The Game Analysis of Low Carbon Supply Chain Emission Reduction Considering Channel Power under the Concern of Fairness

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Abstract. The emission reduction strategies of different channel power structures is studied under the fair, neutral and fair concerns of manufacturers, and compares the emission reduction levels, wholesale and retail prices, and the changes and differences in the profits of supply chain members under various circumstances. The research shows that the increase of emission reduction cost factor is not conducive to the improvement of emission reduction level, price and profit. The profit level of manufacturer under the manufacturer-led structure is not conducive to the manufacturer-led structure due to other structures, but is conducive to the improvement of the profit level of manufacturer under other structures. Manufacturer's equity concern behaviour is beneficial to the improvement of manufacturer's utility, in which the equity concern factor should be kept at a certain level under Nash vertical structure. Equity concerns and emission reduction strategies under decentralized decision-making are not conducive to the improvement of the overall supply chain effectiveness.

1. Introduction

As global temperatures warm, consumer demand for low-carbon products is increasing, prompting companies in the manufacturing sector to take various measures to reduce emissions, but the overall effect is modest. In practice, it is generally believed that manufacturers bear the main responsibility for emission reduction, and retailers help to share the cost of emission reduction. The emission reduction effect of the whole low-carbon supply chain is different under different channel power structures. In addition to being affected by channel power, the emission reduction cost sharing process is also affected by members' fair concern behaviour. The research results on low-carbon supply chain management are relatively significant. Sun et al. [1] discussed the optimal emission reduction strategy under the low-carbon quota policy and consumers' low-carbon preference. Zhou et al. [2] further refined emission reduction strategies and realized the coordination of low-carbon supply chain through the application of different allocation mechanisms of emission reduction costs. In consideration of retailer competition and information asymmetry.

Some scholars believe that supply chain members have the psychology of fair concern. For example, Li et al. [3] discussed the coordination problem of low-carbon supply chain with members' behaviors of fair concern on the premise that carbon emissions can be traded. Shi et al. [4] analyzed the impacts of equity concern coefficient and low carbon coefficient on carbon emissions, pricing strategies of members and supply chain efficiency under the concern of manufacturers equity. Gao et al. [5] analyzed the influence of channel leadership on supply chain performance in the retailer-led green.
supply chain. Yang Lei et al. [6] studied the optimal emission reduction and decision-making of dual-channel low-carbon supply chain. Li et al. [7] compared and analyzed the differences in emission reduction, pricing and profits under three channel power structures, and coordinated the low-carbon supply chain.

From the above analysis, we can know that low carbon supply chain is the core issue of cost allocation and coordination of the supply chain, but at the same time from the perspective of fairness concerns and channel power to study literature is less, so, in this paper, under different channel power to fair neutral and fair members under the concern of the decision variables, the profit function, comparing the emission reductions, to improve the low carbon supply chain efficiency under different structure provide a certain reference.

2. Basic Models and Assumptions
This paper considers a secondary supply chain consisting of a manufacturer and a retailer. This simple structure is conducive to the classification of channel power types in the supply chain. According to the power level of the manufacturer and retailer in the supply chain, it can be divided into manufacturer-led, retailer-led and vertical Nash equilibrium. Considering consumers' low-carbon preference, market demand is a function of product price and emission reduction level, assuming that the demand function is a linear function. We studied the different channel emission reduction strategies under fair neutral and fair concerns, And then we compared and analyzed the differences between emission reduction levels, retail prices and profits. Finally, proposed the corresponding strategies are for each member. The parameters involved in the paper are shown in Table 1:

| Parameter | Definition                              |
|-----------|-----------------------------------------|
| $a$       | Market base scale                       |
| $b$       | The sensitivity of consumers to price   |
| $\varepsilon$ | Consumer preference coefficient for low carbon |
| $e$       | Low carbon emission reduction level     |
| $w$       | Wholesale price of manufacturer's products |
| $c$       | A manufacturer's unit production cost   |
| $m$       | Retailer's profit per item              |
| $p$       | The selling price of the product        |
| $k$       | Cost coefficient of manufacturer emission reduction |

Specific assumptions are as follows:
(1) The retailer's sales process is passive, regardless of sales efforts, and the cost is zero. $p = m + w$.

