optimal order quantity of loss-averse retailer is closely related to the demand distribution and the unit shortage cost. Without considering shortage cost, i.e. $g = 0$, we have $x_2 - y(\theta) \to +\infty$. Thus, the condition $(w-v)F\big(x_1 - y(\theta)\big) + (p-w)F\big(x_2 - y(\theta)\big) > (p-w)$ is always valid. Under this condition, the retailer's order quantity decreases with the growth of the loss aversion coefficient λ and has nothing to do with the random distribution of the market demand. If shortage cost is considered, any of the three conditions of Property 1 is possible, depending on the distribution of the random market demand. In this case, the relationship between the optimal order quantity of the retailer and the loss aversion coefficient λ is determined by the distribution of the random market demand.

Consider the manufacturer's optimal green emission reduction strategy, the manufacturer's expected profit function can be derived from *Equation 3:*

$$E[\pi_m(\theta)] = (w-c)q + p_t[E - (1-\theta)e] - \frac{1}{2}\alpha\theta^2 \tag{Eq.14}$$

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Since $\frac{d^2 E[\pi_m(\theta)]}{d\theta^2} = -\alpha < 0$, the optimal green emission reduction level of risk-neutral manufacturer can be obtained by finding the first-order derivative of *Equation 14* relative to θ:

$$\theta^* = \frac{p_t e}{\alpha} \tag{Eq.15}$$

It can be seen from *Equation 15* that, under decentralized decision-making, the optimal green emission reduction level of the manufacturer is positively correlated with the unit carbon transaction price in the market and the carbon emission of product, negatively correlated with the green cost coefficient of the product, but not related to the retailer's order quantity.

Optimal strategy in centralized mode

Under centralized decision-making, the overall profit of the supply chain can be expressed as *Equation 16*.

$$\pi_{mr}(q,\theta) = p\min(q,D) + v(q-D)^+ - g(D-q)^+ - cq + p_t\left[E-(1-\theta)e\right] - \frac{1}{2}\alpha\theta^2 = \begin{cases} (p-v)x + (v-c)q + p_t[E-(1-\theta)e] - \frac{1}{2}\alpha\theta^2, & x<q \\ (p-c+g)q - gx + p_t[E-(1-\theta)e] - \frac{1}{2}\alpha\theta^2, & x \geq q \end{cases} \tag{Eq.16}$$

The mathematical expectation of the above equation can be obtained as *Equation 17*.

$$\begin{aligned} E[\pi_{mr}(q,\theta)] = {} & \int_M^{q-y(\theta)} \left\{(p-v)[y(\theta)+\varepsilon] + (v-c)q + p_t[E-(1-\theta)e] - \frac{1}{2}\alpha\theta^2\right\} f(\varepsilon)\, d\varepsilon + \\ & \int_{q-y(\theta)}^{N} \left\{(p-c+g)q - g[y(\theta)+\varepsilon] + p_t[E-(1-\theta)e] - \frac{1}{2}\alpha\theta^2\right\} f(\varepsilon) d\varepsilon = \\ & (p-v+g)\int_M^{q-y(\theta)} [y(\theta)+\varepsilon] f(\varepsilon)\, d\varepsilon - (p-v+g)qF\big(q-y(\theta)\big) + (p-c+g)q - \\ & g[y(\theta)+\mu] + p_t [E-(1-\theta)e] - \frac{1}{2}\alpha\theta^2 \end{aligned} \tag{Eq.17}$$

The partial derivatives of *Equation 17* can be computed as *Equations 18–20*.

$$\frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial q^2} = -(p-v+g) f\big(q-y(\theta)\big) \tag{Eq.18}$$

$$\frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial q \partial \theta} = (p-v+g) B f\big(q-y(\theta)\big) \tag{Eq.19}$$

$$\frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial \theta^2} = -B^2(p-v+g) f\big(q-y(\theta)\big) - \alpha \tag{Eq.20}$$

