Hindawi
Discrete Dynamics in Nature and Society
Volume 2018, Article ID 2452406, 15 pages
https://doi.org/10.1155/2018/2452406

Research Article

Optimal Strategies for Manufacturers with the Reference Effect under Carbon Emissions-Sensitive Random Demand

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Received 21 August 2018; Accepted 17 September 2018; Published 9 October 2018

Academic Editor: Lu Zhen

In this paper, we study the optimal strategies for a newsvendor system with joint reference effect, carbon emissions-sensitive random demand, and strategic customers' behavior. The newsvendor's decisions are to determine the selling price, production quantity, and carbon emissions under exogenous and endogenous price cases, respectively. We also explore how the loss aversions affect the newsvendor's decisions. It is shown that the newsvendor has a uniquely optimal policy. The influence of the reference effect makes the final decisions deviate from the optimal solutions of the classical model. Furthermore, the sensitivity analysis indicates that the loss aversions have a great impact on the newsvendor's decisions. Finally, more managerial implications are derived by numerical simulations.

1. Introduction

Environment and resource issues are the hot spot and new focus of games in the 21st century. Efforts of all countries in the world on energy conservation and emission reduction have become one of the most efficient methods to win the competition for economic strength and the dominance of the rules governing international trade. In particular, the issue of global warming has received increasing attention. Since the main cause of global warming is carbon dioxide emissions, controlling carbon emissions has become an effective way to curb global warming (http://www.nrdc.org/globalwarming/gsteps.asp). With the popularity of carbon footprint and the improvement of consumer's awareness of environmental protection, consumers are concerned about the product's carbon emissions besides the price [1]. Researchers recognize that consumers are passionate about the product's carbon footprint labeling and willing to pay higher prices than regular products [2, 3]. In the face of carbon sensitive consumers, enterprises will invest in green technology to improve their own profits [4].

In business practice and academic research, a growing number of people find that optimal solutions of the classic newsvendor model deviate from actual operation and management decisions [5–7]. We know that the classic newsvendor model is based on a strong assumption that the newsvendor is completely rational. But in reality the newsvendor is not completely rational, often showing a lot of psychological behaviors. Due to these behavioral factors, final decisions of the newsvendor deviate from the optimal solution of the classic model. At present, researches on the behavior factors of the newsvendor mainly include bounded rationality [8–10], decision bias [11, 12], the reference effect [13, 14], overconfidence [15, 16], and the fairness [17, 18]. The reference effect has been extensively studied in recent years. Prior studies find that the reference effect of prospect theory plays an important role in the analysis of newsvendor's decision-making behavior [13].

In order to avoid the loss of the surplus stock, enterprises usually clean up excess products at a discount price. With the help of smartphones, computers, and various price trackers, consumers find it easier than ever to get pricing information, to decipher sales patterns, and to pick the best time to buy. The behavior that consumers choose to wait for lower prices to buy to maximize consumer surplus is defined as strategic consumer behavior [19–22]. Du and Chen [23] point out that strategic consumer behavior will diminish firms' opportunity to adopt price skimming strategy. Past studies empirically

Table 1: Comparisons with other recent researches.

Research papers	Carbon emissions	Reference effect	Strategic customer behavior	Stockout loss
Wu et al. [20]		√	√	
Jiang and Chen [25]	√		√	
Cao et al. [26]		√		√
Liu et al. [14]		√	√	
Our paper	√	√	√	√

confirm that the ignorance of strategic customer behavior by retailers will result in about 20 percent losses of their total profit [24].

At present, there are few studies to consider joint reference effect, strategic customer behavior, and the reference effect in supply chain operation management. Previous literatures show that it is very meaningful to study the newsvendor's reference effect and consumers' strategic behavior, which are the two-way behavioral factors that influence the operation management [14]. However, in the literatures integrating strategic customer behavior and the reference effect, they only consider one psychological loss (i.e., clearance loss). We choose an appropriate reference point of newsvendor's profit so that the model can be combined with both clearance loss and stockout loss. In fact, we find that if the newsvendor's sensitivities to these two kinds of losses caused by the reference effect are different, optimal decisions are quite different. All in all, our work is different from the previous studies, as we innovatively integrate the reference effect, two kinds of psychological losses caused by reference effect and strategic customer behavior.

As shown in Table 1, we compare the relevant literatures closely related to our work.

Wu et al. [20] examine the reference effect on a retailer's dynamic pricing and inventory strategies with strategic consumers. They find that consumers can learn about the history of the retailer's discounted prices, form their reference prices, and pick the best time to buy. Different from their research, we study the enterprise's reference effect. Firstly, the enterprise will set a profit reference point as his expectation. Then he would compare the difference between actual profits and the reference point. Finally, the enterprise will make decisions based on the expected total utility that includes actual profits and psychological satisfaction.

Jiang and Chen [25] study newsvendor decision problem with strategic consumer behavior under carbon emissions-sensitive demand. They conclude that if demand changes from price-sensitive to carbon emissions-sensitive, the manufacturer's optimal prices are the same but optimal production, optimal unit carbon emissions, and maximum expected profit go down. Although they consider the behavioral factor of strategic consumers, they assume that the manufacturer is perfect rationality. Thus we introduce the manufacturer's reference effect into the model and analyze the influence of this behavioral factor on his decisions.

