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A study on supply chain information sharing strategy for emission reduction investment in electronic products based on game theory

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Abstract. By analyzing the competition between electronic product manufacturers and retailers in pricing, a dynamic game model is constructed. Using backward induction, the optimal choices and maximum profits under equilibrium conditions are determined. Finally, the constructed model is subjected to data simulation by setting numerical values for relevant parameters to analyze the effects of environmental emission reduction value on the supply chain and the information sharing value of each member. The following conclusions are drawn: when the emission reduction efficiency of manufacturers or the sensitivity of the market to environmental protection is high, the improvement effect of information sharing will outweigh its bilateral marginal effect. Retailers will voluntarily share all demand information and achieve a "win-win" situation in the supply chain.

Keywords: Game Theory; Pricing Strategy; Supply Chain Information Sharing; Electronic Product Emission Reduction

1. Introduction

With the increasingly severe global climate change, the electronic products industry, as a significant source of carbon emissions, has made emission reduction investment a key issue for sustainable development within the industry. Concurrently, supply chains, serving as critical links in the production, distribution, and consumption of electronic products, play a vital role in enhancing supply chain efficiency, reducing costs, and achieving emission reduction goals through information sharing mechanisms.

In the research on green economic development and carbon emission reduction, Ling Yantao et al., integrating different consumer willingness to pay, conducted studies on differentiated product greenness design and pricing [1]. Scholar Zhang Wenbo investigated how manufacturers, under the context of consumer preferences for low carbon and asymmetric information regarding agent marketing capabilities, can identify agent capabilities through emission reduction, pricing, and sales incentive contract design to motivate their efforts and maximize their own profits [2].

While there is a considerable amount of research on pricing, service configuration, sales strategies, delivery times, and other aspects in the supply chain process, involving supply chain management, and the establishment of mathematical models. Qiu Yangyang delved into the pricing and promotion coordination mechanism of the consumer electronics new product supply chain, introducing repurchase reward-penalty joint contracts and dual-channel models to enhance overall profits [3]. Ni Guanqun studied the currently popular online shopping methods and found that group purchases are more favored when positive network effects are strong or when there are many undervalued consumers, and provided mixed strategies, with the superiority of individual purchases versus group purchases depending on market conditions [4]. Chen Bintong et al. proposed a duopoly model by studying the impact of personalized pricing strategies and refund policies on customer return policies [5]. Yiangos Papanastasiou et al. investigated how the existence of social learning affects strategic interactions between dynamic pricing monopolists and forward-looking consumer groups in a simple two-stage model, drawing insights from it [6]. Yong Zhang et al. combined relevant mathematical algorithms to estimate reasonable price ranges for goods and customer expectations, pricing different products for online sales reasonably [7]. Yongjian Li et al. studied optimal pricing and order strategies in supply chain management for fashion products, considering product returns between supply chain partners (B2B), and developed two stochastic models for centralized and decentralized channels to handle sales of new fashion and off-season products [8]. Wanmei Soon discussed models jointly made with pricing choices and other decisions, conducting a comprehensive review of multi-product pricing models, focusing primarily on models where demand depends explicitly on price [9]. Mahmut Parlar (1997) addressed continuous review stochastic inventory problems with random demand and random delivery times, considering interruptions in supply due to randomly occurring events [10]. Shichen Zhang studied demand sharing by retailers and suppliers' decisions on encroachment and quality, suggesting that retailers may prevent supplier encroachment by concealing demand forecasts. Retailers may be more willing to share information to obtain better quality products. Delayed quality decisions by suppliers may benefit both chain members [11].

Information sharing in the supply chain is significant for supply chain management, and scholars have conducted research on enhancing the supply chain. Peng Zuohua et al. analyzed the cooperative mechanism of quantity discounts under complete information and designed a quantity discount applicable in supply chain operations [12]. Lu Shaohua et al. studied a coordination mechanism within the supply chain when there is uneven distribution of interests and complete information [13]. Na Jing et al. focused on the problem of asymmetric information under market development, aiming to control asymmetric information within a normal range to ensure the normal operation and healthy development of market transactions [14]. Chen Lin et al. discussed three scenarios: full information sharing, partial information sharing, and no information sharing in a supply chain composed of two competitive manufacturers and one retailer [15]. Huang Yan Ting et al. analyzed the benefits of sharing technology licenses with manufacturers, distributors, and third parties in a closed-loop supply chain, extending and complementing previous studies on remanufacturing models only combined with technology licenses or information sharing research [16]. Ying Dai et al. considered a dual-channel supply chain consisting of manufacturers and retailers and categorized the decision problem into four information sharing scenarios: non-information sharing, forward information sharing, reverse information sharing, and full information sharing [17]. Mu Yanfen et al. studied the specific impact of manufacturers' different sales channel strategies on retailer sales volume and profits in the context of market demand information and manufacturer direct sales channel fixed cost information symmetry with retailers [18]. Mao Xiaobing analyzed the value of signal data in dual-channel competition through incomplete information static games, proposing that manufacturers guide retailers to purchase signal data through pricing strategies, optimize retail prices, increase both parties' information profits, and profits increase with signal accuracy [19]. Wang Wenbin et al. investigated the impact of retailer information sharing on closed-loop supply chains under incentive mechanisms and found that under specific conditions, retailer information sharing can enhance overall social welfare but may reduce consumer surplus. They designed a recovery responsibility-sharing contract to incentivize retailer information sharing under this circumstance [20]. Xiao Qun et al. compared product pricing, scrap recovery rates, and retailer profits under asymmetric information and information sharing scenarios in the make-to-order (MTO) and make-to-stock (MTS) modes. They introduced a fair profit allocation mechanism using the Nash bargaining model to ensure that the final profit allocation is based solely on the bargaining power of each party [21]. Zhang Pan et al. established a manufacturer demand information sharing model in a closed-loop supply chain with retailer and manufacturer recovery, analyzing the impact of information sharing on supply chain member profits under two recovery modes using refined Bayesian equilibrium theory [22].

2. Problem Model and Assumptions

2.1. Problem Description

This section analyzes a two-tier supply chain consisting of only one manufacturer (an electronic product manufacturer) and one retailer. The manufacturer can determine the wholesale price of environmentally friendly products and the degree of environmental emission reduction of the products. The retailer is responsible for marketing the goods and can determine the final market price of the goods for consumers.

