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Optimal strategies for manufacturer with strategic customer behavior under carbon emissions-sensitive random demand

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Abstract

Purpose – The purpose of this paper is to investigate the manufacturer's production, pricing and green technology investment decision problem when strategic customer behavior and carbon emissions-sensitive random demand is taken into consideration and discuss the impact of carbon emissions-sensitive demand on the manufacturer's operation strategies, total carbon emissions and maximum expected profit.
Design/methodology/approach – The authors formulate a model to introduce carbon emissions-sensitive demand into the newsvendor framework with strategic customer behavior. The authors characterize the rational expectations equilibrium to derive the optimal solutions to the manufacturer. The authors analyze the effects of carbon emissions-sensitive demand on the manufacturer's optimal strategies, total carbon emissions and maximum expected profit by comparative analysis.
Findings – The authors obtain the manufacturer's optimal production, pricing and green technology investment strategies under rational expectations equilibrium in scenario of price-sensitive demand and that of carbon emissions-sensitive demand, respectively. The authors find that as customer demand changes from price-sensitive demand to carbon emissions-sensitive demand, the manufacturer's optimal prices are the same but optimal production quantity, optimal unit carbon emissions and maximum expected profit go down. Though the total emissions decrease, the carbon emissions reduction would not increase as the demand is more carbon emissions-sensitive. Whether it increases or decreases depends on the model parameters.
Originality/value – Carbon emissions-sensitive demand and strategic customer behavior are considered simultaneously in an integrated model. The result can guide the manufacturer decision-making. The proposed model are hoped to shed light to the future works in the field of sustainable supply chain management.

Keywords Green technology investment, Low carbon manufacturing, Pricing strategy, Production strategy, Strategic customer behaviour
Paper type Research paper

1. Introduction

With competition intensifying, technology updates accelerating and market environment changing rapidly, perishable product (short life cycle product) is becoming increasingly common. In addition to traditional service (such as airline,

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hotel), agricultural product, fashion product, etc., more and more high-tech products have the characteristics of perishable products. In order to avoid loss of surplus inventory, firms often charge a discount to deal with the rest of them during the sales process of perishable products. Frequent discounts make customers smart. Customers are able to predict the possibility of the future price cut, and choose to wait for lower prices to buy. The behavior that customers choose to wait for lower prices to buy to gain greater customer surplus is known as strategic customer behavior. The ignorance of strategic customer behavior by retailers will result in 20 percent losses of their total profit (Aviv and Pazgal, 2008). Strategic customer behavior has become a common phenomenon, and its impact on firms operations decision-making has become a hot topic of common concern for practitioners and researchers.

In addition, global warming is occurring at record levels and has already shown that it has a direct relationship with the increasing global carbon dioxide emissions (Chen and Hao, 2015). With popularity of carbon footprint and an increase in the customers' environmental protection awareness, the customer, who purchases a product, pays attention to the carbon emissions of the product except for the price, i.e., carbon emissions-sensitive customer. Research shows that customers prefer carbon footprint labeling of products and are willing to pay them over their average price (Echeverría *et al.*, 2014; Chen *et al.*, 2015). In addition to meet customers' basic needs, low carbon products can also bring customers additional utility in safety and social responsibility. The change of customer demand from price-sensitive to carbon emissions-sensitive puts forward new challenges to the operation strategies of firms.

In order to meet the low carbon demand of customers, firms are willing to invest in green technology to improve its profit (Sengupta, 2012; Chen and Wang, 2015). Green technology investment will increase production cost, however, it can reduce the unit carbon emission of the product for businesses and get additional revenue. Businesses need to trade off the costs and benefits of green technology investment to decide whether to invest.

Our findings help firms in many industries to make optimal decisions. For instance, the customers' willingness to pay for low carbon pork is greater than that of regular pork has been proved in many empirical studies (Ying *et al.*, 2012; Shuai *et al.*, 2014). A low carbon pork manufacturer will invest in green technology to reduce the carbon emissions in pork production and make scientific decisions to meet customers' demand. As to the strategic customer behavior, it is a very common phenomenon. For example, Taobao has made November 11th a yearly shopping carnival since 2010. Almost all of the retailers will provide discounts to costumers. The sales of Tmall (a B2C Website owned by Taobao) reached 57.1 billion RMB and the customer orders reached 0.197 billion in November 11, 2014 (Baidu Encyclopedia, 2015). Obviously, this is strong evidence that strategic customer behavior has become a common phenomenon because many customers had made the shopping list in advance for the discount sales on that day (Du *et al.*, 2015). Therefore, we investigate the manufacturer's production, pricing and green technology investment strategies, considering strategic customer behavior and carbon emissions-sensitive random demand, which has important theoretical value and practical significance.

There is a lot of literature focussing on strategic customer behavior in operations management. However, very few researches have addressed the issue of determining the optimal operation strategies of businesses with carbon emissions-sensitive demand. To the best of our knowledge, the manufacturer's optimal strategies when considering strategic customer behavior and carbon emissions-sensitive demand simultaneously have not been addressed. In order to fill this gap, we address the following two questions in this paper:

1. How the manufacturer determine the optimal production, pricing and green technology investments strategies with strategic customer behavior under carbon emissions-sensitive random demand?
2. What effects does the carbon emissions-sensitive demand on the optimal strategies, total carbon emissions and maximum expected profit of the manufacturer?

The remainder of this paper is organized as follows. Section 2 is dedicated to a literature review. We present modeling descriptions and assumptions in Section 3. Section 4 investigates the optimal strategies of the manufacturer with price-sensitive demand and carbon emissions-sensitive demand, respectively. In Section 5, we analyze the effects of carbon emissions-sensitive demand on the manufacturer's optimal strategies, total carbon emissions and maximum expected profit. A numerical study is conducted in Section 6. In Section 7, we conclude our key findings and highlight possible future work.