Cao et al. [26] investigate the newsvendor model with the reference effect and derive joint inventory, pricing, and advertising decision. They show that the loss-averse solutions are different from the loss-neutral solutions since loss aversion behaviors of a newsvendor affect the order quantity, pricing, and advertising decisions; specifically, the order quantity increases with the stockout aversion parameter and decreases with the surplus aversion parameter. When the price is endogenous, they set some variables that are fixed. Their work is not in a context of energy-saving and emission-reduction. We think an extended study based on their model with carbon emissions-sensitive demand is interesting. Besides that, our study differs from their study in that we introduce strategic consumer behavior to study newsvendor's decisions under endogenous price case.

Liu et al. [14] utilize the reference effect to model newsvendor's decision-making behavior with strategic customers. They find that the ordering quantity and the pricing strategy are influenced by newsvendor's reference effect, loss aversion, product cost, and salvage price. We choose a different reference point from them and analyze the influences of two kinds of losses caused by the reference point on the newsvendor's decisions. In fact, as the newsvendor's sensitivities to these two kinds of losses are different, his decisions will be quite different.

The reference effect in the newsvendor system has been widely studied. However, to our knowledge, few studies investigate influences of the reference effect on low-carbon manufacturing with strategic customers behavior. Our study aims to address the above knowledge gaps in the operations management literature. The newsvendor usually chooses one reference profit point according to the market environment and his management strategy. So the total utility of newsvendor consists of the realized profit and a psychological component that captures how the realized payoff compares with the reference profit point. Only when the production quantity equals the demand can the newsvendor achieve his maximum profit. If the newsvendor regards the theoretical maximum profit as the reference point and the production quantity is not equal to the demand, he may feel extra losses in addition to the actual economic loss. Due to the reference effect, we consider two kinds of losses, namely, (i) the clearance loss (caused by overproduction) and (ii) the stockout loss (caused by underproduction). We investigate the newsvendor's joint production, pricing, and carbon emissions decision problem in two cases of exogenous and endogenous price, respectively. Furthermore, we want to answer the following questions.

(1) Is there an optimal solution in this newsvendor system?

(2) Does the reference effect have an impact on newsvendor's decisions? If there is an impact, how does it affect newsvendor's decisions?

(3) What advices should we give to this newsvendor?

Table 2: Notation.

Notation	Explanation
p	Unit price
c	Unit product cost
v	Unit salvage price of the product which is an exogenous variable
q	The production quantity of the manufacturer
s	Unit shortage cost
$D(e,\varepsilon)$	The random demand and $D = a - bp - ke + \varepsilon$
$f(\cdot)$	Probability density function of ε
$F(\cdot)$	Distribution function of ε
u	The customers' utility from consuming the product
e_0	Unit carbon emissions without green technology investment
e	Unit carbon emissions with green technology investment
h	The coefficient of green technology investment
$I(e)$	Green technology investment

We find that there is always a unique optimal solution. The optimal production quantity of the manufacturer is different from that of the classic model. The manufacturer's optimal production quantity decreases with the clearance loss aversion α but increases with the stockout loss aversion β. When the price is exogenous, the optimal unit carbon emission is independent of the reference effect. Nevertheless, the optimal unit carbon emission decreases with α but increases with β when the price is endogenous. And, the optimal unit price increases with α but decreases with β. We also find that when $\alpha = \beta$, the manufacturer's optimal production is a fixed value and is equal to the value without the reference effect. If the newsvendor's sensitivities to these two kinds of losses are different, there is a big divergence in his decisions.

The rest of this paper is structured as follows. Section 2 specifies the model. Section 3 analyzes the model under the exogenous price. Section 4 solves the newsvendor system under the endogenous price. Section 5 conducts numerical simulations. Section 6 concludes the work.

2. The Model

In this paper, the notations are included in Table 2. We set up a newsvendor model with the reference effect, which includes a manufacturer who sells products to consumers directly under carbon emissions-sensitive random demand. In the context of the above, we investigate production, pricing, and carbon emissions strategies for the manufacturer. Because of the influence of psychological behavior, the manufacturer is driven by the economic payoff and loss aversion. Referring to previous studies [13, 27, 28], we characterize the total utility of the manufacturer as follows:

$$\textit{Utility} = \textit{economic payoff} + \textit{psychological satisfaction}. \quad (1)$$

Utility consists of the realized profit and a psychological component that captures how the realized payoff compares with the reference payoff. We will further present the profit and psychological satisfaction of the manufacturer in detail in the following sections.