In this supply chain, the manufacturer provides products to the retailer at a wholesale price w, and the retailer then sells the products to consumers at a retail price p. The environmental aspects of the product include the manufacturer's use of environmentally friendly materials, reduction of pollutant emissions, and the design of environmentally friendly and energy-saving features during production. Without loss of generality, both the unit production cost of the manufacturer and the unit sales cost of the retailer are standardized to zero. The manufacturer's emission reduction investment cost is the total cost of using expensive environmentally friendly materials, handling waste, and designing energy-saving features. The demand for emission reduction products in the market stems from the encouragement and promotion of green environmental products by the government and reflects consumers' strong environmental awareness. Compared to traditional electronic products, consumers prefer environmentally friendly home appliances. Let s denote the unit emission reduction effect of the product, where a higher proportion of environmentally friendly materials and better energy-saving effects result in a larger emission reduction effect s, and vice versa. In related literature, it is assumed that the marginal increase in emission reduction investment contributes to diminishing returns in emission reduction effects, and the emission reduction cost is a convex function of emission reduction effects, represented by a quadratic form $z = {ks^2}/{2}$, where k is the emission reduction cost coefficient. A smaller k value indicates that the manufacturer can achieve more emission reduction and environmental protection effects with less investment cost, indicating higher efficiency in producing emission reduction products. Because consumers' willingness to consume is influenced by both the product price p and the environmental emission reduction effect s of the product, the demand for this green product in the market is affected by both the product price and the emission reduction effect. Hence, a linear demand function $D = a - p + bs$ is adopted, where a represents potential market demand, and b represents the coefficient of sensitivity of market demand to the emission reduction effect of the product. A higher b value indicates a greater demand for the product in the market based on its emission reduction effect.

For market demand characterized by fluctuations and uncertainty, let $a = a_0 + \varepsilon$, where the random variable ε represents demand fluctuations due to uncertain factors, and satisfies E[ε]=0, $Var(\varepsilon) = \sigma^2$. Retailers generally obtain a set of observation samples (r_1, ……, r_n) about ε through historical data or market research, where $r_i = \varepsilon + u_i$ (i = 1,..., n), with n being the sample size, and the disturbance term u_i is independently and identically distributed as N(0, σ_n^2) and is independent of ε. Taking the sample mean as the retailer's prediction of the uncertainty of market demand information, which is considered private information, denoted as $Y = \varepsilon + \sum_{i=1}^{n} u_i/n$, then $E[Var(Y \mid \varepsilon)] = \sigma_u^2/n$. Define $t = Var(\varepsilon)/E[Var(Y \mid \varepsilon)]$ as the demand forecasting accuracy of the retailer, where $t = n\sigma^2/\sigma_u^2$, and a larger t value indicates more accurate market demand forecasting by the retailer. Assuming the retailer shares $\lambda n(0 \leqslant \lambda \leqslant 1)$ portions of demand observation values, the demand forecasting information obtained by the manufacturer from the retailer is $y=\varepsilon+\sum_{i=1}^{\lambda n} u_i/(\lambda n)$. Define $\tau=Var(\varepsilon)/E[Var(y \mid \varepsilon)]$ as the precision of the information shared by the retailer, where $\tau=\lambda n\sigma^2/\sigma_u^2=\lambda t$. If λ=0, then τ=0, indicating no information sharing; if λ=1, then τ=t, indicating complete information sharing; when $\lambda \in (0,1)$, then $\tau \in (0,1)$, indicating partial information sharing. Thus, the level of information sharing by the retailer can be represented by the ratio λ. Since all entities in the product-service supply chain predict demand using a linear information structure, it can be derived that:

$$E[\,\varepsilon \mid Y\,]=\frac{t}{1+t}Y \tag{1}$$

$$E[\varepsilon \mid y]=\frac{\tau}{1+\tau}y \tag{2}$$

$$E[\,Y \mid y\,]=\lambda y+(1-\lambda)E[\varepsilon \mid y]=\frac{\lambda+\lambda t}{1+\lambda t}y \tag{3}$$

Through further derivation, we obtain:

$$E[Y^2]=E[Yy]=\frac{1+t}{t}\sigma^2 \tag{4}$$

$$E[y^2]=\frac{1+\tau}{\tau}\sigma^2 \tag{5}$$

Based on the above assumptions, and assuming that demand information sharing is a long-term decision. In the game sequence between manufacturers and retailers, the retailer determines the level of information sharing λ before sales begin. When the sales period starts, the retailer first observes the demand and shares n observations with the manufacturer. Subsequently, the manufacturer and the retailer engage in a game. The manufacturer determines its wholesale price w and emission reduction investment z based on the shared demand prediction information y provided by the retailer. Then, the retailer decides the retail price p based on its private demand prediction information Y. Finally, the actual demand occurs, and the manufacturer and the retailer realize profits π_M and π_R respectively. The decision sequence is depicted in Figure 1, and the variable definitions are provided in Table 1.

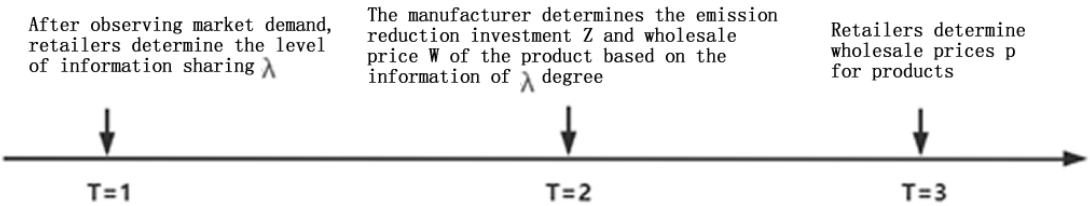

Figure 1. Game Sequence Diagram

Table 1. Variable Definitions

Variable Symbol	Variable Meaning
W	Wholesale price of the product
P	Retail price of the product
s	Unit emission reduction effect
k	Emission reduction cost coefficient
Z	Emission reduction investment
A	Potential market demand
a_0	Fixed value of potential market demand
b	Market emission reduction sensitivity coefficient

Table 1. (continued).