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Combining *Equations 18–20*, the determinant of the Hessian matrix for the expected profit of the supply chain in the centralized mode can be obtained as *Equation 21*.

$$\begin{vmatrix} \frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial q^2} & \frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial q \partial \theta} \\ \frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial \theta \partial q} & \frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial \theta^2} \end{vmatrix} = \alpha(p - v + g) f\big(q - y(\theta)\big) > 0 \qquad \text{(Eq.21)}$$

whereas $\frac{\partial^2 E[\pi_{mr}(q,\theta)]}{\partial q^2} < 0$, $E[\pi_{mr}(q,\theta)]$ is a concave relative to both q and θ. Hence, there exists a unique optimal combination of solutions (q^0, θ^0), such that the overall profit of the supply chain reaches the maximum. Let $\frac{\partial E[\pi_{mr}(q,\theta)]}{\partial q} = 0$ and $\frac{\partial E[\pi_{mr}(q,\theta)]}{\partial \theta} = 0$. The optimal solutions of the supply chain can be obtained as *Equation 22*.

$$\begin{cases} q^0 = F^{-1}\left(\frac{p-c+g}{p-v+g}\right) + y(\theta) \\ \theta^0 = \frac{(p-c)B + p_t e}{\alpha} \end{cases} \qquad \text{(Eq.22)}$$

Equation 22 shows that $\theta^0 = \frac{(p-c)B+p_t e}{\alpha} > 0$. Since (q^0, θ^0) is the unique optimal combination of solutions to the entire supply chain, we have $E[\pi_{mr}(q^0, \theta^0)] > E[\pi_{mr}(q^0, 0)]$.

Therefore, it can be concluded that the supply chain profit can be improved by increasing the product greenness under centralized decision-making, as the carbon quota is laid down by the government and the environmental awareness is growing among consumers. In other words, green products can bring more profits.

Under decentralized decision-making, the manufacturer and the retailer are actually implementing the wholesale price contract. Comparing *Equation 8*, *Equation 15* and *Equation 22*, it can be seen that the green supply chain considering carbon emissions and loss aversion cannot be coordinated under this contract. This calls for a rational and effective contract that ensures the coordination of the supply chain.

Results and discussion

Coordination contract

The previous analysis shows that the green supply chain considering carbon emissions and loss aversion cannot be coordinated under the wholesale price contract. The main reason lies in the fact, under the decentralized decision-making, the manufacturer needs to bear all the cost of green emission reduction but only receives part of the supply chain profit, while the retailer needs to bear all the inventory cost of the entire supply chain induced by oversupply. As a result, the manufacturer is reluctant to improve product greenness, and the retailer is conservative about the order quantity, aiming to reduce the risk. To improve product quality, reduce oversupply risk and achieve supply chain coordination, this paper modifies the traditional revenue sharing contract into a cost sharing-revenue sharing contract $\{k, \varphi\}$, in which the retailer bears (1- k) ($0 < k < 1$) of the manufacturer's green emission reduction cost and receives

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$\varphi(0 < \varphi < 1)$ of the sales profit. Under this contract, the expected profits of the retailer and the manufacturer can be respectively expressed as *Equations 23* and *24*.

$$\pi_r(q,\theta,k,\varphi)=\varphi\left[pmin(q,D)+v(q-D)^+-g(D-q)^+\right]-wq-\frac{1}{2}\alpha(1-k)\theta^2 \quad \text{(Eq.23)}$$

$$\begin{aligned}&\pi_m(q,\theta,k,\varphi)=(1-\varphi)\left[pmin(q,D)+v(q-D)^+-g(D-q)^+\right]\\&+(w-c)q+p_t\left[E-(1-\theta)e\right]-\frac{1}{2}\alpha k\theta^2\end{aligned} \quad \text{(Eq.24)}$$

According to *Equations 23* and *24*, the contract $\{k, \varphi\}$ only includes transfer payment within the supply chain. The total profit of the two parties is still equal to the result of *Equation 16*.