2.1. Economic Payoff. In this section, we assume that each customer purchases one product at most. In the joint production, pricing, and carbon emissions, the manufacturer sets the production quantity q at a unit product cost c and sells directly to consumers at a unit price p. We assume that q cannot be observed by the consumers. As the selling season is very short, the inventory cannot be replenished during the sales period. We suppose that the consumers' demand is sensitive to carbon emissions, which is affected not only by the price p but also by unit carbon emission e. Referring to previous studies [25, 29], we suppose the demand function of the manufacturer as follows:

$$D(p,e,\varepsilon) = a - bp - ke + \varepsilon, \quad (2)$$

where $a > 0$ denotes potential market size and $b \geq 0$ and $k > 0$ represent the demand sensitivity of unit price and unit carbon emissions, respectively. ε is a random variable and represents the stochastic part of the market, $\varepsilon \in [A, B]$. The probability density function and cumulative distribution function (CDF) of ε are $f(x)$ and $F(x)$, respectively, where $f(x) > 0$ on $[A, B]$. The unique complementary and inverse functions of CDF are $\overline{F}(x) = 1 - F(x)$ and $F^{-1}(x)$, respectively. Further, $F(x)$ is twice differentiable, strictly increasing, and absolutely continuous. $F(x)$ satisfies an increasing failure rate (IFR), i.e., $\partial g(x)/\partial x > 0$, where $g(x) = f(x)/\overline{F}(x)$ [30]. In order to ensure positive demand within certain range of p, we require that $A > -a$.

In response to the change of customers demand, the manufacturer can invest in green technology to reduce carbon emissions per unit product. Initial unit carbon emission is e_0, and the unit carbon emissions after green technology investments of the manufacturer is e, $e_0 > e$. Referring to previous studies [25, 29], we suppose that the manufacturer is struggling to reduce unit carbon emissions e_0 to a level e with cost of effort given by

$$I(e) = h(e_0 - e)^2, \quad (3)$$

where, h is a positive coefficient and captures the manufacturer's efficiency in carbon emissions reduction. Obviously, if the manufacturer wants to reduce unit carbon emissions to a relatively low level, he needs to increase investment in green technology. So the manufacturer needs to weigh the benefits of rising demand and technology investments.

Moreover, if there is a consumer demand that is not met at the end of the selling season, a shortage cost s will arise. On the contrary, if there is surplus stock at the end of the selling season, the manufacturer will clean up products with the salvage price v. Because the parameters must meet some conditions to make sense, we assume: $p > c > v > 0$, $s > c$.

Therefore, the profit function of the manufacturer, denoted as π, can be written as

$$\pi = \begin{cases} (p-c)D-(c-v)(q-D)-h(e_0-e)^2, & D<q, \\ (p-c)q-s(D-q)-h(e_0-e)^2, & D \geq q. \end{cases} \quad (4)$$

For convenient calculation and clear results, we introduce the inventory factor $z = q-(a-bp-ke)$ into the model. It represents the risk-free inventory level [25, 26, 31]. So the profit function of the manufacturer can be rewritten as

$$\pi = \begin{cases} (p-v)(a-bp-ke+\varepsilon)-(c-v)(a-bp-ke+z)-h(e_0-e)^2, & \varepsilon < z, \\ (p-c+s)(a-bp-ke+z)-s(a-bp-ke+\varepsilon)-h(e_0-e)^2, & \varepsilon \geq z. \end{cases} \quad (5)$$

When the stochastic part of the market ε is lower than the risk-free inventory level z, the profit function of the manufacturer is $(p-v)(a-bp-ke+\varepsilon)-(c-v)(a-bp-ke+z)-h(e_0-e)^2$. When ε is greater than z, the profit function of the manufacturer can be rewritten as $(p-c+s)(a-bp-ke+z)-s(a-bp-ke+\varepsilon)-h(e_0-e)^2$.

2.2. Psychological Satisfaction. Instead of being completely rational, decision makers in real world often show a lot of psychological behaviors. Due to the influence of these psychological behaviors, decision maker's final decisions deviate from optimal solutions of the classical model. The reference effect is an important psychological concept which receives increasing attention in the operation management, especially in behavioral operation management in recent years. Long and Nasiry [13] prove that the newsvendor's reference effect on profits has a significant impact on newsvendor's decision-making behavior. Referring to previous studies [13, 14], we characterize the psychological satisfaction by a piecewise-linear value function as

$$v(y) = \begin{cases} \eta y, & \text{if } y \geq 0, \\ \lambda \eta y, & \text{if } y < 0, \end{cases} \quad (6)$$

where $\eta \in [0,1]$ characterizes the strength of the reference effect, and $\lambda \in [1,\infty)$ is the coefficient of loss aversion. A higher value of η denotes being more sensitive to the deviation of the reference point; the larger λ is, the more the loss aversion of policymakers is.

The manufacturer usually subjectively chooses the profit reference point based on factors such as market environment and his business strategy. Under the above conditions, the theoretical maximum profit of the manufacturer is

$$\pi_{max} = (p-c)D-h(e_0-e)^2. \quad (7)$$

The manufacturer does not choose a negative reference point because the manufacturer seeks to maximize profits. So the manufacturer will choose one point as a reference point for the profit in $[0, \pi_{max}]$.