ε	Random variable of market demand
r_i	Observation value of the retailer
u_i	Observation error
t	Demand forecasting accuracy of the retailer
τ	Precision of the information shared by the retailer
λ	Level of information sharing

2.2. Modeling and Decision-Making of Supply Chain Demand Information Sharing Considering Emission Reduction Investment

a) Dynamic Game Analysis under Incomplete Information

An analysis of the game process between the manufacturer and the retailer is conducted, and backward induction is used to solve the game equilibrium.

For analytical convenience, we start from the perspective of the retailer, who obtains the market demand information $E[\varepsilon \mid Y]$. Given the wholesale price w and emission reduction degree s, the retailer's conditional expected profit is:

$$E[\pi_R \mid Y] = (p-w)(a_0 + E[\varepsilon \mid Y] - p + bs) \quad (6)$$

Observing the function, when the first-order condition $\partial E[\pi_R \mid Y]/\partial_p = 0$ holds, the function achieves its maximum value, thus:

$$p(w,s) = \frac{1}{2}(a_0 + E[\varepsilon \mid Y] + bs + w) \quad (7)$$

Similarly, from the perspective of the manufacturer, the market demand information obtained from the retailer is $E[\varepsilon \mid y]$. Given the wholesale price w and emission reduction degree s, the manufacturer's conditional expected profit is:

$$E[\pi_R \mid y] = (p-w)(a_0 + E[\varepsilon \mid y] - p + bs) \quad (8)$$

When profit is maximized, the expected market price from the manufacturer's perspective, denoted as $E[p(w,s) \mid y]$, must satisfy the first-order condition $\partial E[\pi_R \mid Y]/\partial_p = 0$, thus, the manufacturer's expected value of the product market price is:

$$E[p(w,s) \mid y] = \frac{1}{2}(a_0 + E[\varepsilon \mid y] + bs + w) \quad (9)$$

Given the expected market price from the manufacturer's perspective, the manufacturer's conditional expected profit is:

$$E[\pi_M \mid y] = w(a_o + E[\varepsilon \mid y] - E[p(w,s) \mid y] + ms) - \frac{1}{2}ks^2 \quad (10)$$

Substituting $E[p(w,s) \mid y]$ into (4-10), we obtain:

$$E[\pi_M \mid y] = \frac{1}{2}w(a_o + E[\varepsilon \mid y] - w + bs) - \frac{1}{2}ks^2 \quad (11)$$

Meanwhile, the Hessian matrix of $E[\pi_M \mid y]$ with respect to W and s is:

$$H(E[\pi_M \mid y]) = \begin{pmatrix} \frac{\partial^2 E[\pi_M|y]}{\partial w^2} & \frac{\partial^2 E[\pi_M|y]}{\partial s\,\partial w} \\ \frac{\partial^2 E[\pi_M|y]}{\partial w\,\partial s} & \frac{\partial^2 E[\pi_M|y]}{\partial w^2} \end{pmatrix} = \begin{pmatrix} -1 & \frac{1}{2}b \\ \frac{1}{2}b & -k \end{pmatrix} \quad (12)$$

By calculating the Hessian matrix of $E[\pi_M \mid y]$ with respect to w and s, it is found that when $k > b^2/4$, $E[\pi_M \mid Y]$ is a joint concave function of w and s. However, when $k \leq b^2/4$, it is obtained that $\partial^2 E[\pi_M \mid y]/\partial s\,\partial k < 0$, $\partial E[\pi_M \mid y]/\partial s \mid_{k=b^2/4} \geqslant 0$. Thus, $\partial E[\pi_M \mid y]/\partial s \geq 0$, indicating that the manufacturer can always increase its profit by increasing the emission reduction degree, which is inconsistent with general reality. Therefore, to make the research more meaningful, it is assumed that 假设$k > b^2/4$, implying that the manufacturer needs higher costs to increase the emission reduction effect. By simultaneously solving $\partial E[\pi_M \mid y]/\partial s = 0$ and $\partial E[\pi_M \mid y]/\partial w = 0$, the optimal solutions w^* and s^* are obtained. Substituting w^* and s^* into equation (7) yields the optimal profit solution, as shown below:

Manufacturer and retailer's optimal decisions based on their respective predictions (under incomplete information):

Optimal wholesale price $w^* = \frac{2ka_0}{4k-b^2} + \frac{2k}{4k-b^2}E[\varepsilon \mid y]$ (13)

Optimal emission reduction degree $s^* = \frac{ba_0}{4k-b^2} + \frac{b}{4k-b^2}E[\varepsilon \mid y]$ (14)

Optimal market price $p^* = \frac{3ka_0}{4k-b^2} + \frac{1}{2}E[\varepsilon \mid Y] + \frac{b^2+2k}{2(4k-b^2)}E[\varepsilon \mid y]$ (15)

Proposition 1: $\partial s^\star/\partial k < 0$, $\partial s^\star/b > 0$, $\partial s^\star/\partial E[\varepsilon \mid y] > 0$

Proof: Based on the previous assumption $a_0 + E[\varepsilon \mid y] > 0$ and $k > b^2/4$, therefore $\frac{\partial s^\star}{\partial k} = -\frac{4b(E[\varepsilon|y]+a_0)}{(b^2-4k)^2} < 0$, $\frac{\partial s^\star}{b} = \frac{(b^2+4k)(E[\varepsilon|y]+a_0)}{(b^2-4k)^2} > 0$, and $\frac{\partial s^\star}{\partial E[\varepsilon|y]} = \frac{b}{-b^2+4k} > 0$.

Proposition 1: Based on the above results, s^* is influenced by k, b, and $E[\varepsilon \mid y]$, where $E[\varepsilon \mid y]$ represents the manufacturer's predicted market demand after information sharing, k and b respectively denote the manufacturer's emission reduction efficiency and market sensitivity to emission reduction. From $\partial s^\star/\partial E[\varepsilon \mid y] > 0$, it can be inferred that retail market demand information sharing positively influences the manufacturer's emission reduction investment decision. $\partial s^\star/\partial k < 0$ and $\partial s^\star/b > 0$ indicate that the higher the manufacturer's emission reduction efficiency and the market's sensitivity to emission reduction products, the greater the manufacturer's emission reduction investment.