2. Literature review

Our study is related to two streams of research: the literature on strategic customer behavior in operations management and the literature on low carbon manufacturing with carbon emissions-sensitive demand.

As to the literature on strategic customer behavior in operations management, early studies focus on durable goods such as Coase (1972), Bulow (1982) and Desai *et al.* (2004). The attention given to perishable products has increased considerably in recent years. Su (2007) studied the pricing model of a monopolist who sold finite inventory to heterogeneous strategic customers in finite period. It showed that the structure of the optimal pricing was determined by the heterogeneity of valuation and customer patience. Aviv and Pazgal (2008) examined the optimal pricing strategy of the seller who sold a perishable product to strategic customers. Inventory contingent discounting and announced fixed-discount strategies were taken into consideration. They showed that the optimal strategy for the customers was determined by their valuation and arrival time to the store. Liu and van Ryzin (2008) investigated whether it is optimal for a firm to create rationing risk by deliberately understocking products when strategic customer behavior is considered. They characterized conditions under which rationing is optimal, and obtained the optimal capacity to maximize the firm's profits. Zhang and Cooper (2008) considered the rationing level as a decision variable based on the risk-neutral scenario of literature (Liu and van Ryzin, 2008). They showed that rationing could improve revenue when prices were fixed in advance. Levin *et al.* (2010) investigated the dynamic pricing model of a monopolist sold a perishable product to finite population of strategic customers. Research showed that the adverse effect of strategic customer behavior can be effectively reduced by joint using of the appropriate pricing policy and the initial capacity when it was a decision variable. Jerath *et al.* (2010) examined the effect of two sales approach (last-minute sales directly to consumers vs through an opaque intermediary) on the profit of service provider facing strategic customer behavior. Lai *et al.* (2010) examined the impact of a posterior price matching policy on the customers' purchasing behavior, a seller's pricing and inventory decisions and their expected payoffs. They showed that the posterior price matching policy can eliminated strategic consumers' waiting incentive. Swinney (2011) investigated the value of quick response production when the valuation of customers for a product was uncertainty and heterogeneous. They showed that the value of quick response is generally lower with strategic customers than with myopic customers. Mersereau and Zhang (2012) assumed that the seller understood the cumulative demand curve but not understood the ratio of strategic customers. They examine the pricing strategy of the seller who uses markdown policy in above setting. They provided a robust pricing strategy that the seller could run well without knowing the ratio of strategic customers. Huang and Van Mieghem (2013) examined how strategic customers were willing to provide more demand information based on the newsvendor model framework. Du *et al.* (2015) studied the single-period joint inventory and pricing decisions with risk preference and strategic customers. They showed that strategic customer behavior had an adverse effect on the seller. Prasad *et al.* (2015) studied the choices of mixed bundling pricing and reserved product pricing for a monopolist offering two products to a mix of myopic and strategic consumers.

Closely related to our work, Su and Zhang (2008) first investigated the newsvendor model with strategic customer behavior and derive the optimal pricing and inventory strategies for the seller. Then they expanded the newsvendor model to supply chain setting, examined the impact of strategic customer behavior on supply chain performance and analyzed how to realize supply chain coordination by using whole price contract or buyback contract. What distinguishes our study to Huang and Van Mieghem (2013) is the demand type. We characterize the price-sensitive demand or carbon emissions-sensitive demand instead of the demand completely independent of the price and carbon emissions. Yang *et al.* (2015) considered the order adjustment problem of quick response strategy based on the newsvendor model with strategic customer behavior developed by Huang and Van Mieghem (2013), and examined the effects of quick response on supply chain performance for various supply chain structures with strategic customer behavior.

Research on low carbon manufacturing with carbon emissions-sensitive demand are just emerging in recent years. A lot of studies, such as Arora (1995), Laroche *et al.*, (2001) and Bansal and Gangopadhyay (2003), showed that a customer is willing to pay additional costs for low carbon products. The conclusion proved that the carbon emissions of a product would affect the customer demand. Zhu and Sarkis (2007) examined the relationships between green supply chain practice, economic and environmental performance by a moderated hierarchical regression analysis. They showed that the market and regulatory pressures made the manufacturer implement green technology investment to improve environmental performance. Sengupta (2012) examined the pricing and investment behavior of a firm. The environmental attributes of the firm's production technology could convey to environmentally conscious consumers by the firm's pricing. They showed that a firm would actively open its green technology investment when then realized that the customer demand was carbon emissions sensitive. Nouira *et al.* (2014) investigated the optimization of manufacturing system with carbon emissions-sensitive demand. They designed the optimal manufacturing system which took the environmental impacts of manufacturing activities and environmental performance of finished products into consideration, and analyzed the impact of the product greenness impacts on systems profit and decisions. Choudhary *et al.* (2015) examined the pricing, transportation mode selection and green technology investment of a monopolist facing carbon emissions-sensitive demand. The results showed that the green technology investment was important to maximize the firm's profit.

Closely related to this paper, Yalabik and Fairchild (2011) examined the green technology investments strategies of the manufacturer who faced twin pressures of carbon emissions-sensitive demand and regulatory penalties. They showed that the manufacturer had an incentive to reduce carbon emissions by green technology investment when the demand of customers were emissions sensitive. What distinguishes our work lies in that we characterize the random demand instead of determinate demand and take strategic customer behavior into consideration.

Nevertheless, despite the increased attention on strategic customer behavior or customer awareness of low carbon in operation management, very few studies have been carried out to examine the manufacturer's optimal production, pricing and green technology investment decisions with above two customer behavior into consideration simultaneously. Our paper contributes to the literature by specifically examining the effect of customer awareness of carbon emissions on production, pricing and green technology investment strategies based on the newsvendor model with strategic customer behavior. One distinction of our model is that an additive demand function which depends on the product price and carbon emissions is explored in scenario of carbon emissions-sensitive demand. Another distinction is systematic consideration of green technology investment, strategic customer behavior and carbon emissions-sensitive demand in low carbon manufacturing setting. The main contribution of this paper are as follows:

1. We derive the optimal production, pricing and green technology investment strategies for the low carbon manufacturer. The results can help related firms make optimal decisions in the new normal.
2. The effect of carbon emissions-sensitive demand on the manufacturer's optimal strategies, the total carbon emissions and the maximum expected profit.
3. Sensitivity analysis of optimal strategies and total carbon emissions reduction to customers' carbon emissions-sensitive degree is discussed.