(2) The manufacturer is responsible for the implementation of the low-carbon emission reduction strategy, and the emission reduction cost is $ke^2 / 2$, and $2kb \geq 3e^2$.

According to parameters and assumptions, the following requirement function can be constructed:

$$Q = a - b(w + m) + \varepsilon e$$  \hspace{1cm} (1)

$$\pi_m = (w - c)\left[ a - b(w + m) + \varepsilon e \right] - \frac{1}{2}ke^2$$  \hspace{1cm} (2)

$$\pi_r = m\left[ a - b(w + m) + \varepsilon e \right]$$  \hspace{1cm} (3)

$$\pi_s = (w + m - c)\left[ a - b(w + m) + \varepsilon e \right] - \frac{1}{2}ke^2$$  \hspace{1cm} (4)

3. Fair and Neutral Emission Reduction Strategies
This paper only studies decentralized strategy, that is, members in the supply chain independently decide their own key variables. Among them, wholesale price and emission reduction level of products are the decision variables of manufacturers, unit profit of products sold is the decision variables of retailers, and the decision-making sequence is determined according to the channel power of members. In order to distinguish the profit function of manufacturer, retailer and supply chain as a whole, variables $m$, $r$ and $sc$ are used as subscripts; in decentralized decision-making, variables involved in
manufacturer-led, retailer-led and vertical Nash strategy are respectively used as subscripts 1, 2 and 3. When fairness concerns are concerned, variables increase * to superscript.

3.1. Manufacturer-led under fair and neutral conditions

Under the manufacturer's leadership, the reverse decision order is determined according to the Stackelberg game: the retailer first sets the profit per unit product, and then the manufacturer determines the wholesale price and emission reduction level according to the retailer's decision.

To equation (3), solve the first derivative with respect to \( m \), and set the first derivative equal to zero, we can get:

\[
\left( a + c e_i - b w_i \right) / 2b = 0
\]

By substituting \( m_i \) into Equation (2), the manufacturer's profit function can be obtained, and the first and second derivatives and partial derivatives of \( \pi_m \) with respect to \( w_i \) and \( e_i \) are obtained, and the Hesse matrix of \( \pi_m \) can be written:

\[
\begin{pmatrix}
- b w_i + (a + c e_i + b c) / 2b & - a c e_i / 4b c - e_i^2 \\
-a c e_i / 4b c - e_i^2 & (a - b c) / 2b c - e_i^2
\end{pmatrix}
\]

From the matrix, we can get the first-order master and child formula:

\[
\begin{align*}
\pi_m &= k (a - b c)^2 / 2 (4 b k - e_i^2) \\
\pi_{m1} &= b k (a - b c)^2 / (4 b k - e_i^2) \\
\pi_{m2} &= k (a - b c)^2 (6 b k - e_i^2) / 2 (4 b k - e_i^2)^2
\end{align*}
\]

3.2. Retailer-led under fair and neutral conditions

Under the retailer's leadership, according to a Stackelberg game rule: first the manufacturer sets the wholesale price and the level of low carbon reduction, and then the retailer decides the profit per unit product sold. According to Equation (2), the first and second derivatives and partial derivatives of \( \pi_m \) with respect to \( w_i \) and \( e_i \) are obtained, and the Hesse matrix is as follow:

\[
\begin{pmatrix}
- c (a - b c) / 4 b k - e_i^2 & - (a + c e_i + b c) / 2 b c - e_i^2 \\
- (a + c e_i + b c) / 2 b c - e_i^2 & (a - b c) / 2 b c - e_i^2
\end{pmatrix}
\]

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\pi_m &= k (a - b c)^2 / 2 (4 b k - e_i^2) \\
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\pi_{m2} &= k (a - b c)^2 (6 b k - e_i^2) / 2 (4 b k - e_i^2)^2
\end{align*}
\]

3.3. Nash equilibrium under fair and neutral conditions
In Nash equilibrium, supply chain members are independent of each other and make decisions that are beneficial to them. Therefore, according to Equations (2) and (3) and some conclusions of the above situation, it can be seen that: there are optimal solutions for $w_1$, $m_1$ and $e_1$.