We regard the theoretical maximum profit as the reference point for the manufacturer, i.e., $\pi_r = \pi_{max} = (p-c)D-h(e_0-e)^2$ [26]. Because the realized profit of the manufacturer is less than his expectation, the manufacturer may feel extra loss in addition to the actual economic loss, i.e., $\pi \leq \pi_r$. From (6), $y = \Delta\pi = \pi - \pi_r \leq 0$, so $v(y) = \lambda\eta y$. The manufacturer's underproduction and overproduction will make the actual profit lower than the reference point, and the manufacturer may have a different response to these two kinds of losses.

When $q > D$, the loss caused by overproduction is defined as the clearance loss $\Delta\pi_1$. We define the clearance loss aversion utility as $v(\Delta\pi_1) = \lambda_1\eta\Delta\pi_1 \triangleq \alpha\Delta\pi_1$, where α shows the degree of decision-makers' aversion on the clearance loss with the reference effect and $\alpha \geq 0$. So, the clearance loss aversion utility can be denoted by

$$v(\Delta\pi_1) = \alpha\Delta\pi_1 = -\alpha(c-v)(q-D). \quad (8)$$

Similarly, when $q \leq D$, the loss caused by underproduction is defined as the stockout loss $\Delta\pi_2$. We define the stockout loss aversion utility as $v(\Delta\pi_2) = \lambda_2\eta\Delta\pi_2 \triangleq \beta\Delta\pi_2$, where β shows the degree of decision-makers' aversion on the stockout loss with the reference effect and $\beta \geq 0$. So, the stockout loss aversion utility can be denoted by

$$v(\Delta\pi_2) = \beta\Delta\pi_2 = -\beta(p-c+s)(D-q). \quad (9)$$

So, in this paper, $v(y)$ can be written as

$$v(y) = \begin{cases} -\alpha(c-v)(q-D), & \textit{if } q > D, \\ -\beta(p-c+s)(D-q), & \textit{if } q \leq D. \end{cases} \quad (10)$$

If $\alpha = \beta$, the manufacturer has the same sensitivity to the clearance loss and the stockout loss. When $\alpha > \beta$, the manufacturer is more sensitive to the clearance loss; that is, he pays more attention to the actual loss. On the contrary, when $\alpha < \beta$, the manufacturer is more sensitive to the stockout loss; that is, he pays more attention to the potential loss.

2.3. The Total Utility. Thus the total utility function of the manufacturer is

$$U = \pi + v(\Delta\pi_i), \quad i = 1, 2. \tag{11}$$

Furthermore, if the actual demand is lower than the production quantity, that is, $q > D$, the total utility function is

$$U_{q>D} = \pi_{q>D} + v(\Delta\pi_1). \tag{12}$$

If the actual demand is higher than the production quantity, that is, $D \geq q$, the total utility function is

$$U_{D\geq q} = \pi_{D\geq q} + v(\Delta\pi_2). \tag{13}$$

Therefore, the total utility function of the manufacturer can be expressed as

$$U = \begin{cases} (p-c)D - (1+\alpha)(c-v)(q-D) - h(e_0-e)^2, & D < q, \\ (p-c)q - s(D-q) - \beta(p-c+s)(D-q) - h(e_0-e)^2, & D \geq q. \end{cases} \tag{14}$$

Similar to (5), we rewrite the above function with the inventory factor $z = q - (a - bp - ke)$ as

$$U = \begin{cases} (p-c)(a-bp-ke+\varepsilon) - (1+\alpha)(c-v)(z-\varepsilon) - h(e_0-e)^2, & \varepsilon < z, \\ (p-c)(a-bp-ke+z) - s(\varepsilon-z) - \beta(p-c+s)(\varepsilon-z) - h(e_0-e)^2, & \varepsilon \geq z. \end{cases} \tag{15}$$

The expected total utility function of the manufacturer is

$$\begin{aligned} E(U) = {} & (p-c)(a-bp-ke+\mu) - h(e_0-e)^2 \\ & - (1+\alpha)(c-v)\Lambda(z) \\ & - (1+\beta)(p-c+s)\Theta(z), \end{aligned} \tag{16}$$

where, $\mu = \int_A^B xf(x)dx$, $\Lambda(z) = \int_A^z (z-x)f(x)dx$, $\Theta(z) = \int_z^B (x-z)f(x)dx$.

Our ultimate goal is to maximize expected total utility of the manufacturer. In the following, we will explore optimal decisions of the manufacturer under price exogenous and price endogenous cases and discuss how the reference effect affects the manufacturer's decisions.

3. Analysis under the Exogenous Price

In some industries, the selling price of products is determined by external factors such as competitive market or government, and manufacturers do not have the ability to make the selling price of products. Low-carbon products usually involve the national economy and the people's livelihood. In order to guarantee the rights and interests of the people, in many countries, this kind of resources is priced by the government. Because of the fierce competition in the market today, the exogenous price is also common. In this case, we seek the optimal production quantity and the optimal carbon emissions. As the manufacturer has no pricing power, he can only determine production and carbon emissions by maximizing expected utility. In this case, the strategic consumer behavior has no effect on the decisions of the manufacturer.

Given the price, we explore best decisions of the manufacturer to achieve his maximum expected utility. We can get the following propositions. We note that proofs of these propositions here and after can be founded in the Appendix.