Similarly, for w^*, through the same analysis, $\partial w^\star/\partial E[\varepsilon \mid y] > 0$ exists, implying that the greater the degree of information sharing by the retailer, the higher the wholesale price. This suggests that if the market demand prediction information shared by the retailer can bring positive assistance to the decision-making process, the manufacturer will increase the emission reduction investment to achieve a higher level of environmental protection effect to drive product sales, and increase the wholesale price to gain more profits.

Based on the equilibrium results during the sales period, combined with equations (6) and (11), the expected profits of the manufacturer, retailer, and the entire supply chain system are determined as follows:

$$\Pi_M = E[\pi_M] = \frac{ka_0^2}{2(4k-b^2)} + \frac{k\tau\sigma^2}{2(4k-b^2)(1+\tau)} \tag{16}$$

$$\Pi_R = E[\pi_k] = \frac{k^2a_0^2}{(4k-b^2)^2} + \frac{t\sigma^2}{4(1+t)} + \frac{(6k-b^2)(b^2-2k)\tau\sigma^2}{4(4k-b^2)^2(1+\tau)} \tag{17}$$

$$\Pi_{SC} = \Pi_M + \Pi_R = \frac{(6k-b^2)ka_0^2}{2(4k-b^2)^2} + \frac{t\sigma^2}{4(1+t)} + \frac{(-b^4+6b^2k-4k^2)\tau\sigma^2}{4(4k-b^2)^2(1+\tau)} \tag{18}$$

For ease of expression, let Φ represent the environmental value of emission reduction in the supply chain of emission reduction products. When k→∞, when the emission reduction cost is extremely high, the manufacturer will no longer invest in emission reduction costs, thus:

$$\Phi = \Pi_{sc} - \lim_{k\to\infty}\Pi_{sc} = \frac{b^2(16k-3b^2)(\tau\sigma^2+\tau{a_0}^2+{a_0}^2)}{16(4k-b)^2(1+\tau)} \tag{19}$$

Proposition 2: $\Phi > 0$, $\partial\Phi/\partial\lambda > 0$ and $\partial^2\Phi/\partial\lambda\,\partial b > 0$, $\partial^2\Phi/\partial\lambda\,\partial b < 0$.

Proof: From Φ, we have $\frac{\partial \Phi}{\partial \lambda}=\frac{t\,\partial \Phi}{\partial \tau}=\frac{b^2(16k-3b^2)t\sigma^2}{16(4k-b^2)^2(1+\tau)^2}$, thus $\Phi > 0$ and $\partial\Phi/\partial\lambda > 0$. Also, because $\frac{\partial^2 \Phi}{\partial \lambda\,\partial b}=\frac{bk(8k-b^2)t\sigma^2}{(4k-b^2)^3(1+\tau)^2}$ and $\frac{\partial^2 \Phi}{\partial \lambda\,\partial k}=\frac{-b^2(8k-b^2)t\sigma^2}{2(4k-b^2)^3(1+\tau)^2}$, then $\partial^2\Phi/\partial\lambda\,\partial b > 0$ and $\partial^2\Phi/\partial\lambda\,\partial b < 0$.

Proposition 2 indicates that an increase in the market's sensitivity to emission reduction products can lead to increased profits for the entire supply chain. Moreover, an increase in the degree of information sharing by the retailer can effectively enhance the environmental benefits of the product. Simultaneously, as the market's demand for environmentally friendly products or the manufacturer's emission reduction efficiency increases, the role of demand information sharing in improving emission reduction effects becomes more apparent.

b) Decision and Value Analysis of Information Sharing

From macro factors and based on the method of solving environmental value Φ as mentioned above, we can similarly deduce the information sharing value of each member of the supply chain. To better understand the decision-making process of information sharing by the retailer before the sales period begins, we describe the profit impact of demand information sharing on the supply chain and its members using $V_i(i \in \{M,R,SC\})$.

As discussed earlier, when $\lambda = 0$ and $\tau = 0$, indicating no information sharing by the retailer, $\Pi_i(i \in \{M,R,SC\})$ represents the profit without information sharing:

$$\begin{cases} \Pi_M = \frac{ka_0^2}{2(4k-b^2)} \\ \Pi_R = \frac{k^2a_0^2}{(4k-b^2)^2}+\frac{t\sigma^2}{4(1+t)} \\ \Pi_{SC} = \frac{(6k-b^2)ka_0^2}{2(4k-b^2)^2}+\frac{t\sigma^2}{4(1+t)} \end{cases} \tag{20}$$

When $\lambda = 1$ and $\tau = t$, indicating complete information sharing by the retailer, $\Pi_i(i \in \{M,R,SC\})$ represents the profit with full information sharing:

$$\begin{cases} \Pi_M = \frac{ka_0^2}{2(4k-b^2)}+\frac{k\tau\sigma^2}{2(4k-b^2)(1+\tau)} \\ \Pi_R = \frac{k^2a_0^2}{(4k-b^2)^2}+\frac{t\sigma^2}{4(1+t)}+\frac{(6k-b^2)(b^2-2k)\tau\sigma^2}{4(4k-b^2)^2(1+\tau)} \\ \Pi_{SC} = \frac{(6k-b^2)ka_0^2}{2(4k-b^2)^2}+\frac{t\sigma^2}{4(1+t)}+\frac{(-b^4+6b^2k-4k^2)\tau\sigma^2}{4(4k-b^2)^2(1+\tau)} \end{cases} \tag{21}$$

Subtracting Equation (20) from Equation (20) yields the value added by member profits under information sharing:

$$\begin{cases} V_M = \frac{k\tau\sigma^2}{2(4k-b^2)(1+\tau)} \\ V_R = \frac{(6k-b^2)(b^2-2k)\tau\sigma^2}{4(4k-b^2)^2(1+\tau)} \\ V_{sc} = \frac{(-b^4+6b^2k-4k^2)\tau\sigma^2}{4(4k-b^2)^2(1+\tau)} \end{cases} \tag{22}$$

According to the analysis in Proposition 2, after demand information sharing, the manufacturer can more accurately adjust wholesale prices and emission reduction investments based on market fluctuations, making information sharing beneficial to the manufacturer $V_M > 0$. For the retailer, sharing demand forecast information will produce both positive and negative effects, and whether to profit from it depends on the relative size of these two effects.