Solve the equations

$$\begin{cases} a + w_3 + bc - 2bw_1 - bm_1 = 0 \\ (w_3 - c)e - ke_3 = 0 \\ a + w_3 - bw_1 - 2bm_1 = 0 \end{cases}$$

we can obtain: $e_3 = \frac{e(a - bc)}{3kb - e^2}$, $w_3 = \frac{k(a - bc)}{3kb - e^2} + c$ (21), $p_3 = \frac{2k(a - bc)}{3kb - e^2} + c$ (22)

By substituting $w_1$, $e_1$ and $p_3$ into equations (2), (3) and (4), we can get:

$$\pi_{w_1} = \frac{bk^2(a - bc)^2}{(3kb - e^2)^2}$$

(23) $\pi_{m_1} = \frac{k(2bk - e^2)(a - bc)^2}{2(3kb - e^2)^2}$ (24) $\pi_{e_1} = \frac{k(4bk - e^2)(a - bc)^2}{2(3kb - e^2)^2}$ (25)

4. Mitigation strategies with equity concerns

The research on equity concern theory shows that members pay more attention to their own negative injustice. Since the low-carbon emission reduction strategy in the paper is taken by manufacturers, retailers are in a passive position and have no other costs. Therefore, only manufacturers with negative equity concerns are considered in this paper. Therefore, the manufacturer's utility function can be expressed as:

$$u_m = (1 + \beta)\left[(w - c)(a - bm - bw + \varepsilon e) - \frac{1}{2}ke^2\right] - \beta m(a - bm - bw + \varepsilon e)$$ (26)

$$u_r = \pi_c = m(a - bm - bw + \varepsilon e)$$ (27)

To facilitate the expression of the subsequent calculation process, let $N = a - bc$, $M_1 = 2bk - e^2$, $M_2 = 3bk - e^2$, $M_3 = 4bk - e^2$, $L_4 = 2bk[2(1 + \beta) + \beta\gamma] - (1 + \beta)e^2$, $L_5 = bk(1 + \beta + \beta\gamma) + (1 + \beta)M_1$

4.1. Manufacturer-led situations with equity concerns

Under the guidance of the manufacturer, the problem solving process is similar to fairness and neutrality. According to Equations (26) and (27), it can be obtained that:

$$e_1 = \frac{e(1 + \beta)}{N / L_4}$$ (28), $w_1 = 2k(1 + \beta + \beta\gamma)N / L_4 + c$ (29), $p_3 = c + k(3 + 3\beta + 2\beta\gamma)N / L_4$ (30)

By substituting $w_1'$, $e_1'$ and $p_1'$ into equations (2), (3) and (4), we can get:

$$\pi_{w_1'} = \frac{bk^2(1 + \beta)^2N^2}{L_4^2}$$ (31), $\pi_{m_1} = \frac{k(1 + \beta)N^2(2bk\beta\gamma + L_4)}{2L_4^2}$ (32), $\pi_{e_1'} = \frac{k(1 + \beta)N^2[2bk(1 + \beta + \beta\gamma) + L_4]}{2L_4^2}$ (33)

4.2. Retailer-led situations with equity concerns

Led by retail, the problem solving process is similar to fairness and neutrality. According to Equations (26) and (27), it can be obtained that:

$$p_3 = \frac{N}{2M_1 + N + 2b + c}$$ (34), $e_2 = \frac{e N}{2M_1}$ (35)

$$w_2 = \frac{bk(1 + \beta + \beta\gamma)N}{2b(1 + \beta + \beta\gamma)M_1 + c}$$ (36)

By substituting $w_2'$, $e_2'$ and $p_2'$ into profit function, we can get:

$$\pi_{w_2'} = \frac{k(1 + \beta)N^2}{4M_1(1 + \beta + \beta\gamma)}$$ (37), $\pi_{m_2} = \frac{k(1 + \beta + 3\beta\gamma)N^2}{8M_1(1 + \beta + \beta\gamma)}$ (38), $\pi_{e_2'} = \frac{3kn^2}{8M_1}$ (39)
4.3. Nash equilibrium situations with equity concerns
In the case of vertical Nash, both the manufacturer and the retailer make decisions at the same time. According to Equations (26) and (27), it can be obtained that:

\[ e_3^* = e (1 + \beta) N / L_a, \]
\[ w_i^* = k (1 + \beta + \beta \gamma) N / L_a + c, \]
\[ p_i^* = k (2 + 2 \beta + \beta \gamma) N / L_a + c. \]

