Research on Low-Carbon Supply Chain Decision-Making Considering Low-Carbon Reputation Under Different Power Structures

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Abstract. This study considers a two-echelon low-carbon supply chain consisting of a manufacturer and a retailer under different power structures. In response to consumers' preferences for low-carbon products, the manufacturer invests in emissions reduction, while the retailer engages in low-carbon marketing to build a low-carbon reputation in the supply chain. Three game models are developed to examine the effects of cost coefficients on investment levels, marketing levels, and profits under different power structures in consideration of the manufacturer and the retailer's bargaining power. Our findings reveal that the VN power structure is most effective in encouraging both the manufacturer and the retailer to invest in emissions reduction and low-carbon marketing when the cost coefficients are high. When one cost coefficient is high and the other one is low, the emissions reduction investments level and low-carbon marketing level are the highest under the MS or RS power structures. Additionally, when either the emissions reduction investment level or low-carbon marketing level is relatively high, supply chain members earn maximum profits under their dominant power structure. However, when both levels are relatively low, profits are lowest under the VN power structure. These findings offer important management guidance for different supply chain enterprises seeking to build a low-carbon reputation in different circumstances.

Keywords: low-carbon reputation · emissions reduction · low-carbon marketing · different power structures · game theory

1 Introduction

For a long time, economic progress has been accompanied by significant environmental costs and overuse of non-renewable resources, resulting in large quantities of greenhouse gas emissions that contribute to global warming. In this context, fostering sustainable economic development that minimizes resource utilization and reduces environmental harm has emerged as a pressing socioeconomic imperative. China has proactively promoted low-carbon economic transformation, taking 'carbon emissions peak' and 'carbon neutrality' as key developmental objectives, and has introduced and refined corresponding policies to reduce emissions [1, 2]. This effort has had a profound impact on supply chain enterprises that have incorporated the low-carbon development goal into their production processes.

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Currently, a growing number of supply chain enterprises have prioritized emissions reduction by adopting innovative technologies and employing energy-saving process improvements to manufacture low-carbon goods with minimal carbon emissions and energy consumption. For instance, Midea Group has pursued a low-carbon development strategy centered on green design, green production, and green logistics; Micoe Group has focused on developing hot water heaters that integrate solar and air energy. Under the influence of relevant policies and rising awareness of the value of low-carbon lifestyles, consumers increasingly prefer low-carbon energy-saving products [3]. Hence, retailers promote their low-carbon products via low-carbon marketing to help consumers better understand the low-carbon information of such products. Whether through offline physical appliance retailers such as Gome and Suning or online e-commerce retailers, these retailers vigorously promote the low-carbon attributes of their products, which not only to recommend low-carbon products to consumers but also to provide guarantees for manufacturers' low-carbon production. Manufacturers' emissions reduction investment and retailers' low-carbon marketing are both instrumental in building a low-carbon reputation, which in turn cultivates consumers' trust and propensity to purchase their products.

Different types of supply chain leaders consider different factors when making low-carbon reputation decisions: retailers may be concerned about the promoting the effect of emissions reduction efforts by manufacturers on low-carbon products and put more emphasis on the balance between low-carbon marketing costs and profits. Manufacturers, like retailers, ensure a balance between investments and revenues while paying attention to retailers' low-carbon marketing effort. Therefore, the power structure of the supply chain has become a key factor affecting low-carbon reputation decisions. The article focuses on the following key issues in low-carbon supply chain management: 1) Which supply chain power structure is more conducive to promoting the low-carbon reputation? 2) What is the impact of cost coefficients on supply low-carbon reputation decisions? 3) What is the profit situation of manufacturers and retailers under different power structures?

The remainder of this paper is organized as follows. In Sect. 2, the related literature is reviewed. Based on the models built in Sect. 3, Sect. 4 compares results under different power structures and corresponding numerical examples are showed in Sect. 5. Finally, Sect. 6 concludes the paper.

2 Literature Review

"Low carbon" is a concept proposed after "green", which has been widely recognized since its inception. Many scholars combine "low-carbon" with "supply chain" and propose the concept of low-carbon supply chain. Zhang and Qu define low-carbon supply as a supply in which enterprises attach great importance to low-carbon environmental protection and they comprehensively consider the impacts of resource integration on the environment in the complete operational process of raw material procurement, production, manufacturing, distribution, marketing, delivery and recycling [4, 5]. Based on the concept, many related studies have been conducted.