Similar to the proof of Theorem 1, the following result can be derived from *Equation 23*.

Theorem 2. Under the cost-and-revenue sharing contract, for any $0 \le \theta < 1$, the expected utility of the loss-averse retailer $E\left[U\left(\pi_r(q,\theta,k,\varphi)\right)\right]$ is a concave function relative to q, and $max_{q>0}\, E\left[U\left(\pi_r(q,\theta,k,\varphi)\right)\right]$ has a unique optimal solution q^{λ} that satisfies *Equation 25*.

$$\begin{aligned}&\int_{x_3-y(\theta)}^{q-y(\theta)}(\varphi v-w)f(\varepsilon)d\varepsilon+\int_{q-y(\theta)}^{x_4-y(\theta)}(\varphi p-w+\varphi g)f(\varepsilon)d\varepsilon+\\&\lambda\left[\int_{M}^{x_3-y(\theta)}(\varphi v-w)f(\varepsilon)d\varepsilon+\int_{x_4-y(\theta)}^{N}(\varphi p-w+\varphi g)f(\varepsilon)d\varepsilon\right]=0\end{aligned} \quad \text{(Eq.25)}$$

where $x_3 = \frac{wq-\varphi vq-\frac{1}{2}\alpha(1-k)\theta^2}{\varphi(p-v)}$ and $x_4 = \frac{\varphi(p+g)q-wq-\frac{1}{2}\alpha(1-k)\theta^2}{\varphi g}$.

Finding the expectation of *Equation 24*, the expected profit function of the manufacturer can be obtained as *Equation 26*.

$$\begin{aligned}&E\left[\pi_m(q,\theta,k,\varphi)\right]=(1-\varphi)(p-v+g)\int_{M}^{q-y(\theta)}\left[y(\theta)+\varepsilon\right]f(\varepsilon)d\varepsilon-\\&(1-\varphi)(p-v+g)qF\left(q-y(\theta)\right)+\left[(1-\varphi)(p+g)+w-c\right]q-\\&(1-\varphi)g\left[y(\theta)+\mu\right]+p_t[E-(1-\theta)e]-\frac{1}{2}\alpha k\theta^2\end{aligned} \quad \text{(Eq.26)}$$

The above equation shows that, for any $q > 0$, $max_{0\le\theta<1}\, E[\pi_m(q,\theta,k,\varphi)]$ has a unique optimal solution θ^{λ} that satisfies *Equation 27*.

$$\theta = \frac{B(1-\varphi)(p-v+g)F\left(q-y(\theta)\right)-(1-\varphi)Bg+p_te}{\alpha k} \quad \text{(Eq.27)}$$

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Next, the author analyzed how the cost-and-revenue sharing contract coordinates the green supply chain considering carbon emission and loss aversion. Firstly, the manufacturer, as the leader of the Stacklberg game, can set proper parameter values $\{k, \varphi\}$ according to the known loss aversion level λ of the retailer, forcing the retailer to choose the optimal ordering strategy $q^{\lambda} = q^{0} = F^{-1}\left(\frac{p-c+g}{p-v+g}\right) + y(\theta)$, i.e. $q^{\lambda} = q^{0}$ satisfying *Equation 25*. Then, it can be seen that $\theta = \frac{(1-\varphi)(p-c)B+p_t e}{\alpha k}$ by substituting $q = q^{0}$ into *Equation 27*. Compared with *Equation 22*, it is learned that the value of *k* must equal $\frac{(1-\varphi)(p-c)B+p_t e}{(p-c)B+p_t e}$ under the coordination contract.