By substituting \( w_i^*, e_3^* \) and \( p_i^* \) into profit function, we can get:

\[ \pi_{w3}^* = bk^2 (1 + \beta)^2 N^2 / L_a^2, \]
\[ \pi_{m3}^* = k (1 + \beta) N^2 (L_a - bk (1 + \beta - \beta \gamma)) / 2L_a^2, \]
\[ \pi_{sc3}^* = k (1 + \beta) N^2 (L_a + bk (1 + \beta + \beta \gamma)) / 2L_a^2. \]

4.4. A comparative analysis of equity neutrality and equity concerns

**Proposition 1**: The level of emission reduction under fair concern of manufacturer is not higher than that under fair neutral.

**Proof process**: According to the previous results, we calculated \( e_1^*-e_1, e_2^*-e_2, e_3^*-e_3 \)
\[ e_1^*-e_1 = -2bk \beta \gamma e N / M_3 L_1 < 0, \quad e_2^*-e_2 = 0, \quad e_3^*-e_3 = -bk \beta \gamma e N / M_2 L_3 < 0 \]

**Proposition 2**: The wholesale price and selling price under the fair concern of the manufacturer shall not be lower than the wholesale price and selling price under the fair and neutral condition.

**Proof process**: According to the previous results, we calculated \( w_1^*-w_1, w_2^*-w_2, w_3^*-w_3 \) and \( p_1^*-p_1, p_2^*-p_2, p_3^*-p_3 \).
\[ w_1^*-w_1 = 2k \beta \gamma N M_1 / M_3 L_1 > 0, \quad w_2^*-w_2 = \beta \gamma N / 2b (1 + \beta + \beta \gamma) > 0, \quad w_3^*-w_3 = k \beta \gamma N M_1 / M_3 L_3 > 0, \]
\[ p_1^*-p_1 = 2k \beta \gamma N (bk - e^2) / M_3 L_1 > 0, \quad p_2^*-p_2 = 0, \quad p_3^*-p_3 = k \beta \gamma N (bk - e^2) / M_2 L_3 > 0 \]

**Proposition 3**: Retailer profits under equity concerns are lower than retailer profits under equity neutrality.

**Proof process**: According to the previous results, we calculated \( \pi_{w1}^* - \pi_{w1}, \pi_{m1}^* - \pi_{m1}, \pi_{sc1}^* - \pi_{sc1} \)
\[ \pi_{w1}^* - \pi_{w1} = -2b^2k^2 N^2 \beta \gamma \left( (1 + \beta) M_1 + L_1 \right) / M_3^2 L_1^2 < 0, \quad \pi_{m1}^* - \pi_{m1} = -\beta \gamma k N^2 / 4M_1 (1 + \beta + \beta \gamma) < 0, \]
\[ \pi_{sc1}^* - \pi_{sc1} = -b^2k^2 N^2 \beta \gamma \left( (1 + \beta) M_1 + L_3 \right) / M_2^2 L_3^2 < 0 \]

5. Numerical Analysis
We carried out numerical simulation to discuss the impact of emission reduction cost factor and equity concern factor on emission reduction level, price and profit under three channels of power. The parameters are assigned as follows: \( a = 1000, b = 50, c = 6, \epsilon = 40, \gamma = 2 \).
As shown in Figure 2, the profit of manufacturers and retailers and the cost of emission reduction change negatively, the manufacturer's fair concern is bad for the manufacturer-led structure and good for other structures.

Fig.2  The impact of \( k \) on profits

6. Conclusion
Manufacturer's emission reduction cost factor changes in the opposite direction with emission reduction level, price and profit. under the manufacturer-led structure, the equity concern factor is inversely proportional to the manufacturer's profit; under other leading structures, The equity concern factor changes in a positive direction with manufacturers' profits.

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