Proposition 1. *When the price p is exogenous, there is a unique optimal inventory factor z^*, and it meets the following condition:*

$$F(z^*) = \frac{(1+\beta)(p-c+s)}{(1+\alpha)(c-v) + (1+\beta)(p-c+s)}, \tag{17}$$

and given price p, there is a unique optimal unit carbon emissions e^*, that is,

$$e^* = e_0 - \frac{k(p-c)}{2h}. \tag{18}$$

From Proposition 1, we can see that when the price is exogenous, the optimal unit carbon emission is independent of the reference effect. However, when the price is exogenous, the optimal inventory factor is related to aversions of the clearing loss and stockout loss. We also find that as the demand sensitivity of unit carbon emissions k increases, the optimal unit carbon emission e^* falls, holding all else constant. This provides an economic explanation for government to launch a massive campaign to educate all citizens to improve their awareness of environmental protection.

We can further obtain the inventory factor as follows:

$$z^* = F^{-1}\left(\frac{(1+\beta)(p-c+s)}{(1+\alpha)(c-v) + (1+\beta)(p-c+s)}\right). \tag{19}$$

The production quantity of the manufacturer meets the following condition: $q = z + (a - bp - ke)$. With the above *analysis, we can get the optimal production quantity of the manufacturer* q^*,

$$q^* = a - bp - k\left(e_0 - \frac{k(p-c)}{2h}\right) + F^{-1}\left(\frac{(1+\beta)(p-c+s)}{(1+\alpha)(c-v)+(1+\beta)(p-c+s)}\right). \quad (20)$$

We find that the optimal production quantity of the manufacturer is related to the market environment, the sensitivity of consumers to the price and carbon emissions, the efficiency in carbon emissions reduction, and the manufacturer's loss aversions. Specifically, the optimal production quantity increases in potential market size. The manufacturer adjusts the optimal output according to the distribution of random variables in demand. And, consumers' sensitivities for the price and carbon emissions have negative influences on the optimal production. Then, we will discuss the effect of loss aversions on the optimal production.

Proposition 2. *When the manufacturer has the same sensitivity of aversion between the clearance loss and the stockout loss ($\alpha = \beta$), the optimal production quantity is not related to the above loss aversion behavior, and it is the same as the optimal production quantity of the manufacturer without the reference effect.*

For the above interesting phenomenon, this is due to the difference between the two kinds of loss aversions to the optimal production. When the manufacturer showed the same feeling of aversion for two kinds of losses, the two effects counteract each other. Cao et al. [26] derive a similar result for the loss aversion caused by the newsvendor's reference effect in terms of the exogenous price.

Proposition 3. *When the price is exogenous and α is not equal to β, the manufacturer's optimal production quantity decreases with α but increases with β.*

From Proposition 3, we verify the explanation of Proposition 2. We find that the optimal output decision is different from the optimal solution of the classic model on account of the manufacturer's reference effect. Zhang et al. [30] find the newsvendor's optimal order quantity decreases in the loss aversion coefficient in terms of the exogenous price. However, we find that when the manufacturer is more sensitive to the clearance loss, he will reduce the production quantity accordingly. While he will increase the output in order to eliminate the potential loss if he is more sensitive to the stockout loss.

4. Analysis under the Endogenous Price

When the price is endogenous, we assume that the manufacturer faces strategic consumers. The whole sales period is divided into two phases: in the first phase, the manufacturer sells the products at full price, while, in the second phase, the manufacturer empties the products at the salvage price. Frequent discounts make consumers more selective when they buy products. As consumers can foresee that the product

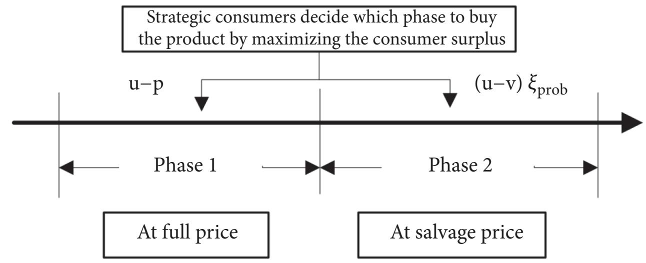


Figure 1: The sequence of events.

may be discounted in the future, they choose to wait at the full price and to buy when the product is discounted. The behavior that consumers choose to wait for buying at lower prices to maximize consumer surplus is known as strategic consumer behavior [14, 25].

We assume that consumers are homogeneous; that is, all consumers have the same utility to the product, u. The utility satisfies the following condition: $u > p$. This condition states that there is a positive consumer surplus when a product is sold to customers. Further, for consumers, the utility of the product in the first or second phase will remain unchanged. Strategic consumers can buy discounted products at the second phase with a certain probability. The beliefs of consumers in this probability is ξ_{prob}. Strategic consumers determine the stage of purchasing a product by comparing the expected consumer surplus over the two phases. Figure 1 shows the sequence of events. The consumers' reservation price is r, which is the private information of consumers and cannot be observed by the manufacturer. When the consumer reservation price is larger than the retail price, the consumer may buy the product at full price. The beliefs of the manufacturer over the consumers' reservation price is δ_r.