Yu et al. derive equilibrium emissions reduction and pricing strategies in cost and revenue sharing contracts through Stackelberg differential games and the results indicate that consumers' environmental awareness and tax rates have a significant impact on emissions reduction [6]. Based on the government's adoption of carbon total allocation and quota trading policies, as well as consumer preference for low-carbon products, Shao et al. apply Stackelberg game theory to establish an emissions reduction model with a leading manufacturer and a following retailer to analyze the emissions reduction behavior and the effect of supply chain enterprises under various modes [7]. Gao proposes the optimal incentive strategy for low-carbon supply chain, where supply chain members will achieve higher carbon emissions reduction driven by profits [8]. Miao analyzes the low-carbon promotion problem of retailers and finds that the effective range under the maximum low-carbon advertising level of retailers is negatively correlated with the cost coefficient of low-carbon advertising and the maximum low-carbon advertising level and it is positively correlated with the sensitivity of consumers to low-carbon advertising and the marginal profit of manufacturers' low-carbon products [9].

In recent years, climate issues have become a global challenge. Many governments and environmental organizations have been formulating policies to incentive manufacturers to produce low-carbon products. In order to cultivate consumers' environmental awareness, the government also provides subsidies for consumers who choose low-carbon products [10]. Low-carbon reputation reflects the importance and commitment of enterprises to environmental responsibility and sustainable development, and can bring positive impacts such as brand effect and market competitiveness to enterprises. Low-carbon reputation can serve as an important indicator of low-carbon competitiveness in future international trade [11]. Consumers' low-carbon awareness and the low-carbon reputation may occasionally change alternately due to the impacts of market environment, thereby affecting the sales of low-carbon products [10]. Research by Tait et al. shows that consumers in countries with more developed economies have a stronger desire for low-carbon products. With the increasing awareness of low-carbon among consumers, the operation of enterprises will inevitably be affected [12]. Wang et al. construct three differential game models for manufacturers and retailers in the supply chain to analyze the long-term impacts of different types of carbon trading policies on the operation of enterprises in the supply chain, considering that low-carbon reputation can affect consumers' demand [13]. Scholars such as Zhu have incorporated dual subsidy policies and the dynamic changes in low-carbon reputation of products into the low-carbon supply chain, and finds that the level of low-carbon reputation is optimal under the coordination of manufacturers and retailers [14].

3 Model Description

Consider a two-echelon low-carbon supply chain consisting of a manufacturer and a retailer, where the manufacturer manufactures low-carbon products through emissions reduction investment, and the retailer are responsible for low-carbon marketing to promote low-carbon products. In order to establish a supply chain with low-carbon reputation, the manufacturer needs to spend on emissions reduction investment cost, while the retailer needs to spend on low-carbon marketing cost. The manufacturer wholesales products to the retailer at a unit wholesale price w, and the retailer then sells them to consumers at a unit sales price p. In order to solve decision-making problems, game models are used to analyze investment choice and marketing choice under different power structures: Nash Game between the manufacturer and the retailer (VN), manufacturer Stackelberg game (MS), and retailer Stackelberg game (RS).

The following assumptions are made when formulating the models under different power structure.

1. Consumers are assumed to have low-carbon and price preference, i.e., they prefer to buy low-carbon products with low prices when they understand the products through retailers' marketing.
2. The unit emissions reduction cost and the the unit low-carbon marketing cost are assumed to be quadratic functions of the emissions reduction investment level and the low-carbon marketing level, respectively.
3. Assuming that both manufacturer and retailer are risk-neutral and altruism-neutral and all the parameters associated with market demand and cost are known to them.
4. In order to make all supply chain members profitable, $3\eta\lambda - \lambda c^2 - \eta\tau^2 > 0$, $4\eta\lambda - \lambda c^2 - 2\eta\tau^2 > 0$ and $4\eta\lambda - \eta\tau^2 - 2\lambda c^2 > 0$ are supposed to be satisfied.

Based on the above assumptions, the demand is negatively linearly correlated to the retail sales price and positively linearly correlated to the emissions reduction investment level and the low-carbon marketing level, as follows:

$$D = a - p + ce + \tau m \tag{1}$$

where a is the maximum potential market demand, c and τ represents the sensitivity coefficients of the emissions reduction investment level and the low-carbon marketing level, respectively. The parameter e and m represents the emissions reduction investment level and the low-carbon marketing level, respectively. The quadratic function, $\eta e^2/2$, is used to model the unit emissions reduction investment cost where η reflects investment cost coefficient. The quadratic function, $\lambda m^2/2$, is used to model the unit low-carbon marketing cost where λ reflects marketing cost coefficient.