3. Model descriptions and assumption

This paper investigates production and pricing strategies for a monopolistic manufacturer who produces a product and distributes to customers directly. We divide the whole sales period into two phases. In phase one, the manufacturer sells the products at full price p; in phase two, the manufacture sells the leftover products at salvage price s, which is exogenous variable. If the product is sold out in phase one, the phase two does not exist and shortage cost is not considered in this paper. We assume that the customers are strategic customer, i.e., the customers will take into account the possibility of purchasing the product at salvage price in phase two, to choose to purchase the product at full price or wait to purchase the product at salvage price to maximize the expected surplus. All customers have the same valuation to the product, i.e., all customers are homogeneous. We assume that each customer purchases a product at most. We suppose that the customers demand is carbon emissions-sensitive, which is affected by unit carbon emissions of the manufacturer except for the unit price. Referring to the demand function of Yalabik and Fairchild (2011), we assume the demand function of the manufacturer is:

$$D(\tau, \varepsilon) = a - bp - \gamma\tau + \varepsilon \tag{1}$$

where τ represents the carbon emissions per unit product produced by the manufacture, a represents potential market size, b and γ represent the sensitivity of demand to unit price and unit emission of the product, respectively. ε is a random variable defined on the range $[A,B]$. We let $F(x)$ represent the cumulative distribution function of ε and $f(x)$ the probability density function, let $\overline{F} = 1 - F$. Demand distributions satisfy IFR, i.e., $f(x)/(1 - F(x))$ is increasing in x. Many of the commonly applied demand distributions are IFR: the normal, the exponential, the Weibull and the gamma (Cachon, 2004). In order to assure that positive demand is possible for some range of p, we require that $A > -a$.

In response to the change of customer demand, the manufacturer can invest in reducing the unit carbon emissions. The manufacturer's initial unit carbon emissions is τ_0, and the unit carbon emissions after green technology investments of manufacturer is τ, $\tau < \tau_0$. Referring to the green technology investment function of Yalabik and Fairchild (2011), we assume that the cost of reducing unit carbon emissions to a level τ, denoted by $I(\tau)$, is:

$$I(\tau) = t(\tau_0 - \tau)^2 \tag{2}$$

where t is the coefficient, represents the efficiency, of green technology investment of the manufacturer. Meanwhile, the production cost is c, the value of unit product to the customer, i.e., the customers' utility from consuming the product is v, and the customers' reservation price is r. Therefore, the decision of the green technology investment of the manufacturer is replaced by the decision of unit carbon emissions of the manufacturer. So the manufacturer needs to decide the production quantity q, unit price p and unit carbon emission τ under carbon emissions-sensitive random demand. We list the parameters and variables variables below:

Notation	Descriptions
$D(\tau, \varepsilon)$	The random demand and $D = a - bp - \gamma\tau + \varepsilon$
$f(\cdot)$	Probability density function of ε
$F(\cdot)$	Distribution function of ε. $F(\cdot)$ satisfy IFR and $\overline{F}(\cdot) = 1 - F(\cdot)$
c	Unit produce cost
p	Unit price. We assume that it can be observed by the customers
q	The production quantity of the manufacturer. We assume that it cannot be observed by the customers
s	Unit salvage price of the product which is an exogenous variable
v	The customers' utility from consuming the product
r	The customers' reservation price, which is customers' private information and cannot be observed by the manufacturer
ξ_r	The beliefs of the manufacturer over the customer' reservation price
ξ_{prob}	The beliefs of customers over their chances of obtaining the product at salvage price
τ_0	Unit carbon emissions before green technology investment
τ	Unit carbon emissions after green technology investment
$I(\tau)$	Green technology investment, $I(\tau) = t(\tau_0 - \tau)^2$

Because the parameters must meet certain conditions to make sense, we assume:

1. $p \leqslant r$. Only when the retail price is not more than the customer reservation price, may the customer purchase the product at full price.
2. $v > p > c > s > 0$. This condition states that there is a positive profit margin for the manufacturer and customers when a product is sold to customers. In addition, the production cost is greater than the salvage price, which indicates that the manufacturer will lose money when the product failed to sell at full price. This prompts the manufacturer to arrange the production plan according to the customers' demand, because the excess inventories generate losses.

The sequence of events is as follows: first, the manufacturer forms the belief of customers' reservation price ξ_r and decides the full price, production quantity and unit carbon emissions; second, the customers form the beliefs ξ_{prob} of probability of the product selling at salvage price s according to the information of market price and form the reservation price r; third, the customers' demand is satisfied and the products are sold at full price p; finally, all remaining products are sold at salvage prices.

4. The optimal strategies for the manufacturer

We characterize the game between the manufacturer and the customers with rational expectations (RE) equilibrium in this paper. Rational expectations hypothesis is proposed by Muth (1961) and is introduced into operations management by Desai *et al.* (2004) to analyze the decision problems of the enterprises in the presence of strategic customer behavior. Since then, the rational expectations hypothesis has been adopted by scholars all over the world (Yang *et al.*, 2015; Jiang and Chen, 2012; Jiang and Chen, 2015). In order to examine the effect of carbon emissions-sensitive demand, we investigate the manufacturer's optimal strategies in two scenarios of price-sensitive demand and carbon emissions-sensitive demand.