Obviously, the manufacturer will set $p = \delta_r$ to maximize the profit. According to the definition of rational expectation equilibrium [32, 33], the solution of rational expectation equilibrium (p, z, r, δ_r, ξ_{prob}) must meet the following conditions: (i) $r = u - (u - v)\xi_{prob}$; (ii) $p = \delta_r$; (iii) z, e are a solution of $\text{argmax}_{z,e} E(U)$; (iv) $\xi_{prob} = F(z)$; and (v) $\delta_r = r$.

Conditions (i), (ii), and (iii) show that the manufacturer and strategic consumers will choose the action to maximize their own utility. Conditions (iv) and (v) ensure that the solution satisfies the rational expectation hypothesis; that is, the actual economic situation is consistent with the people's expectation. Many researchers denote that the nature of the problem is a static game and the solution of rational expectation equilibrium satisfies the definition of Nash equilibrium [33, 34]. From the above analysis we can get

$$p = u - (u - v) F(z). \quad (21)$$

Price p is a function of $F(z)$. We have proved that given p, the total utility function of the manufacturer $E[U(z, p, e)]$ is jointly strict concave in z and e. That is, there are unique z, e which maximize $E[U(z, p, e)]$. So, we can obtain

$$\begin{aligned} & p = u - (u - v) F(z), \\ & (1+\beta)(p - c + s)(1 - F(z)) - (1+\alpha)(c - v) F(z) \\ & \quad = 0, \\ & 2h(e_0 - e) - k(p - c) = 0. \end{aligned} \tag{22}$$

Solving (22), we can derive the optimal production quantity, the optimal retail price, and the optimal carbon emissions of the manufacturer.

Proposition 4. *When the price p is endogenous and consumers have strategic behaviors, there is a unique optimal inventory factor z^*, and it meets the following condition:*

$$F(z^*) = \frac{(1+\beta)(2u - c - v + s) + (1+\alpha)(c - v) - \varphi(\alpha,\beta)}{2(1+\beta)(u - v)}, \tag{23}$$

where $\varphi(\alpha,\beta) = (((1+\beta)(v + s - c) + (1+\alpha)(c - v))^2 + 4(1+\alpha)(1+\beta)(c - v)(u - v))^{1/2}$.

From Proposition 4, when the price p is endogenous and consumers have strategic behavior, the loss aversions affect the optimal inventory factor. And manufacturers pay more attention to the product value determination of consumers; that is, he will adjust the risk-free inventory level according to the utility of consumers from the product.

Proposition 5. *When the price p is endogenous with strategic customers behavior, there is a unique optimal unit price p^*,*

$$p^* = u - (u - v) F(z^*), \tag{24}$$

and the unique optimal unit carbon emissions e^*,

$$e^* = e_0 - \frac{k(p^* - c)}{2h}. \tag{25}$$

From Proposition 5, we can find that the optimal unit price is related to the loss aversions, which is caused by considering the reference effect. Because the optimal unit carbon emission is related to unit price, in this case, the reference effect will affect the optimal carbon emissions of products. We find that as the demand sensitivity of unit carbon emissions k increases, the optimal unit carbon emission e^* falls, holding all else constant. Similar to previous literature such as [25], the manufacturer will be keen on green technology investment demonstrably with carbon emissions-sensitive random demand.

For convenient calculation and clear results, we define $\Psi(\alpha,\beta) \triangleq ((1+\beta)(2u - c - v + s) + (1+\alpha)(c - v) - \varphi(\alpha,\beta))/(2(1+\beta)(u - v))$. We can further obtain the inventory factor, $z^* = F^{-1}(\Psi(\alpha,\beta))$. According to $q = z + a - bp - ke$, we can get the optimal production quantity of the manufacturer q^*,

$$\begin{aligned} q^* = {} & F^{-1}(\Psi(\alpha,\beta)) + a - ke_0 - \frac{k^2 c}{2h} \\ & + \left(\frac{k^2}{2h} - b\right)(u - (u - v) F(z^*)). \end{aligned} \tag{26}$$

When the price p is endogenous and consumers have strategic behaviors, the consumers' utility from consuming the product affects the optimal production quantity. When $k^2/2h > b$, the optimal production quantity increases with the consumers' utility, while the optimal production quantity decreases with the consumers' utility if $k^2/2h \le b$.

We can find that when $\alpha = \beta$, $F(z^*) = ((2u - c - v + s) + (c - v) - \varphi(\alpha,\beta))/(2(u - v))$, where $\varphi(\alpha,\beta) = (((v + s - c) + (c - v))^2 + 4(c - v)(u - v))^{1/2}$. We find that when the manufacturer has the same sensitivity of aversion between the clearance loss and the stockout loss, optimal decisions are not related to the above loss aversion behavior, and it is the same as decisions of the manufacturer without the reference effect.