The profits of manufacturers, retailers, and two-echelon low-carbon supply chain systems are respectively as follows.

$$\Pi_m = w(a - p + ce + \tau m) - \frac{1}{2}\eta e^2 \tag{2}$$

$$\Pi_r = (p - w)(a - p + ce + \tau m) - \frac{1}{2}\lambda m^2 \tag{3}$$

$$\Pi_{sc} = p(a - p + ce + \tau m) - \frac{1}{2}\left(\eta e^2 + \lambda m^2\right) \tag{4}$$

In a two-echelon low-carbon supply chain under VN power structure, the manufacturer and the retailer make decisions simultaneously: the manufacturer determines the wholesale price of the products w and the emissions reduction investment level e while the retailer determines the sales price p of the products and the low-carbon marketing level m. The model is:

$$\begin{cases} max\Pi_m^{VN}(w, e) = w(a - p + ce + \tau m) - \frac{1}{2}\eta e^2 \\ max\Pi_r^{VN}(k, m) = (p - w)(a - p + ce + \tau m) - \frac{1}{2}\lambda m^2 \end{cases} \tag{5}$$

Table 1. The optimal value of decision-making under different power structures

Parameter	VN	MS	RS
Emissions Reduction Investment Level e^*	$\frac{ac\lambda}{3\eta\lambda-\lambda c^2-\eta\tau^2}$	$\frac{ac\lambda}{4\eta\lambda-2\eta\tau^2-\lambda c^2}$	$\frac{ac\lambda}{4\eta\lambda-2\lambda c^2-\eta\tau^2}$
Low-carbon Marketing Level m^*	$\frac{a\eta\tau}{3\eta\lambda-\lambda c^2-\eta\tau^2}$	$\frac{a\eta\tau}{4\eta\lambda-2\eta\tau^2-\lambda c^2}$	$\frac{a\eta\tau}{4\eta\lambda-2\lambda c^2-\eta\tau^2}$
Retailer's profits Π_m^*	$\frac{a^2\lambda^2\eta(2\eta-c^2)}{2(3\eta\lambda-\lambda c^2-\eta\tau^2)^2}$	$\frac{a^2\eta^2\lambda(2\lambda-\tau^2)}{2(4\eta\lambda-2\eta\tau^2-\lambda c^2)^2}$	$\frac{a^2\eta\lambda}{2(4\eta\lambda-2\lambda c^2-\eta\tau^2)}$
Manufacturer's profits Π_r^*	$\frac{a^2\eta^2\lambda(2\lambda-\tau^2)}{2(3\eta\lambda-\lambda c^2-\eta\tau^2)^2}$	$\frac{a^2\eta\lambda}{2(4\eta\lambda-2\eta\tau^2-\lambda c^2)}$	$\frac{a^2\lambda^2\eta(2\eta-c^2)}{2(4\eta\lambda-2\lambda c^2-\eta\tau^2)^2}$
Supply Chain System's profits Π_{sc}^*	$\frac{a^2\lambda\eta(4\eta\lambda-\lambda c^2-\eta\tau^2)}{2(3\eta\lambda-\lambda c^2-\eta\tau^2)^2}$	$\frac{a^2\eta\lambda(6\eta\lambda-\lambda c^2-3\eta\tau^2)}{2(4\eta\lambda-2\eta\tau^2-\lambda c^2)^2}$	$\frac{a^2\eta\lambda(6\eta\lambda-3\lambda c^2-\eta\tau^2)}{2(4\eta\lambda-2\eta\tau^2-\lambda c^2)^2}$

In order to facilitate the solution of the equilibrium, let the profit per unit product k be the equal of p-w, then substitute it into the Eq. (5) and obtain the model as follows:

$$\begin{cases} \max \Pi_m^{VN}(w, e) = w(a - w - k + ce + \tau m) - \frac{1}{2}\eta e^2 \\ \max \Pi_r^{VN}(k, m) = k(a - w - k + ce + \tau m) - \frac{1}{2}\lambda m^2 \end{cases} \tag{6}$$

According to the Eq. (6), the Hessian matrix of Π_m^{VN} and Π_r^{VN} is:

$$H = \begin{bmatrix} -2 & c & -1 & \tau \\ c & -\eta & 0 & 0 \\ -1 & c & -2 & \tau \\ 0 & 0 & \tau & -\lambda \end{bmatrix}$$

When $2\eta - c^2 > 0$ and $3\eta\lambda - \lambda c^2 - \eta\tau^2 > 0$, the Hessian matrix is a negative definite matrix, so Π_m^{VN} and Π_r^{VN} has a unique optimal solution. By solving $\frac{\partial \Pi_m^{VN}}{\partial w} = 0$, $\frac{\partial \Pi_m^{VN}}{\partial e} = 0$, $\frac{\partial \Pi_r^{VN}}{\partial k} = 0$ and $\frac{\partial \Pi_m^{VN}}{\partial m} = 0$, we can obtain the optimal wholesale price of products, the optimal emissions reduction investment level, the optimal sales price of products, and the optimal low-carbon marketing level.

Finally, by substituting the obtained optimal solutions into the profit function, the optimal profit of the manufacturer and the retailer can be achieved.

Similarly, backward induction is used to solve the models under MS and RS power structure, and to obtain the optimal equilibrium decisions and corresponding profits under different power structures. Finally, the equilibrium results are obtained as shown in the Table 1.