4.1 Price-sensitive demand model

When the demand is price-sensitive, the demand function of the manufacturer can be simplified to the traditional additive form $D_1(\varepsilon) = a - bp + \varepsilon (a > 0,\ \ b > 0)$. Obviously, the manufacturer do not invest in reducing the unit carbon emission. So the optimal of the manufacture's unit carbon emissions in this situation, denoted τ_1^*, is $\tau_1^* = \tau_0$. We denote the variables of price-sensitive demand scenario by subscript 1.

First, we examine the decision-making behavior of strategic customers. The customers' decision problem is to purchase immediately at full price or wait for markdown to maximize their expected surplus. The expected surplus of the customer is $v - p$ when he purchases the product at full price and $(v - s)\xi_{prob}$ when he purchases the product at salvage price. Therefore, the customer's maximum expected surplus is max $\{v - p,\ (v - s)\xi_{prob}\}$. The customer will buy the product at full price p if and only if $v - p \geqslant (v - s)\ \xi_{prob}$. Then given ξ_{prob}, we derive the customer's reservation price $r(\xi_{prob}) = v - (v - s)\xi_{prob}$.

Second, we examine the decision problem for the manufacturer. The manufacturer must decide the production quantity q and unit price p. The profit function of the manufacturer, denoted $\pi(q,p)$, is:

$$\pi(q,p) = \begin{cases} pD_1(\varepsilon) - cq + s(q - D_1(\varepsilon)); D_1(\varepsilon) \leqslant q \\ pq - cq; D_1(\varepsilon) > q \end{cases}$$

For convenient calculation and clarity of the results, $z_1 = q - (a - bp)$ is defined as inventory factor according to Petruzzi and Dada (1999), which represents the riskless inventory level. So the profit function of the manufacturer can be rewritten as:

$$\pi(z_1,p) = \begin{cases} (p - s)(a - bp + \varepsilon) - (c - s)(a - bp + z_1); \varepsilon \leqslant z_1 \\ (p - c)(a - bp + z_1); \varepsilon > z_1 \end{cases}$$

The expected profit function of the manufacturer is:

$$E[\pi_1(z_1,p)] = \int_A^{z_1} [(p-s)(a-bp+x)-(c-s)(a-bp+z)]f(x)dx$$

$$+\int_A^{B} [(p-c)(a-bp+z_1)]+f(x)dx$$

Defining $\Lambda(z_1) = \int_A^{z_1}(z_1-x)f(x)dx$ and $\Theta(z_1) = \int_{z_1}^{B}(x-z_1)f(x)dx$, we can write:

$$E[\pi_1(z_1,p)] = (p-c)(a-bp)-(c-s)\Lambda(z_1)-(p-c)\Theta(z_1) \tag{3}$$

The beliefs of the manufacturer over the customer' reservation price is ξ_r. Obviously, the manufacturer will set $p=\xi_r$, $z_1 = argmax_{z_1}E[\pi_1(z_1,p)]$. According to the definition of rational expectation equilibrium (Desai *et al.*, 2004), the solution of RE equilibrium (p, z_1, r, ξ_r, ξ_{prob}) must meet the following conditions: (i) $r=v-(v-s)\xi_{prob}$; (ii) $p=\xi_r$; (iii) $z_1 = argmax_{z_1}E[\pi_1(z_1,p)]$; (iv) $\xi_{prob}=F(z_1)$; (v) $\xi_r=r$.

Condition (i), (ii) and (iii) indicate that the manufacturer and customers will choose the action to maximize their own utility. Condition (iv) and (v) ensure the solution meet rational expectations hypothesis, i.e., the actual situation of economic in line with people's expectations. The nature of the problem is a static game that both sides act simultaneously. The manufacturer determine the production quantity to maximize its expected profit. The customers determine the customer reservation price to maximize their expected surplus. The solution of RE equilibrium which satisfies the definition above is the Nash equilibrium.

As to the optimal strategies of the manufacturer with price-sensitive demand in RE equilibrium, the following proposition is obtained:

P1. In RE equilibrium, the optimal production strategy (q_1^*) and pricing strategy (p_1^*) with price-sensitive demand exist and are unique, and all the customers buy immediately. $q_1^* = z_1^* + (a-bp_1^*)$ where $z_1^* = \overline{F}^{-1}\left(\sqrt{c-s/v-s}\right)$, $p_1^* = s+\sqrt{(v-s)(c-s)}$.

Proof. In RE equilibrium, we have $p=v-(v-s)\ F(z_1)$:

$$\frac{\partial E[\pi_1(z_1,p)]}{\partial z_1} = (p-c)-(p-s)F(z_1).$$

$$\frac{\partial^2 E[\pi_1(z_1,p)]}{\partial z_1^2} = -(p-s)f(z_1) < 0,$$

which indicates the optimal z_1 of the manufacturer exist and is unique. Let $\partial E[\pi_1(z_1,p)]/\partial z_1 = 0$, we can obtain $p-c-(p-s)\ F(z_1)=0$. Therefore, we can obtain p_1^* and z_1^* by solving the equation set:

$$\begin{cases} p-c-(p-s)F(z_1) = 0 \\ p = v-(v-s)F(z_1) \end{cases}$$

According to the definition of inventory factor, we can obtain q_1^*. The results is shown in *P1*. This completes the proof. ■

P1 indicates that the manufacturer has the unique optimal strategies with price-sensitive demand. Su and Zhang (2008) obtain the optimal pricing strategy and optimal quantity with price-independent demand. By comparative analysis, we find that the optimal price of the manufacturer is equal and the expressions of the optimal quantity and inventory factor are identical regardless of whether the demand is related to price or not. This conclusion is interesting. It indicates that the optimal pricing strategy with strategic customer behavior is robust. Regardless of whether the demand is relate to price or not and how sensitivity the demand affects the price, the optimal pricing strategy of the manufacturer keep unchanged. The optimal order strategy of the manufacturer is affected by the demand type. But the affected part is the quantity which responds to the determinate part of the demand, i.e., $a-bp$. The method of determining the quantity which responds to the random part of the demand (i.e. ε) is robust, for the expressions of key ratio in the two scenarios are identical.