When $\alpha \neq \beta$, we introduce the Cramer's Rule to determine the influence of the manufacturer's loss aversion on his decisions. By using the Cramer's Rule, we can get $\partial p/\partial\alpha > 0$, $\partial F(z)/\partial\alpha < 0$, $\partial p/\partial\beta < 0$, and $\partial F(z)/\partial\beta > 0$. So the following proposition is obtained.

Proposition 6. *When the price p is endogenous, consumers have strategic behavior, and $\alpha \neq \beta$, the manufacturer's optimal production quantity decreases with α but increases with β. And the optimal unit price increases with α but decreases with β.*

Liu et al. [14] derive a result that the newsvendor' optimal order is a decreasing function of the loss aversion caused by the newsvendor's reference effect in terms of the endogenous price and strategic consumers behavior. However, we find that whether the price is exogenous or endogenous, the reference effect maintains a good consistency on manufacturer's optimal production quantity; that is, q^* decreases with α and increases with β. In addition, when the price p is endogenous and consumers have strategic behavior, the formulation of the optimal price is affected by the reference effect. They also find that the newsvendor's optimal price is an increasing function of the loss aversion caused by the reference effect. Obviously, our conclusion is consistent with their conclusion when we do not consider the stockout loss.

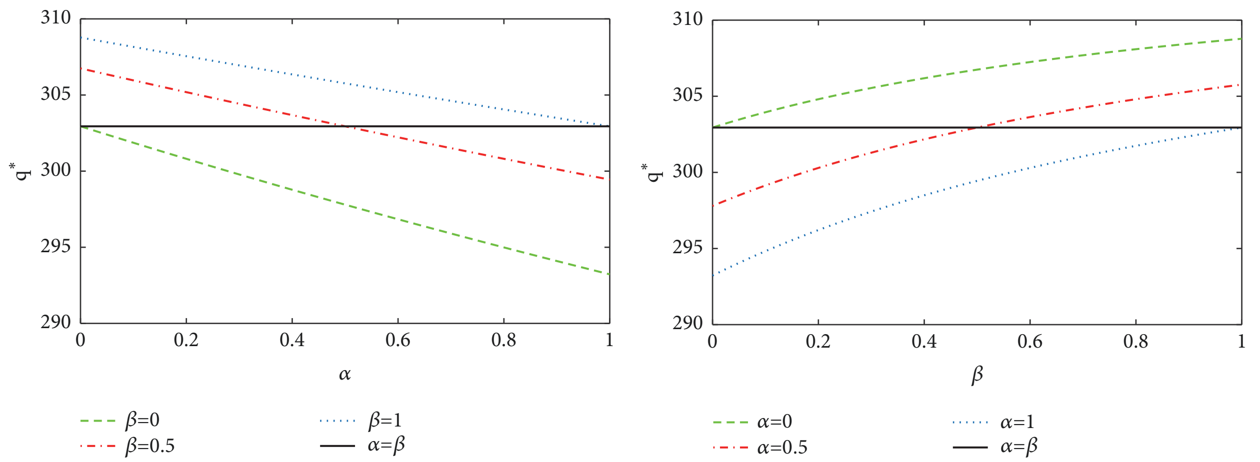
From (25), we can get the following proposition.

Proposition 7. *When the price p is endogenous, consumers have strategic behavior, and $\alpha \neq \beta$, the optimal unit carbon emission decreases with α and increases with β.*

If manufacturer's sensitivities for two loss aversions are different, his reaction to the carbon emissions-sensitive demand is opposite. When the manufacturer is more sensitive to the clearance loss, he is more motivated to invest in green technology to reduce unit carbon emissions. When the manufacturer is more sensitive to the stockout loss, he has a negative attitude towards reducing unit carbon emissions. In the next section, we will conduct numerical experiments to verify the impact of loss aversion caused by the manufacturer's reference effect on his decision making.

5. Numerical Simulations

In this section, we consider numerical simulations to analyze the feasibility of the analysis models, to illustrate the impact of the reference effect on the manufacturer's decision making, and to verify the propositions presented in the last section.



(a) The degree of aversion on the clearance loss

(b) The degree of aversion on the stockout loss

FIGURE 2: The impact of reference effect on the optimal production under the exogenous price.

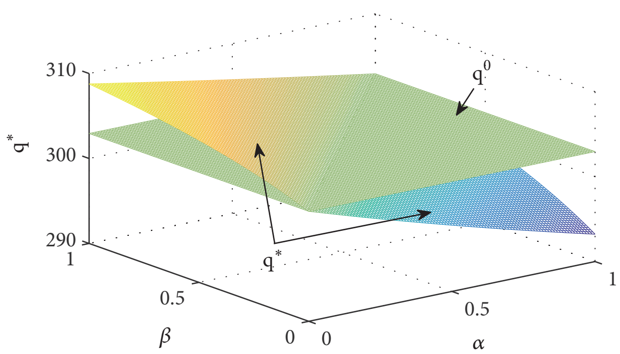


FIGURE 3: The impact of reference effect on the optimal production under the exogenous price.