4 Results and Discussions

In this section, based on the equilibrium results obtained in Sect. 4, they are compared under three different power structures to find out the preferred investment choice, marketing choice and the power structure. These results can provide insights for supply chain members in formulating emissions reduction investment strategies and low-carbon marketing strategies in low-carbon supply chain.

Theorem 1

(1) If $\lambda > \tau^2$ and $\eta > \max\left\{c^2, \frac{\lambda c^2}{4\lambda-2\tau^2}\right\}$, then $e^{VN*} > e^{MS*} > 0$ and $e^{VN*} > e^{RS*} > 0$;
(2) If $\lambda > \tau^2$ and $\max\left\{\frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\} < \eta < c^2$, then $e^{RS*} > e^{VN*} > e^{MS*} > 0$;
(3) If $\frac{1}{2}\tau^2 < \lambda < \tau^2$ and $\eta > \max\left\{c^2, \frac{\lambda c^2}{4\lambda-2\tau^2}\right\}$, then $e^{MS*} > e^{VN*} > e^{RS*} > 0$;
(4) If $\frac{1}{2}\tau^2 < \lambda < \tau^2$ and $\max\left\{\frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\} < \eta < c^2$,then $e^{RS*} > e^{VN*} > 0$ and $e^{MS*} > e^{VN*} > 0$.

Proof
It is known that $\eta > \max\left\{\frac{c^2}{2}, \frac{\lambda c^2}{3\lambda-\tau^2}, \frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\} = \max\left\{\frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\}$ because $3\eta\lambda - \lambda c^2 - \eta\tau^2 > 0$, $4\eta\lambda - \lambda c^2 - 2\eta\tau^2 > 0$ and $4\eta\lambda - \eta\tau^2 - 2\lambda c^2 > 0$ are supposed to be satisfied.

Compare the optimal investment level of emission reduction under MS and VN power structure,

$$e^{MS*} - e^{VN*} = \frac{ac\lambda}{4\eta\lambda - 2\eta\tau^2 - \lambda c^2} - \frac{ac\lambda}{3\eta\lambda - \lambda c^2 - \eta\tau^2}$$
$$= ac\eta\lambda\left[\frac{\tau^2 - \lambda}{\left(4\eta\lambda - 2\eta\tau^2 - \lambda c^2\right)\left(3\eta\lambda - \lambda c^2 - \eta\tau^2\right)}\right]$$

so when $\lambda > \tau^2$, $0 < e^{MS*} < e^{VN*}$; when $\frac{1}{2}\tau^2 < \lambda < \tau^2$, $e^{MS*} > e^{VN*} > 0$.

Compare the optimal investment level of emission reduction under RS and VN power structure,

$$e^{RS*} - e^{VN*} = \frac{ac\lambda}{4\eta\lambda - 2\lambda c^2 - \eta\tau^2} - \frac{ac\lambda}{3\eta\lambda - \lambda c^2 - \eta\tau^2} = ac\lambda^2\left[\frac{c^2 - \eta}{\left(4\eta\lambda - 2\lambda c^2 - \eta\tau^2\right)\left(3\eta\lambda - \lambda c^2 - \eta\tau^2\right)}\right]$$

so when $\eta > \max\left\{c^2, \frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\} = \max\left\{c^2, \frac{\lambda c^2}{4\lambda-2\tau^2}\right\}$,$0 < e^{RS*} < e^{VN*}$; when $\max\left\{\frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\} < \eta < c^2$, $e^{RS*} > e^{VN*} > 0$.

Theorem 1 compared the impact of different emissions reduction investment cost coefficients and low-carbon marketing cost coefficients on the manufacturer's emissions reduction investment level under different power structures. Based on Theorem 1, when the cost coefficients are both high, the manufacturer makes the highest emissions reduction investment under the VN power structure. When the emissions reduction investment cost coefficient is relatively high, and the low-carbon marketing cost coefficient is low, the manufacturer makes the highest emissions reduction investment under the MS power structure. On the contrary, when the cost coefficient of emissions reduction investment is relatively low and the cost coefficient of low-carbon marketing is high, the manufacturer makes the highest emissions reduction investment under the RS power structure.

This is because when the cost of emissions reduction investment is high, the manufacturer increases the wholesale prices through bargaining with the retailer, in order to make up for the profit losses incurred through high investment costs. Under the MS channel power structure, the manufacturer gains dominance over the supply chain while the retailer are situated in a more passive position. Consequently, the manufacturer have stronger bargaining power, and the retailer are more willing to accept higher wholesale prices if his own low-carbon marketing costs are low.