Substitute z_1^* and p_1^* into Equation (3), we can obtain the manufacturer' maximum expected profit with strategic customer behavior in the situation of price-sensitive demand:

$$E\left[\pi_1\left(z_1^*, p_1^*\right)\right] = \left(p_1^* - c\right)\left(a - bp_1^*\right) - (c-s)\Lambda\left(z_1^*\right) - \left(p_1^* - c\right)\Theta\left(z_1^*\right).$$

4.2 Carbon emissions-sensitive demand model

With strengthening of the customers' environmental protection awareness and the popularity of carbon footprint, the customer, who purchases product, pays attention to the carbon emissions of the product except for the price. The change of the customer demand is ignored in the decision-making process, which may have negative effects on the manufacturer. So next, we examine the optimal strategies of the manufacturer with carbon emissions-sensitive demand.

In the situation of carbon emissions-sensitive demand, the manufacturer needs to determine the unit carbon emissions τ except for the production quantity q and unit price p. We can write the profit function of the manufacturer in the situation of carbon emissions-sensitive demand:

$$\pi(q, p, \tau) = \begin{cases} pD(\tau, \varepsilon) - cq + s(q - D(\tau, \varepsilon)) - t(\tau_0 - \tau)^2; D(\tau, \varepsilon) \le q \\ pq - cq - t(\tau_0 - \tau)^2; D(\tau, \varepsilon) > q \end{cases}$$

Similar to the situation of price-sensitive demand, we define inventory factor $z = q - (a - bp - \gamma\tau)$, $\Lambda(z) = \int_A^z (z-x) f(x)dx$, and $\Theta(z) = \int_z^B (x-z) f(x)dx$. The expected profit function of the manufacturer with strategic customer behavior in the situation of carbon emissions-sensitive demand can be simplified as:

$$E[\pi(z, p, \tau)] = (p-c)(a - bp - \gamma\tau) - (c-s)\Lambda(z) - (p-c)\Theta(z) - t(\tau_0 - \tau)^2 \tag{4}$$

The solution of the game still follows the rational expectations hypothesis. The belief of the manufacturer over the customer' reservation price is ξ_r. Obviously, the manufacturer will set $p = \xi_r$, z and τ are the solution of $argmax_{z,\tau} E[\pi(z, p, \tau)]$. The solution of RE equilibrium (p, z, τ, r, ξ_r, ξ_{prob}) must meet the following conditions: (i) $r = v - (v-s)\xi_{prob}$; (ii) $p = \xi_r$; (iii) z and τ is a solution of $argmax_{z,\tau} E[\pi(z, p, \tau)]$; (iv) $\xi_{prob} = F(z)$; (v) $\xi_r = r$.Condition (i), (ii) and (iii) indicate that the manufacturer and customers will choose the action to maximize their own utility. Condition (iv) and (v) ensure that the solution meet rational expectations hypothesis, i.e., the actual situation of economic is in line with people's expectations.

As to the optimal production quantity (q^*), optimal price (p^*) and the optimal unit carbon emissions (τ^*) of the manufacturer with carbon emissions-sensitive demand in RE equilibrium, the following proposition is obtained:

P2. The optimal production quantity, optimal price and the optimal unit carbon emissions of the manufacturer with carbon emissions-sensitive demand in RE equilibrium exist and are unique. $q^* = z^* + (a - bp^* - \gamma\tau^*)$ where $z^* = \overline{F}^{-1}\left(\sqrt{c-s/v-s}\right)$, $p^* = s + \sqrt{(v-s)(c-s)}$ and $\tau^* = \tau_0 - \gamma/2t\left[\sqrt{(v-s)(c-s)} - (c-s)\right]$.

Proof. In RE equilibrium, we can obtain:

$$p = v - (v-s)F(z) \tag{5}$$

Given p:

$$\frac{\partial E[\pi(z,p,\tau)]}{\partial z} = p - c - (p-s)F(z);$$

$$\frac{\partial^2 E[\pi(z,p,\tau)]}{\partial z^2} = -(p-s)f(z) < 0.$$

$$\frac{\partial E[\pi(z,p,\tau)]}{\partial \tau} = -\gamma(p-c) + 2t(\tau_0 - \tau);$$

$$\frac{\partial^2 E[\pi(z,p,\tau)]}{\partial \tau^2} = -2t < 0.$$

$$\frac{\partial^2 E[\pi(z,p,\tau)]}{\partial z \partial \tau} = \frac{\partial^2 E[\pi(z,p,\tau)]}{\partial \tau \partial z} = 0.$$

Then we can obtain that:

$$\begin{vmatrix} \frac{\partial^2 E[\pi(z,p,\tau)]}{\partial z^2} & \frac{\partial^2 E[\pi(z,p,\tau)]}{\partial z \partial \tau} \\ \frac{\partial^2 E[\pi(z,p,\tau)]}{\partial \tau \partial z} & \frac{\partial^2 E[\pi(z,p,\tau)]}{\partial \tau^2} \end{vmatrix} = 2t(p-s)f(z) > 0$$

Given p, $E[\pi(z,p,\tau)]$ is strict concave function with respect to z and τ. That is, there: are unique z and τ which maximize $E[\pi(z, p, \tau)]$. Let $\partial E[\pi(z,p,\tau)]/\partial z = 0$, $\partial E[\pi(z,p,\tau)]/\partial \tau = 0$ and combine Equation (5), we can obtain the equations:

$$\begin{cases} p - c - (p-s)F(z) = 0 \\ -\gamma(p-c) + 2t(\tau_0 - \tau) = 0 \\ p = v - (v-s)F(z). \end{cases}$$