Proposition 3 When $2 < b^2/k < 4$, $V_R > 0$ and λ^*=1; when $b^2/k \leqslant 2$, $V_R \leq 0$ and λ^*=0.

Proof: From $V_R = \frac{(6k-b^2)(b^2-2k)\pi\sigma^2}{4(4k-b^2)^2(1+\tau)}$, it follows that $\frac{\partial V_R}{\partial \lambda}=\frac{t\,\partial V_R}{\partial \tau}=\frac{(6k-b^2)(b^2-2k)t\sigma^2}{4(4k-b^2)^2(1+\tau)^2}$. Given $k > b^2/4$, when $2 < b^2/k < 4$, $V_R > 0$ and $\partial V_R/\partial\lambda > 0$; when $b^2/k \leqslant 2$, $V_R \leq 0$ and $\partial V_R/\partial\lambda \leqslant 0$.

Proposition 3 indicates that sharing demand forecast information by the retailer is not always detrimental to themselves. When there is a high demand for green environmental products in the market or when the manufacturer's emission reduction efficiency is high, the improvement in emission reduction effects brought about by information sharing will outweigh the bilateral effects. The profit increase from increasing emission reduction investment can effectively offset the profit loss caused by the exacerbation of bilateral effects. Therefore, full information sharing will help increase the retailer's profit, thus achieving a win-win situation. "Voluntarily" providing comprehensive demand forecast information to the retailer helps manufacturers respond to market changes. When there is a low demand for environmental products in the market, and when the manufacturer's emission reduction efficiency is low, the service of information sharing may be affected, leading to a certain degree of impact on the benefits of emission reduction investment. Due to the exacerbation of bilateral effects, this impact may not be compensated. Therefore, in such cases, sharing demand forecast information may affect the retailer's profit, making them unwilling to share.

Since information sharing can help manufacturers obtain more profits, and $\frac{\partial V_M}{\partial \lambda}=\frac{kt\sigma^2}{2(4k-b^2)(1+\tau)^2}>0$, indicating that increasing the level of information sharing will also increase the manufacturer's profit, manufacturers will be more inclined to encourage retailers to share information. When $b^2/k \leqslant 2$, the motivations of manufacturers and retailers regarding demand information sharing are not aligned because although information sharing can bring profit gains to manufacturers, the retailer's profit will be damaged. In this case, manufacturers can provide certain economic incentives to retailers to encourage them to share private forecast information. However, only when demand information sharing can increase the profit of the entire supply chain system will manufacturers have enough profit increment to compensate for the retailer's profit loss.

Proposition 4: $V_{\text{sc}}>0$ if and only if $3-\sqrt{5}<b^2/k<4$, and V_{sc} is maximized when $\lambda=1$.

Proof: From $V_{\text{sc}}=\frac{(-b^4+6b^2k-4k^2)w^2}{4(4k-b^2)^2(1+\tau)}$], it follows that $V_{\text{sc}}>0$ if and only if $-b^4+6b^2k-4k^2>0$. Combined with $k>b^2/4$, it must satisfy $3-\sqrt{5}<b^2/k<4$. Moreover, from $\frac{\partial V_{\text{sc}}}{\partial \lambda}=\frac{t\,\partial V_{\text{sc}}}{\partial \tau}=\frac{(-b^4+6b^2k-4k^2)t\sigma^2}{4(4k-b^2)^2(1+\tau)^2}$, when $3-\sqrt{5}<b^2/k<4$, $\frac{\partial V_{\text{sc}}}{\partial \lambda}>0$, indicating that V_{sc} is maximized at $\lambda=1$.

Proposition 4 indicates that only when $3-\sqrt{5}<b^2/k<4$, demand information sharing by the retailer can enhance the total profit of the entire supply chain, and complete information sharing can maximize the profit increase.

This is because an increase in market demand for emission-reduction products or an improvement in the manufacturer's emission reduction efficiency will help enhance the green value of the supply chain. The higher m or the smaller k, the more likely the emission reduction improvement from demand information sharing will outweigh its bilateral effects. However, when $b^2/k \leq 3-\sqrt{5}$, which means low market demand for emission-reduction products or low efficiency in manufacturer's emission reduction, the enhancement of emission reduction effect from demand information sharing is limited. It is difficult to offset the adverse effects of bilateral effects, resulting in a loss of supply chain performance.

3. Numerical Experiments and Sensitivity Analysis

In order to analyze the information sharing behavior in the two-tier supply chain and its impact on equilibrium decisions and service value, data simulation is conducted to compare the effects of different factors on information value, emission reduction effectiveness, and incentive benefits. Subsequently, optimal strategies are proposed for electronic product manufacturers.

3.1. Sensitivity Analysis of Demand Information Sharing Level

To rationally analyze the constructed mathematical model, the relevant parameter values are set as shown in Table 2, and case analysis is performed using Mathematica mathematical tools.

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Table 2. Parameter Values Setting

Parameter	a_0	σ^2	t	k	b
Value	1	0.36	1.5	{1,1.5,2,4}	{0.8,1.3,1.5,1.8}

3.2. *Impact of Information Sharing Level on Environmental Emission Reduction*

Analyzing the impact of the information sharing level on environmental emission reduction s, emission reduction cost z, and environmental emission reduction value Φ. This involves comparing the trend of changes in the environmental emission reduction function based on different values of the market emission reduction sensitivity coefficient b and the emission reduction cost coefficient k, as shown in Table 3.