When the cost coefficients are both high, one party's bargaining inevitably results in a loss of profit for the other. Therefore, to avoid bargaining, the manufacturer tends to choose the VN power structure for maximum emissions reduction investment. However, if cost coefficients are both low, appropriate bargaining can help increase wholesale and sales of products, in turn enhancing the profits of members of the supply chain. For this reason, under the VN power structure, the manufacturer tends to avoid heavy investment in emissions reduction.

Theorem 2

(1) If $\eta > c^2$ and $\lambda > \max\left\{\tau^2, \frac{\eta\tau^2}{4\eta-2c^2}\right\}$, then $m^{VN*} > m^{MS*} > 0$ and $m^{VN*} > m^{RS*} > 0$;
(2) If $\eta > c^2$ and $\max\left\{\frac{2\eta\tau^2}{4\eta-c^2}, \frac{\eta\tau^2}{4\eta-2c^2}\right\} < \lambda < \tau^2$, then $m^{MS*} > m^{VN*} > m^{RS*} > 0$;
(3) If $\frac{1}{2}c^2 < \eta < c^2$ and $\lambda > \max\left\{\tau^2, \frac{\eta\tau^2}{4\eta-2c^2}\right\}$, then $m^{RS*} > m^{VN*} > m^{MS*} > 0$;
(4) If $\frac{1}{2}c^2 < \eta < c^2$ and $\max\left\{\frac{2\eta\tau^2}{4\eta-c^2}, \frac{\eta\tau^2}{4\eta-2c^2}\right\} < \lambda < \tau^2$, then $m^{RS*} > m^{VN*} > 0$ and $m^{MS*} > m^{VN*} > 0$.

Theorem 2 compared the impact of different emissions reduction investment cost coefficients and low-carbon marketing cost coefficients on the retailer's low-carbon marketing under different power structures. Based on Theorem 2, when the cost coefficient are both high, the retailer conducts the most low-carbon marketing under the VN power structure. When the emissions reduction investment cost coefficients is relatively low, and the low-carbon marketing cost coefficient is high, the retailer conducts the most low-carbon marketing under the RS power structure. On the contrary, the retailer conducts the most low-carbon marketing under the MS power structure.

Theorem 3

(1) If $\eta > \max\left\{c^2, \frac{\lambda c^2}{4\lambda-2\tau^2}\right\}$, then $\Pi_m^{MS*} > \Pi_m^{VN*} > \Pi_m^{RS*} > 0$;
(2) If $\max\left\{\frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\} < \eta < c^2$, then $\Pi_m^{MS*} > \Pi_m^{VN*} > 0$ 和 $\Pi_m^{RS*} > \Pi_m^{VN*} > 0$;
(3) If $\max\left\{\frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}, A\right\} < \eta < B$, then $\Pi_m^{RS*} > \Pi_m^{MS*} > \Pi_m^{VN*} > 0$;
(4) If $\max\left\{\frac{\lambda c^2}{4\lambda-2\tau^2}, \frac{2\lambda c^2}{4\lambda-\tau^2}\right\} < \eta < A$ or $B < \eta < c^2$, then $\Pi_m^{MS*} > \Pi_m^{RS*} > \Pi_m^{VN*} > 0$.

Among them, $A = \frac{\lambda c^2\left(5\lambda - \tau^2 - \sqrt{\lambda^2 + 2\lambda\tau^2 - 2\tau^4}\right)}{8\lambda^2 - 4\lambda\tau^2 + \tau^4}$ and $B = \frac{\lambda c^2\left(5\lambda - \tau^2 + \sqrt{\lambda^2 + 2\lambda\tau^2 - 2\tau^4}\right)}{8\lambda^2 - 4\lambda\tau^2 + \tau^4}$.

Proof

First, compare the manufacturer's profits under MS and VN power structure. For all η, there exists

$$\Pi_m^{MS*} - \Pi_m^{VN*} = \frac{a^2\eta^3\lambda\left(\lambda - \tau^2\right)^2}{2\left(4\eta\lambda - 2\eta\tau^2 - \lambda c^2\right)\left(\lambda c^2 + \eta\tau^2 - 3\eta\lambda\right)^2} > 0$$

Then, compare the manufacturer's profits under RS and VN power structure.

$$\Pi_m^{VN*} - \Pi_m^{RS*} = \frac{a^2\eta\lambda^3\left(2\eta - c^2\right)\left(c^2 - \eta\right)\left(3\lambda c^2 + 2\eta\tau^2 - 7\eta\lambda\right)}{2\left(4\eta\lambda - 2\eta\tau^2 - \lambda c^2\right)^2\left(\lambda c^2 + \eta\tau^2 - 3\eta\lambda\right)^2}$$