Note that the manufacturer's profit must not fall below the profit in decentralized decision-making. Otherwise, it will not actively participate in the cost-and-revenue sharing contract. In other words, the wholesale price per unit of product *w* must satisfy the following set of *Equation 28*.

$$\begin{cases} \frac{\partial E[U(\pi_r(q,\theta,k,\varphi))]}{\partial q}\Big|_{q^{\lambda}=q^{0},\theta^{\lambda}=\theta^{0}} = 0 \\ \frac{\partial E[\pi_m(q,\theta,k,\varphi)]}{\partial \theta}\Big|_{q^{\lambda}=q^{0},\theta^{\lambda}=\theta^{0}} = 0 \\ E[\pi_m(q,\theta,k,\varphi)]\Big|_{q^{\lambda}=q^{0},\theta^{\lambda}=\theta^{0}} = \delta \end{cases} \quad \text{(Eq.28)}$$

where δ is any constant that is no smaller than $E[\pi_m(\theta^*)]$. The overall profit of the supply chain can be allocated elastically between the retailer and the manufacturer by adjusting the value of δ. The allocation depends on the bargaining power of the two parties. Moreover, there should also be an upper limit to the wholesale price. Otherwise, there will be no solution to the contract parameters, making the contract meaningless. In particular, when δ satisfies $0 < \delta - E[\pi_m(\theta^*)] < E[\pi_{mr}(q^{0},\theta^{0})] - E[\pi_r(q^*)]$, the overall profit of the supply chain is optimized, and both the manufacturer and the retailer are expected to receive more profit than the decentralized decision-making. Thus, the two parties can receive Pareto optimal profits under certain conditions, using the proposed cost-revenue sharing contract.

Considering the different decision-making goals between loss aversion and risk neutrality, the above cost-revenue sharing contract fulfills three conditions: maximizing the overall profit of the supply chain; maximizing the expected utility of the loss-averse party (retailer); ensuring that the expected profit of the risk-neutral party (manufacturer) is no less than its retained profit. Through reasonable parameter design, both members of the supply chain will be encouraged to actively participate in this cost-revenue sharing contract.

Numerical examples

The above model was subjected to numerical experiments on the Matlab. Firstly, the loss-averse retailer and the risk-neutral manufacturer were compared in terms of the decision variables and expected profits (utilities) under different decision-making modes, aiming to verify the effectiveness of the proposed coordination contract. After that, the author carried out a sensitivity analysis on the parameters of the decentralized model, e.g. loss aversion coefficient and wholesale price, to see their impacts on the optimal order quantity of the retailer. The market demand was assumed as

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$D(\theta) = 50 + 4\theta + \varepsilon$, with $\varepsilon \sim U[-50,50]$ and $H(\theta) = 0.5 \times 200\theta^2$. The other parameters are listed in *Table 1*.

Table 1. *Parameter settings*

Parameter	p	w	c	g	v	p_t	e	E	λ	k	φ	μ
Value	45	20	15	5	10	5	10	8	1.2	0.37	0.89	841

The above model was adopted to calculate the optimal decision variables and the expected profits (utilities) of the retailer, the manufacturer and the supply chain under three conditions, namely, centralized decision-making, decentralized decision-making and the cost-and-revenue-sharing contract. The calculated results are shown in *Table 2*.

Table 2. *Comparison of optimal decision variables and expected profits (utilities) under different decision-making modes*

Decision-making mode	q	θ	$\pi_r(q)$	$E[U(\pi_r)]$	π_m	π_{mr}
Centralized decision-making	91	0.85	—	—	—	1584
Decentralized decision-making	74	0.25	686	572	366	1052
Coordination contract	91	0.85	743	604	841	1584

As shown in *Table 2*, the retailer's order quantity was 18.7% smaller under decentralized decision-making than under centralized decision-making, owing to the double marginalization effect. After introducing the cost-and-revenue sharing contract, the expected profit of the entire supply chain reached that under the centralized decision-making, the manufacturer saw its green emission reduction level increasing from 0.25 (decentralized decision-making) to 0.85 (centralized decision-making) and expected profit growing by nearly 1.3 times, and the retailer witnessed a 5.6% increase in expected utility and an 8.3% growth in expected profit from the levels under centralized decision-making. Therefore, the proposed coordination contract both improves the expected profit of the entire supply chain and achieves the Pareto optimization of the profits (utilities) of the manufacturer and the retailer. Both parties of the supply chain will be incentivized to conclude such a contract.