Table 3. Impact on Supply Chain Environmental Emission Reduction

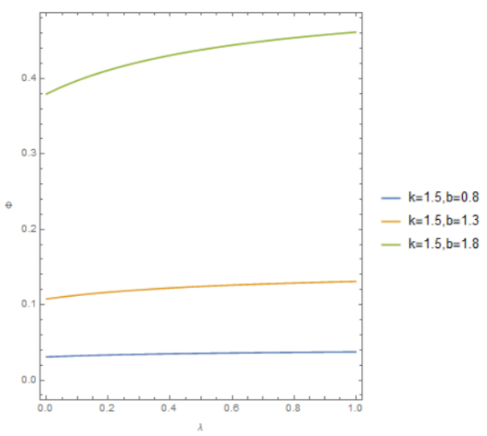
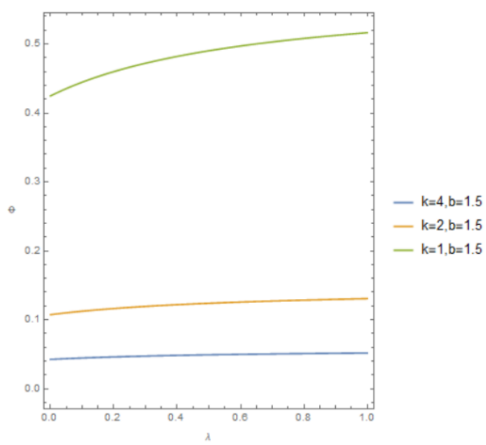
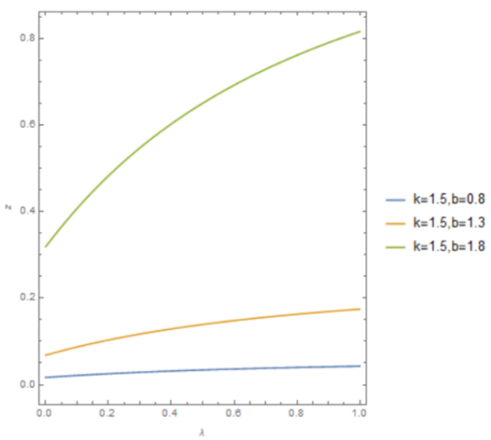
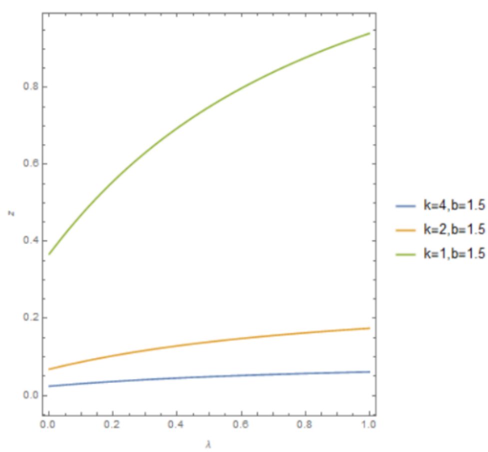
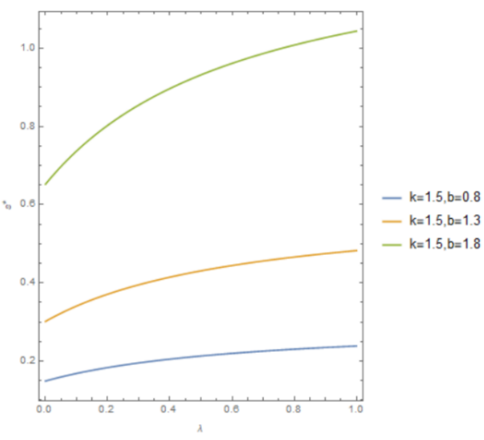
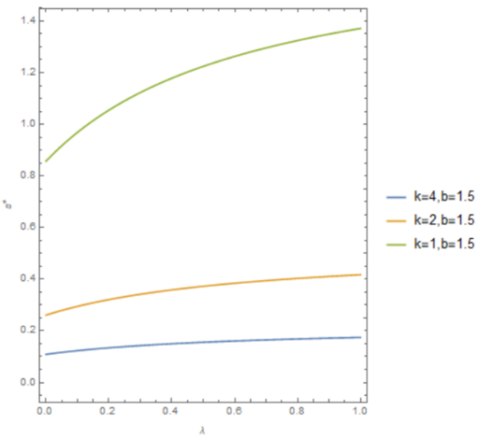
	Fixed k Value, Varying b Value	Fixed b Value, Varying k Value
The Impact of Information Sharing Level λ on Environmental Emission Reduction Value Φ		
The Impact of Information Sharing Level λ on Emission Reduction Cost z		

Table 3. (continued).

The Impact of Information Sharing Level λ on Emission Level s	 

From the figures, it can be observed that with the increase in the information sharing level \lambda by retailers, the manufacturer's investment in emission reduction, the environmental emission reduction level of the supply chain, and the environmental emission reduction value will continuously increase. Analyzing the individual impacts of emission efficiency k and market emission sensitivity b on environmental emission reduction in the supply chain, it can be seen from the figures that when the emission efficiency k remains constant, the curve of the change in the environmental emission reduction value Φ with the increase in b becomes steeper. This indicates that the more sensitive consumers are to emission-reducing products and the greater the degree of information sharing by retailers, the greater the environmental emission reduction value in the supply chain. Similarly, when the market emission sensitivity b remains constant, with the increase in the manufacturer's emission efficiency (reduction in k), the curve of the change in the environmental emission reduction value Φ becomes steeper. This implies that the higher the manufacturer's emission efficiency, the greater the degree of information sharing by retailers, and the greater the environmental emission reduction value in the supply chain. The manufacturer's emission reduction investment and emission level also undergo similar changes; that is, the higher the emission efficiency k and the market emission sensitivity b, the higher the emission reduction investment and emission level, and vice versa.

3.3. Impact of Information Sharing on Profit of Supply Chain Members

The test set analyzes and compares the changes in information sharing value among manufacturers, retailers, and the entire supply chain under different values of k and b. From Figure 2, it can be observed that all V_M curves are in the first quadrant of the Cartesian coordinate system, that is, $V_M \geqslant 0$ always exists in $\lambda \in [0,1]$, and it increases with the increase of λ, reaching the maximum value at $\lambda=1$. This implies that retailer information sharing always brings profit increase to manufacturers, and the profit increases with the degree of information sharing. When information is fully shared, the profit of manufacturers is maximized.