Suppose that $\eta_1 = c^2$, $\eta_2 = \frac{3\lambda c^2}{7\lambda - 2\tau^2}$; and $\eta_2 < \frac{2\lambda c^2}{4\lambda - \tau^2}$, so $\eta_2 < \max\left\{\frac{\lambda c^2}{4\lambda - 2\tau^2}, \frac{2\lambda c^2}{4\lambda - \tau^2}\right\}$. When $\eta > \eta_1$ or $\eta < \eta_2$, $\Pi_m^{VN*} - \Pi_m^{RS*} > 0$. $\eta > \max\left\{\frac{\lambda c^2}{4\lambda - 2\tau^2}, \frac{2\lambda c^2}{4\lambda - \tau^2}\right\}$ are supposed to be satisfied, so $\eta < \eta_2$ is unable to achieve, thus only when $\eta > \max\left\{\eta_1, \frac{\lambda c^2}{4\lambda - 2\tau^2}\right\}$, there exists $\Pi_m^{VN*} > \Pi_m^{RS*} > 0$; similarly, when $\eta_2 < \eta < \eta_1$, considering $\eta > \max\left\{\frac{\lambda c^2}{4\lambda - 2\tau^2}, \frac{2\lambda c^2}{4\lambda - \tau^2}\right\}$, so when $\max\left\{\frac{\lambda c^2}{4\lambda - 2\tau^2}, \frac{2\lambda c^2}{4\lambda - \tau^2}\right\} < \eta < \eta_1$, there exists $\Pi_m^{VN*} - \Pi_m^{RS*} < 0$.

Finally, compare the manufacturer's profits under RS and MS power structure.

$$\Pi_m^{MS*} - \Pi_m^{RS*} = \frac{a^2\eta\lambda\left[\left(\tau^4 + 8\lambda^2 - 4\lambda\tau^2\right)\eta^2 + \left(2\lambda c^2\tau^2 - 10\lambda^2c^2\right)\eta + 3\lambda^2c^4\right]}{2\left(4\eta\lambda - 2\eta\tau^2 - \lambda c^2\right)\left(2\lambda c^2 + \eta\tau^2 - 4\eta\lambda\right)^2}$$

Suppose that $F(\eta) = \left(\tau^4 + 8\lambda^2 - 4\lambda\tau^2\right)\eta^2 + \left(2\lambda c^2\tau^2 - 10\lambda^2c^2\right)\eta + 3\lambda^2c^4$. Because of $\tau^4 + 8\lambda^2 - 4\lambda\tau^2 > 0$ and the discriminant of the root of $F(\eta) = 0$, $\Delta = 4\lambda^2c^4\left(\lambda^2 + 2\lambda\tau^2 - 2\tau^4\right) > 0$, there are two different real roots:

$$\eta_3 = \frac{\lambda c^2\left(5\lambda - \tau^2 + \sqrt{\lambda^2 + 2\lambda\tau^2 - 2\tau^4}\right)}{8\lambda^2 - 4\lambda\tau^2 + \tau^4} \qquad \eta_4 = \frac{\lambda c^2\left(5\lambda - \tau^2 - \sqrt{\lambda^2 + 2\lambda\tau^2 - 2\tau^4}\right)}{8\lambda^2 - 4\lambda\tau^2 + \tau^4}$$

So when $\eta_4 < \eta < \eta_3$, $F(\eta) < 0$, there exists $\Pi_m^{MS*} - \Pi_m^{RS*} < 0$. Considering $\eta > \max\left\{\frac{\lambda c^2}{4\lambda - 2\tau^2}, \frac{2\lambda c^2}{4\lambda - \tau^2}\right\}$, when $\max\left\{\frac{\lambda c^2}{4\lambda - 2\tau^2}, \frac{2\lambda c^2}{4\lambda - \tau^2}, \eta_4\right\}\eta < \eta_3$, there exists $0 < \Pi_m^{MS*} < \Pi_m^{RS*}$; When $\eta > \eta_3$ or $\max\left\{\frac{\lambda c^2}{4\lambda - 2\tau^2}, \frac{2\lambda c^2}{4\lambda - \tau^2}\right\} < \eta < \eta_4$, $F(\eta) > 0$, there exists $\Pi_m^{MS*} > \Pi_m^{RS*} > 0$.

Theorem 3 compares the impact of different emissions reduction investment cost coefficients on the manufacturer's profits under various power structures. According to Theorem 3, when the emissions reduction investment cost coefficient is relatively high, the MS power structure generates the greatest amount of profits for the manufacturer, while the RS power structure yields the smallest amount of profits. When the emission reduction investment cost coefficient is relatively low, the VN power structure generates the least amount of profits for manufacturers.

This is because high emissions reduction investment cost coefficients tend to suppress the initiative of the manufacturer to invest in emissions reduction. In comparison, the more advantageous the power structure is for the manufacturer, the greater bargaining power he can wield to achieve greater profits. Clearly, under the MS power structure, the manufacturer has the strongest bargaining power, allowing him to set wholesale prices relatively high to ensure his own returns. By comparison, under the RS power structure, the manufacturer is challenged by a lack of bargaining power; if he invests heavily in emissions reduction, the profits will inevitably be much lower than those under the MS power structure.