Solving the equation set, we can derive the optimal production quantity, the optimal price and the optimal unit carbon emissions of the manufacturer shown in *P2*. This completes the proof. ■

P2 indicates that the optimal strategies of the manufacturer with carbon emissions-sensitive random demand exist and are unique. It worth noting that the manufacturer will make green technology investment definitely with carbon emissions-sensitive demand. Substituting τ^* into Equation (2), we can obtain that the optimal green technology investments of the manufacturer is $I(\tau^*)=\gamma^2/4t\left(\sqrt{(v-s)(c-s)}-(c-s)\right)^2$. In order to analyze the effect of γ on the green technology investment. We write $I(\tau^*)$ as $I(\gamma)$. Obviously, $dI(\gamma)/d\gamma>0$. We can obtain that the higher the customer's carbon emissions-sensitive degree is, the more green technology investment the manufacturer willing to make. The conclusion shed a light to governments that they can effectively promote the firms' improvement of green technology by developing customer awareness of low carbon.

Substituting z^*, p^* and τ^* into Equation (4), we can obtain that the manufacturer' maximum expected profit with strategic customer behavior in the situation of carbon emissions-sensitive demand is:

$$E\left[\pi\left(z^*,p^*,\tau^*\right)\right]=\left(p^*-c\right)\left(a-bp^*-\gamma\tau^*\right)-(c-s)\Lambda\left(z^*\right)-\left(p^*-c\right)\Theta(z^*)-t\left(\tau_0-\tau^*\right)^2.$$

5. Effect of the carbon emissions-sensitive demand

As the customer demand changes from traditional price-sensitive to carbon emissions-sensitive, the optimal strategies of the manufacturer need to be adjusted accordingly. What effects does the change of customer demand on the optimal strategies of the manufacturer? Next proposition will answer this question:

P3. $p_1^*=p^*$, $z_1^*=z^*$, $q_1^*>q^*$, $\tau_1^*>\tau^*$.

Proof. Obviously $p_1^*=p^*$, $z_1^*=z^*$. Because $q_1^*-q^*=\gamma\tau^*>0$, we get $q_1^*>q^*$. Because $\tau_1^*-\tau^*=\gamma/2t\left[\sqrt{(v-s)(c-s)}-(c-s)\right]>0$, we get $\tau_1^*>\tau^*$. This completes the proof. ■

P3 indicates that the optimal pricing strategy of the manufacturer keeps unchanged and the optimal production quantity and unit carbon emissions are decreasing when the customer demand changes from price-sensitive to carbon emissions-sensitive. The game between the manufacturer and customers follow the RE equilibrium. Therefore, the pricing strategy of the manufacturer will not change as long as the demand fluctuation (the probability density function and cumulative distribution function of ε) remain the same. This is why the optimal pricing strategies of the manufacturer in two scenarios are identical. Why the optimal production quantity of the manufacturer is decreasing? Obviously, there are always exists part of demand loss when the customers are carbon emissions-sensitive (the unit carbon emissions is not equal to zero). In order to avoid the losses of overage, the manufacturer is able to cut production to cope with the decline of the demand. The main cause for reduction of unit carbon emissions is: when the customer's demand is negative affected by the unit carbon emissions, the manufacturer will make green technology investments, which results in reduction of unit carbon emissions, to maximize the expected profit.

The customers prefer low carbon products by the publicity and guidance of governments. Whether such movement of governments can promote reduction of carbon emissions of firms? As the effect of change of customer demand on total carbon emissions of the manufacturer, the following proposition is obtained:

P4. $\tau_1^*q_1^*>\tau^*q^*$.

Proof. According to *P3*, we get $q_1^*>q^*$ and $\tau_1^*>\tau^*$. Then we can obtain $\tau_1^*q_1^*>\tau^*q^*$. This completes the proof. ■

$\tau_1^* q_1^*$ represents the total carbon emissions of the manufacturer with price-sensitive demand, and $\tau^* q^*$ represents the total carbon emissions of the manufacturer with carbon emissions-sensitive demand. *P4* indicates that the total carbon emissions of the manufacturer reduces when the customer demand changes from price-sensitive to carbon emissions-sensitive. It means that the publicity and guidance about environmental protection of governments, which make the unit carbon emissions of the products become the important factor affecting the customer's purchase decision-making, can effectively reduce firms' carbon emissions. The conclusion is intuitive. According to *P2*, we know that the green technology investment is increasing in the carbon emissions-sensitive degree of customers. Obviously, an increasing green technology investment will reduce the total carbon emissions of the manufacturer.

Whether the further strengthen of customers' consciousness of low carbon can further reduce the firm's total carbon emissions? In order to answer this question, we let: $H(\gamma)=\tau_1^* q_1^*-\tau^* q^*=U^2\gamma^3-2U\tau_0\gamma^2+\left(\tau_0^2+Uq_1^*\right)\gamma$, where $U=1/2t\left[\sqrt{(v-s)(c-s)}-(c-s)\right]$. As to the relation of $H(\gamma)$ (represents the manufacturer's total reduction of carbon emissions) and γ (represents the sensitive degree of customers to the unit carbon emissions), the following proposition is obtained:

P5. When $3Uq_1^*-\tau_0^2\geq 0$, $\boldsymbol{H}$ $(\boldsymbol{\gamma})$ is increasing in γ ; when $3Uq_1^*-\tau_0^2<0$, H (γ) is decreasing in γ with:

$$\gamma\in\left(\frac{2\tau_0-\sqrt{\tau_0^2-3Uq_1^*}}{3U},\frac{2\tau_0+\sqrt{\tau_0^2-3Uq_1^*}}{3U}\right)$$

and $H(\gamma)$ is increasing in γ with:

$$\gamma\in\left(0,\frac{2\tau_0-\sqrt{\tau_0^2-3Uq_1^*}}{3U}\right]\cup\left[\frac{2\tau_0+\sqrt{\tau_0^2-3Uq_1^*}}{3U},+\infty\right)$$