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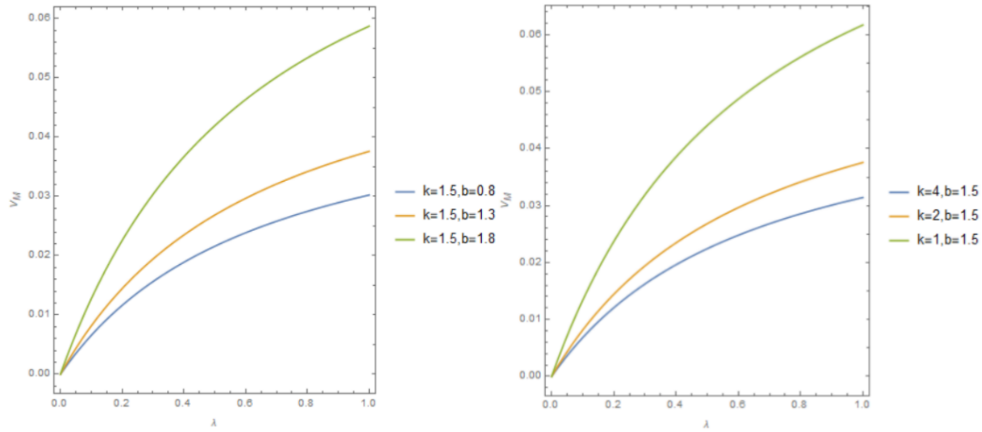
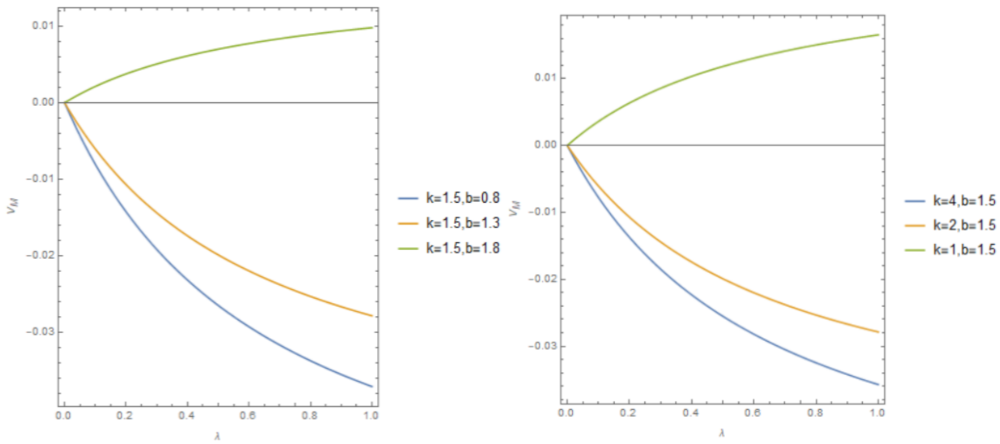


(a) (b)

Figure 2. The impact of information sharing level $\boldsymbol{\lambda}$ on the value V_M brought by information sharing

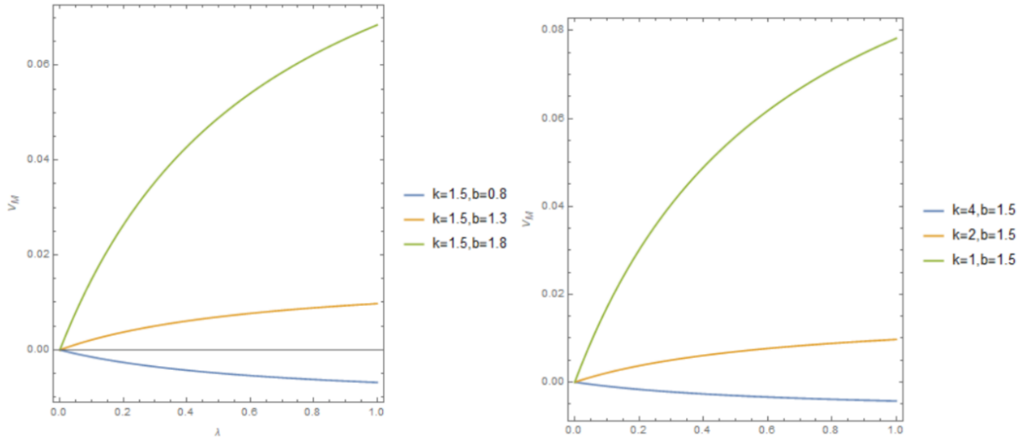
Observing Figure 3, the positivity and negativity of V_R are not constant with different values of k and b. When V_R is always less than or equal to 0, with the increase in the degree of information sharing by retailers, the profit brought by information sharing gradually decreases, resulting in “negative growth”. When V_R is always greater than or equal to 0, with the increase in the degree of information sharing, the profit brought by information sharing to retailers gradually increases, resulting in “positive feedback”. Whether information sharing can bring profit increase or decrease to retailers depends on the emission reduction efficiency k and market emission sensitivity b of manufacturers.



(a) (b)

Figure 3. The impact of information sharing level $\boldsymbol{\lambda}$ on the value V_R brought by information sharing

Similarly, observing Figure 4, the positivity and negativity of V_{sc} are also not constant with different values of k and b. When V_{sc} is always less than or equal to 0, with the increase in the degree of information sharing by retailers, the profit change of the entire supply chain shows a gradual “negative growth”. When V_{sc} is always greater than or equal to 0, with the increase in the degree of information sharing, the profit of the entire supply chain gradually increases positively, and it also increases gradually. At λ=1, that is, when information is fully shared, the profit increase is maximized. This means that information sharing can only achieve a “win-win” situation for the entire supply chain within specific ranges of k and b values.



(a) (b)

Figure 4. The impact of information sharing level $\boldsymbol{\lambda}$ on the value V_{sc} brought by information sharing

According to the above analysis, there are only two forms of information sharing by retailers: $\lambda = 0$ or $\lambda = 1$. That is, when sharing market demand information is detrimental to themselves, retailers will not engage in information sharing, i.e., $\lambda = 0$; when sharing market demand information is beneficial to themselves, or the benefits obtained through incentive contracts can offset the losses caused by information sharing, retailers will engage in complete information sharing, i.e., $\lambda = 1$.