Theorem 4

(1) If $\lambda > \max\left\{\tau^2, \frac{\eta\tau^2}{4\eta-2c^2}\right\}$, then $\Pi_r^{RS*} > \Pi_r^{VN*} > \Pi_r^{MS*} > 0$;
(2) If $\max\left\{\frac{2\eta\tau^2}{4\eta-c^2}, \frac{\eta\tau^2}{4\eta-2c^2}\right\} < \eta < \tau^2$, then $\Pi_r^{MS*} > \Pi_r^{VN*} > 0$ and $\Pi_r^{RS*} > \Pi_r^{VN*} > 0$;
(3) If $\max\left\{\frac{2\eta\tau^2}{4\eta-c^2}, \frac{\eta\tau^2}{4\eta-2c^2}\right\} < \lambda < C$ or $D < \lambda < \tau^2$, then $\Pi_m^{RS*} > \Pi_m^{MS*} > \Pi_m^{VN*} > 0$;
(4) If $\max\left\{\frac{2\eta\tau^2}{4\eta-c^2}, \frac{\eta\tau^2}{4\eta-2c^2}, C\right\} < \lambda < \min\left\{\tau^2, D\right\}$, then $\Pi_m^{MS*} > \Pi_m^{RS*} > \Pi_m^{VN*} > 0$'.

Among them, $C = \frac{\eta\tau^2\left(5\eta-c^2-\sqrt{\eta^2+2\eta c^2-2c^4}\right)}{8\eta^2-4\eta c^2+c^4}$ and $D = \frac{\eta\tau^2\left(5\eta-c^2+\sqrt{\eta^2+2\eta c^2-2c^4}\right)}{8\eta^2-4\eta c^2+c^4}$.

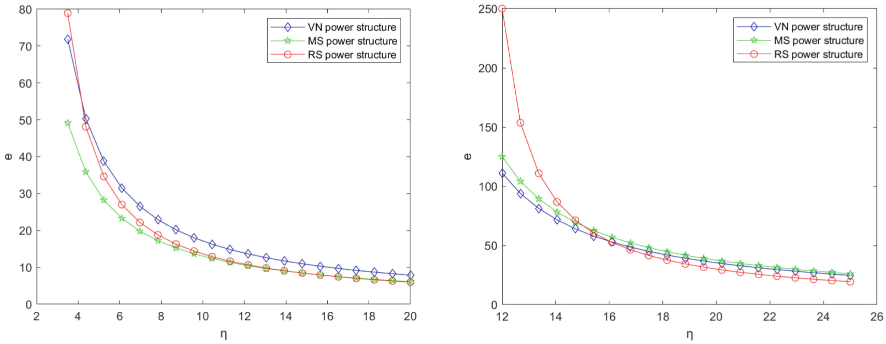
Theorem 4 compares the impact of different low-carbon marketing cost coefficients on the retailer's profits under different power structures. According to Theorem 4, when the low-carbon marketing cost coefficient is relatively high, the RS power structure generates the greatest amount of profits for the retailer, while the MS power structure generates the smallest amount of profits. When the low-carbon marketing cost coefficient is relatively low, the VN power structure generates the least amount of profits for the retailer.

5 Numerical Study

In order to further intuitively compare and analyze the impact of cost coefficients on the low-carbon reputation decision-making under different power structures, the paper conducts simulation analysis through numerical experiments. To meet the assumed conditions, two groups of parameters are listed as follows: $a = 200$, $\eta = 15$, $\lambda = 15$, $c_1 = 2$, $\tau_1 = 2$; $a = 200$, $\eta = 15$, $\lambda = 15$, $c_2 = 4$, $\tau_2 = 4$.

5.1 Numerical Study of Emissions Reduction Investment Decision

From Fig. 1(a), under the premise that λ is greater than τ^2, it can be seen that when η is relatively low, the manufacturer has the highest level of emissions reduction investment under RS power structure, followed by VN power structure, and finally MS power



a. $\lambda > \tau^2$ b. $\frac{1}{2}\tau^2 < \lambda < \tau^2$

Fig. 1. The effect of η on e

structure. Once η exceeds a threshold $\eta_1 \approx 4.160$, the manufacturer makes the most emissions reduction investments in the VN power structure. More specifically, when η is at [4.16,15.02], there exists $e^{VN*} > e^{RS*} > e^{MS*} > 0$, and when η is at [15.02,20], there exists $e^{VN*} > e^{MS*} > e^{RS*} > 0$.