Proof. The derivation of $H(\gamma)$ is $H'(\gamma)=3U^2\gamma^2-4U\tau_0\gamma+\tau_0^2+Uq_1^*$. The vertex coordinates of $H'(\gamma)$ is $\left(2\tau_0/3U, Uq_1^*-\tau_0^2/3\right)$. According to the property of a cubic function, we obtain that $H(\gamma)$ is increasing in γ when $Uq_1^*-\tau_0^2/3\geqslant 0$, i.e., $3Uq_1^*-\tau_0^2\geqslant 0$. When: $Uq_1^*-\tau_0^2/3<0$, i.e., $3Uq_1^*-\tau_0^2<0$, let $H'(\gamma)=0$, we can obtain two roots of this equation: i.e., $2\tau_0+\sqrt{\tau_0^2-3Uq_1^*}/3U$ and $2\tau_0-\sqrt{\tau_0^2-3Uq_1^*}/3U$. According to the property of cubic function and $\gamma>0$, we obtain that $H(\gamma)$ is decreasing in γ with:

$$\gamma\in\left(\frac{2\tau_0-\sqrt{\tau_0^2-3Uq_1^*}}{3U},\frac{2\tau_0+\sqrt{\tau_0^2-3Uq_1^*}}{3U}\right)$$

and $H(\gamma)$ is increasing in γ with:

$$\gamma\in\left(0,\frac{2\tau_0-\sqrt{\tau_0^2-3Uq_1^*}}{3U}\right]\cup\left[\frac{2\tau_0+\sqrt{\tau_0^2-3Uq_1^*}}{3U},+\infty\right).$$

This completes the proof. ■

P5 indicates that more sensitive the customer to the carbon emissions (greater γ), more reduction of total carbon emissions of the manufacturer in most circumstances. This means that the government investments in training environmental awareness of customers have positive effect on carbon emissions reduction of firms. The stronger customer environmental awareness, the better firms' carbon reduction. However, it is worth noting that enhancing the environmental awareness of customers does not increase but decrease the carbon emissions reduction of the manufacturer in some circumstances. The reason for this phenomenon is as follows. There are two factors that affect the total carbon emissions of the manufacturer, including unit carbon emissions and the optimal production quantity. Obviously, the optimal unit carbon emissions of the manufacturer is decreasing in γ. However, the relationship between optimal production quantity of the manufacturer and γ is not sure. According to the expression $q^* = z^* + (a - bp^* - \gamma\tau^*)$, we know that q^* is decreasing in γ and τ^*. So the optimal production quantity of the manufacturer is increasing in γ under certain conditions and is decreasing in γ for another circumstance. Therefore, enhancing the environmental awareness of customers will decrease the carbon emissions reduction of the manufacturer when the effects of unit carbon emissions and the optimal production quantity on the total carbon reduction of the manufacturer are reverse. This conclusion is very interesting and implies that the government should pay attention to the carbon reduction behavior when investing in propaganda environmental protection and adjusting propaganda strategy once carbon emissions of the firms rise is founded.

We analyze the effects of change of customer demand from price-sensitive to carbon emissions-sensitive on the optimal strategies and total carbon emissions of the manufacturer. What effect does the change of customer demand on the maximum expected profit of the manufacturer? Next proposition will answer this question.

P6. $E\left[\pi_1\left(z_1^*, p_1^*\right)\right] > E[\pi(z^*, p^*, \tau^*)]$.

Proof. $E\left[\pi_1\left(z_1^*, p_1^*\right)\right] - E[\pi(z^*, p^*, \tau^*)] = (p^* - c)\gamma\tau^* + U^2 t\gamma^2 > 0$, then $E\left[\pi_1\left(z_1^*, p_1^*\right)\right] > E\left[\pi\left(z^*, p^*, \tau^*\right)\right]$. This completes the proof. ■

P6 shows that the maximum expected profit of the manufacturer reduces when the customer demand changes from price-sensitive to carbon emissions-sensitive. There are two reasons to explain this situation. On the one hand, in response to the demand change, the manufacturer must make green technology investments to reduce unit carbon emissions; on the other hand, some customers will give up for the carbon emissions of the products. The maximum expected profit of the manufacturer reduces under the joint action of the two reasons.

6. Numerical results

In this section, we provide a numerical study to illustrate the feasibility of the analytical models and analyze the impact of customers' carbon sensitive degree (γ) on the optimal strategies, total carbon emissions and maximum expected profit of the manufacturer. we specify that $a = 100$ unit, $b = 2$, $\varepsilon \sim N(0, 9)$, $\tau_0 = 2$ unit, $t = 90$, $v = 17$ unit, $c = 2$ unit and $s = 1$ unit. Then, we derive the optimal pricing $p_1^* = p^* = 5$ and inventory factors $z_1^* = z^* = 2.02$ of the manufacturer in price-sensitive and carbon emissions-sensitive demand, respectively. We also can obtain the optimal production quantity, unit carbon emissions, the total carbon emissions and maximum expected profit of the manufacturer in price-sensitive and carbon emissions-sensitive demand, as shown in Figures 1-3.