4. Conclusion and Suggestions

In the current era of frequent updates and iterations of electronic products, with new products emerging constantly to meet the diverse needs of consumers, there is an increasing demand from both consumers and society for environmentally friendly and emission-reducing products. Mastering market demand information plays a crucial role for enterprises in reasonably regulating their investment in emission reduction and assisting in the market pricing of new products. This paper investigates the demand prediction information sharing and incentive issues in the supply chain regarding the emission reduction investment and product pricing of manufacturers under incomplete information by constructing a dynamic game model.

Starting from the Stackelberg game between manufacturers and retailers in the supply chain, this paper establishes a mathematical model to obtain the optimal decision under equilibrium results. Subsequently, the environmental emission reduction value on the supply chain is derived from the profit under equilibrium results. Then, the value generated by information sharing on the supply chain is obtained. Finally, the following conclusions are drawn:

(1) For manufacturers, information sharing does indeed enhance the growth of their own profits and can effectively assist manufacturers in investing in emission reduction for products under fluctuating market demand. This, in turn, can effectively enhance the environmental emission reduction value of the supply chain. At the same time, the environmental emission reduction value of the supply chain is also influenced by the emission reduction efficiency of manufacturers and the market's sensitivity to emission reduction. The higher the efficiency or sensitivity, the more significant the role of information sharing in enhancing the environmental emission reduction value of the supply chain.

(2) Although retail market demand information sharing can always help manufacturers increase profits, it can lead to losses in profits for retailers themselves and the entire supply chain. This is because when the emission reduction efficiency of manufacturers is very low or the market is extremely insensitive to emission reduction products, the value enhancement brought by information sharing is difficult to compensate for the loss of benefits due to the bilateral marginal effects. In this case, retailers may resist information sharing.

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(3) When the emission reduction capabilities of manufacturers and the demand for environmental products in the market are not extremely high, although information sharing may result in loss of profits for retailers, the overall profitability of the entire supply chain can be improved. To achieve this goal, manufacturers can encourage retailers to share all demand forecasting information through two-part compensation contracts, thereby achieving a win-win situation. As retailers improve the accuracy of market demand forecasting, manufacturers increase their emission reduction efficiency, and the market attaches increasing importance to environmentally friendly products, the difficulty of implementing incentive contracts will be reduced.

References

[1] Ling, Y., Xu, J., & Zhang, H. (2021). Green product vertical differentiation design and pricing strategy based on heterogeneous consumer preferences. Journal of Industrial Engineering and Engineering Management, 35(06), 208-217. DOI: 10.13587/j.cnki.jieem.2021.06.018.
[2] Zhang, W. (2017). Sales incentive contract design considering consumer low-carbon preferences under asymmetric information. Chongqing University.
[3] Qiu, Y. (2021). Research on pricing-promotion coordination mechanism in consumer electronics new product supply chain. Jiangsu University. DOI: 10.27170/d.cnki.gjsuu.2021.001937.
[4] Ni, G. (2019). Research on group buying pricing model based on network effect. PloS One, 1.
[5] Chen, B., & Chen, J. (2016). Price competition or service? Research on personalized pricing and refund guarantee. Retail Industry Journal.
[6] Papanastasiou, Y., & Savva, N. (2016). Dynamic pricing under social learning and strategic consumers. Management Science, 63(4), 901-1269.
[7] Zhang, Y., Chin, F. Y. L., & Ting, H. F. (2014). Research on bundled commodity online pricing. Journal of Global Optimization, 58(2), 377-387.
[8] Li, Y., Wei, C., & Cai, X. (2012). Optimal pricing and order policy for B2B fashion product returns. International Journal of Production Economics, 135(2), 637-646.
[9] Soon, W. (2011). Review of bundled commodity pricing models. Applied Mathematics and Computation, 217(21), 8149-8165.
[10] Parlar, M. (1997). Analysis of continuous review inventory problems with stochastic supply interruptions. European Journal of Operational Research, 99(2), 366-385.
[11] Zhang, S., Wei, L., & Zhang, J. (2022). Demand forecasting sharing dominated by retailers and supplier encroachment and quality decision. European Journal of Operational Research, 301(1), 39-50.
[12] Peng, Z., & Tian, P. (2006). Quantity discount contract design in the supply chain based on complete information. Journal of Industrial Engineering and Engineering Management, 02, 114-116.
[13] Lu, S., & Xia, Y. (2005). Coordination mechanism of supply chain with complete information. Journal of Wuhan University of Technology (Transportation Science & Engineering Edition), 06, 917-920.
[14] Jing, N., & Li, H. (2013). Analysis of the impact of asymmetric information on product supply chain and pricing. In Proceedings of the 3rd International Conference on Education and Educational Management (EEM 2013), 26.
[15] Chen, L., & Li, T. (2016). Research on demand forecasting information sharing with competitive manufacturers. Chinese Journal of Management Science, 24(S1), 711-717.
[16] Huang, Y., & Wang, Z. (2017). Research on technical licensing of information sharing in closed-loop supply chains. International Journal of Production Economics, 191(9), 113-127.
[17] Dai, Y., Dou, L., Song, H., Zhou, L., & Li, H. (2022). Bidirectional information sharing of uncertain demand forecasting in dual-channel supply chains. Computers & Industrial Engineering, 169, 108-162.
[18] Mu, Y., Nie, J., & Shi, C. (2018). Impact of asymmetric market demand and cost information on manufacturers opening direct sales channels. Management Review, 30(9), 143-151.

[19] Mao, X. (2018). Research on demand signal sharing strategy in dual-channel competition. Management Review, 30(1), 202-209.
[20] Wang, W., & Ding, J. (2020). Study on the impact of retail information sharing on closed-loop supply chain under reward and punishment mechanism. Operations Research and Management, 29(7), 89-98.
[21] Xiao, Q., & Ma, S. (2016). Study on the impact of information asymmetry on MTO and MTS models in closed-loop supply chain. Chinese Journal of Management Science, 24(5), 139-148.
[22] Zhang, P., & Lei, M. (2020). Demand information sharing of closed-loop supply chain manufacturers and design of recovery channels. Journal of Systems Engineering, 35(2), 232-243.