From Fig. 1(b), the figure shows that when η is relatively low, the manufacturer has the lowest level of emissions reduction investment under the VN power structure. More specifically, when η is at [12,15.04], there exists $e^{RS*} > e^{MS*} > e^{VN*} > 0$, and when η is at [15.04,16.02], there exists $e^{MS*} > e^{RS*} > e^{VN*} > 0$. Once η exceeds a threshold $\eta_2 \approx 16.02$, the manufacturer makes the most emissions reduction investments under MS power structure, followed by VN power structure and RS power structure.

5.2 Numerical Study of Low-Carbon Marketing Decision

Figures 2 shows the impact of λ on m in two cases. By numerical study, the content of Theorem 2 (1) and Theorem 2 (4) can be extended to determine the power structure that enable the retailer to conduct maximum low-carbon marketing within a specific range.

5.3 Numerical Study of Equilibrium Profit

Substitute two groups of parameters into the optimal decision and profit functions to obtain the optimal decision and profit situation under three power structures, as shown in Tables 2 and 3.

From Table 2, it can be seen that when the sensitivity coefficient is relatively low, the manufacturer and the retailer construct the optimal low-carbon reputation under the VN power structure, while the profit of the supply chain is also optimal. In addition, they obtain optimal profits under their dominant power structure, while the other party's profits are far below their own, resulting in overall supply chain profits being lower than those under the VN power structure. From Table 3, it shows that when the sensitivity

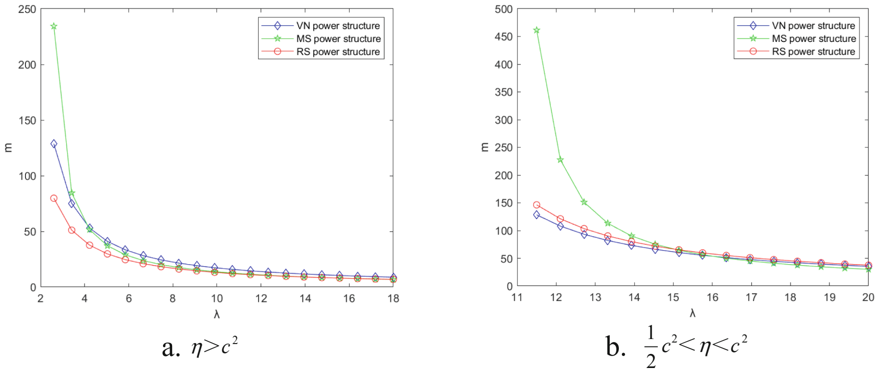


Fig. 2. The effect of λ on m

Table 2. Results when $\lambda > \tau^2$ and $\eta > c^2$

Parameter	VN	MS	RS
e^*	10.81	8.3	8.3
m^*	10.81	8.3	8.3
Π_m^*	5679.59	6250	3385.42
Π_r^*	5679.59	3385.42	6250
Π_{sc}^*	11359.18	9635.42	9635.42

Table 3. Results when $\frac{1}{2}\tau^2 < \lambda < \tau^2$ and $\frac{1}{2}c^2 < \eta < c^2$

Parameter	VN	MS	RS
e^*	61.54	66.67	66.67
m^*	61.54	66.67	66.67
Π_m^*	24852.07	25000	29166.67
Π_r^*	24852.07	29166.67	25000
Π_{sc}^*	49704.14	54166.67	54166.67

coefficient is relatively high, they construct the optimal low-carbon reputation under the power structure dominated by the other party, while obtaining the optimal profit; and both supply chain members and the entire supply chain can obtain profits higher than those under the VN power structure.

6 Conclusions

In the low-carbon supply chain composed of a manufacturer and a retailer, this paper considers three power structures (VN, MS, RS), using game theory to analyze and compare the low-carbon reputation decisions and profits of supply chain members under different power structures, in order to provide a basis for decision-making of low-carbon supply chain members. The research can be concluded as follows.

First, different cost coefficients affect the power structure of supply chain members in choosing to construct the optimal low-carbon reputation. When the cost coefficients of both sides are high, supply chain members will choose to build the optimal low-carbon reputation under the power structure where they have the equal bargaining power. When one party's cost coefficient is high and the other party's cost coefficient is low, supply chain members will choose a power structure where they dominate.

Moreover, the relationship between the cost coefficients and the sensitivity coefficients is an important influencing factor for supply chain low-carbon goodwill reputation. When the cost coefficients is higher than the sensitivity coefficients, the VN power structure will become the optimal channel for building low-carbon reputation. On the contrary, investment and marketing under the power structure of MS or RS can not only bring higher profits but also create better low-carbon reputation.

This study still has some shortcomings. It considers the low-carbon supply chain of a manufacturer and a retailer, the study can be expanded to a complex supply chain between competitive manufacturers and competitive retailers. Additionally, in order to encourage the low-carbon economy, the government subsidizes enterprises that implement carbon emissions reduction so the low-carbon reputation decision combined with different carbon emissions reduction policies will also be an interesting question.

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