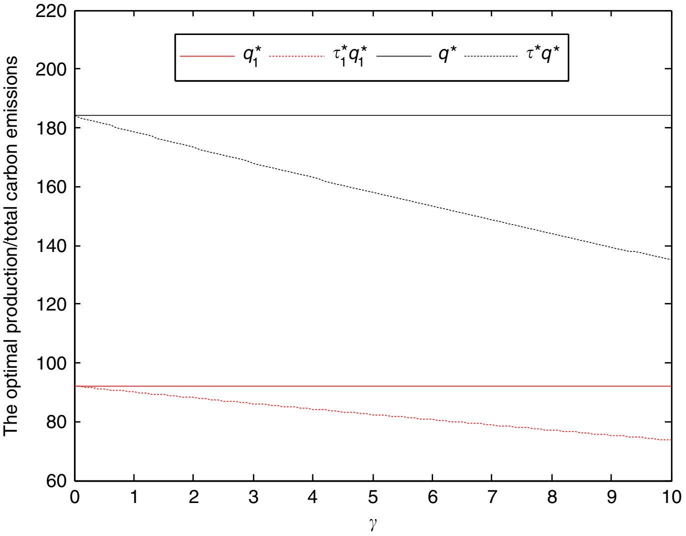

Figure 1.
Effect of γ on the optimal production quantity and the total carbon emissions

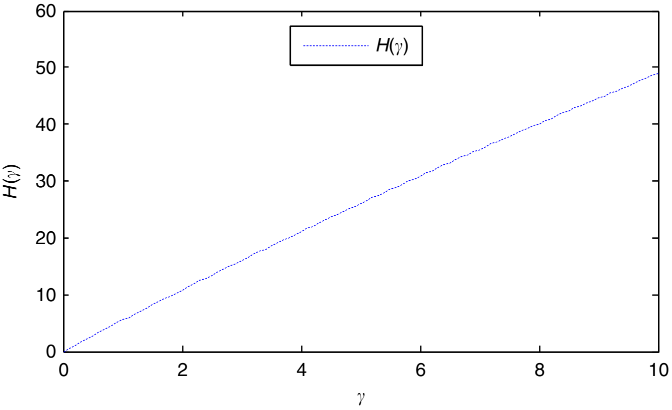

Figure 2.
Effect of γ on $H(\gamma)$

Figure 1 demonstrates the effect of γ on the optimal production and total carbon emissions of the manufacturer. It shows that customers' carbon sensitive degree (γ) has no effect on the optimal production and total carbon emissions of the manufacturer in price-sensitive demand. However, with the increase of γ, the optimal production and total carbon emissions of the manufacturer in carbon emissions-sensitive demand are decreasing. The finding means that greater γ will result in more green technology investment.

Figure 2 demonstrates the effect of γ on the total carbon emissions reduction ($H(\gamma) = \tau_1^* q_1^* - \tau^* q^*$ represents the total reduction of carbon emissions of the manufacturer). According to the value of related parameters specified in this section, we have $3Uq_1^* - \tau_0^2 = 0.60 \geqslant 0$. Hence, more sensitive the customer to the carbon

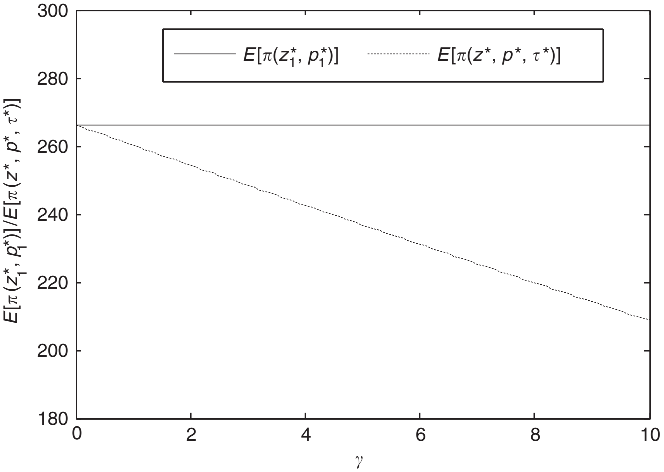

Figure 3.
Effect of γ on the maximum expected profit

emissions (greater γ), more reduction of total carbon emissions of the manufacturer in this situation. The result is in line with the *P5*.

Figure 3 shows that the manufacturer's maximum expected profit with price-sensitive demand is greater that with carbon emissions demand. From Figure 3, we also find that the manufacturer's maximum expected profit with price-sensitive demand is decreasing in γ. From Figures 2 and 3, we can obtain that the increasing γ will reduce the total carbon emissions, but it is at the expense of decreasing the manufacturer's maximum expected profit.

7. Conclusions

In the practice of firms, there are two significant changes for customer demand: one is strategic customer behavior and another is carbon emissions-sensitive demand. Combined with the two changes of customer demand, this paper examines the optimal operation strategies of the manufacturer. Then, we analyze the effects of carbon emissions-sensitive demand on the optimal strategies, the total carbon emissions and the maximum expected profit of the manufacturer.

When the customer demand changes from price-sensitive to carbon emissions-sensitive, we find that: the optimal pricing strategies keep unchanged; the optimal production quantity and unit carbon emissions reduce; the total carbon emissions also reduces. However, it is interesting that the carbon emissions reduction is not increasing in carbon emissions-sensitive degree of customers. Whether it is increasing or decreasing in carbon emissions-sensitive degree of customers depends on the relationship of model parameters. We also find that the maximum expected profit of the manufacturer reduces when the customer demand changes from price-sensitive to carbon emissions-sensitive. The numerical study shows that change of customers' carbon emissions-sensitive degree have influence on the manufacturer's production decision, green technology investment and maximum expected profit. With the increasing customers' carbon emission-sensitive degree, the manufacturer's production and maximum expected profit will decrease, but the manufacturer's green technology investment will increase.

In order to reduce carbon emissions, almost all of the governments will implement carbon emissions policy (such as cap tax, cap and trade, etc.) to regulate firms' carbon emission behavior. The implementation of carbon emissions policy have a knock-on effect on firms' operation decisions. However, our work does not take the carbon emissions policy into consideration. Hence, one key research direction is to examine the firms' optimal operation decisions by incorporating carbon emissions policy into our model. Second, we implement the research based on the newsvendor model framework. However, the supply chain environment gets more close to the actual situation. Another future research direction is to examine the firms' optimal operation strategies with strategic customer behavior and carbon emissions-sensitive random demand in low carbon supply chain.

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