Next, the loss aversion behavior and purchase price were subjected to sensitivity analysis, aiming to disclose their impacts on the retailer's optimal order quantity. Relevant numerical experiments were carried out with the loss aversion coefficient λ and the wholesale price *w* as variables. The experimental results are presented in *Figures 1* and *2*.

As shown in *Figure 1,* the retailer's optimal order quantity decreased with the increase of the loss aversion coefficient. It can be seen from Property 1 that the third condition is always satisfied under the uniform distribution of the random market demand. In this case, the retailer's order quantity is negatively correlated with the loss aversion coefficient, and the overage cost is greater than the shortage cost. To avoid losses, the loss-averse retailer will cut down the order quantity.

As shown in *Figure 2,* the retailer's optimal order quantity dropped almost linearly with the rising purchase price. This trend can be attributed to the following reasons. When the retail price is exogenous, the retailer will receive less profit per unit of

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product with the growth in the unit product wholesale price; the rising purchase cost will indirectly push up the overage capacity cost. To minimize its loss, the loss-averse retailer cannot but reduce the order quantity.

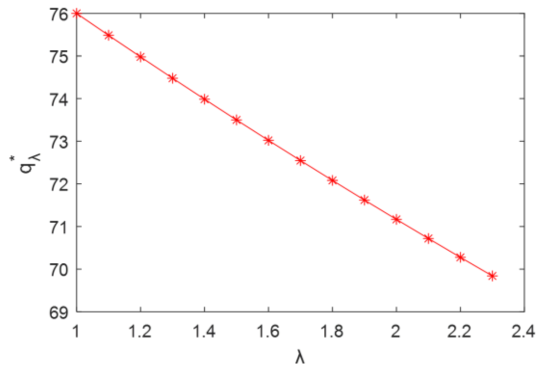

Figure 1. *Effect of loss aversion level on optimal order quantity*

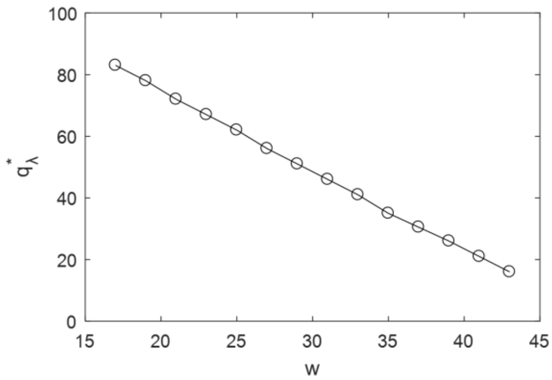

Figure 2. *Effect of wholesale price on optimal order quantity*

Conclusions

This paper explores the coordination of a two-echelon green supply chain, consisting of a loss-averse retailer and a risk-neutral manufacturer, in the context of carbon emissions. Considering the loss aversion of the retailer, the objective function was set up by the prospect theory. On this basis, a Stackelberg game model was constructed under decentralized decision-making, and the manufacturer's optimal green emission reduction decision and the retailer's optimal order quantity were solved by inverse induction. The results were compared with those under the optimal decision of the supply chain under centralized decision-making. Then, a cost-and-revenue sharing coordination contract was designed to ensure the Pareto optimization of the profits (utilities) of both parties under the loss-averse decision goal.

The above conclusions were drawn based on the revenue sharing contract. The future research will extend the research problem to discuss other coordination mechanisms (e.g. flexible quantity contract, buy-back contract and price discount contract). To make our model more realistic, the loss aversion of the manufacturer will be added, and multiple manufacturers and retailers will be considered.

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