We refer to the previous research results [25, 26] and specify that $a = 200$, $b = 1.5$, $c = 10$, $v = 5$, $s = 15$, $u = 50$, $e_0 = 20$, $h = 90$, $k = 2$. We also assume that ε follows the uniform distribution, $\varepsilon \sim U[100, 200]$. According to [35, 36], the loss aversion with the reference effect of the newsvendor is usually not greater than 2. Here, we denote that $\alpha, \beta \in [0, 1]$. Then we illustrate the optimal production quantity and carbon emissions under the exogenous price and the endogenous price, respectively. When the price is endogenous, we also analyze the optimal price.

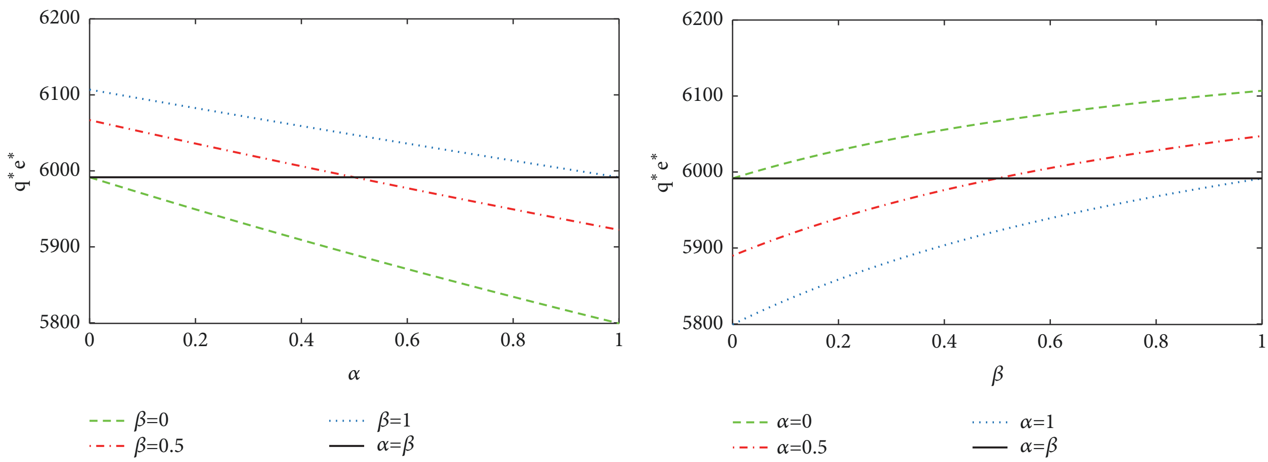
When the price is exogenous, we assume the unit price p is 30. We can get the optimal production quantity and total carbon emissions, which are in Figures 2–5.

From Figures 2 and 3, we have verified some explanations of Propositions 2 and 3. As is illustrated in Figure 2, we find that when $\alpha = \beta$, the manufacturer's optimal production is a fixed value and is equal to the value without considering the reference effect. When the price is exogenous and α is not equal to β, from Figure 2(a) the manufacturer's optimal production quantity decreases with α, while from Figure 2(b) it increases with β. We also find that α will amplify the effect of β on the optimal production quantity, while β will reduce the impact of α on the optimal production quantity. In Figure 3, q^0 represents the optimal production without the reference effect under the exogenous price. We find that when $\alpha < \beta$, that is, when the manufacturer is more sensitive to the stockout loss, the manufacturer's optimal production is higher than the value without the reference effect. Conversely, when the manufacturer pays more attention to the clearance loss, i.e., $\alpha > \beta$, the manufacturer's optimal output is lower than the value without the reference effect. We also find that α will amplify the effect of β on the optimal production quantity, while β will reduce the impact of α on the optimal production quantity.

Because the price is exogenous, optimal unit carbon emission is 19.78 when $p = 30$. From Figures 4 and 5, we can illustrate the impact of reference effect on total carbon emissions under the exogenous price. When α is not equal to β, from Figure 4(a) we find that total carbon emission decreases with α, while from Figure 4(b) it increases with β. When $\alpha = \beta$, total carbon emission is a fixed value. In Figure 5, $q^0 e^0$ represents total carbon emissions without the reference effect under the exogenous price. From Figure 5, when $\alpha < \beta$, total carbon emission is higher than the value without the reference effect. If $\alpha > \beta$, total carbon emissions will be lower than the value without the reference effect.

When the price p is endogenous and consumers have strategic behavior, we can get the optimal price, the optimal production quantity, optimal unit carbon emissions, and total carbon emissions, which are shown in Figures 6–13, respectively.

From Figure 6, we can verify the formulation of Proposition 6; that is, the optimal unit price increases with α (Figure 6(a)) but decreases with β (Figure 6(b)). When $\alpha = \beta$, the optimal unit price is a fixed value and is equal to the value without the reference effect. In Figure 7, p^0 represents the optimal price without the reference effect under the endogenous price. From Figure 7, when $\alpha < \beta$, the optimal unit price is lower than the value that does not consider the reference effect. If $\alpha > \beta$, the optimal unit price will be higher than the value without the reference effect.



(a) The degree of aversion on the clearance loss

(b) The degree of aversion on the stockout loss

FIGURE 4: The impact of reference effect on total carbon emissions under the exogenous price.

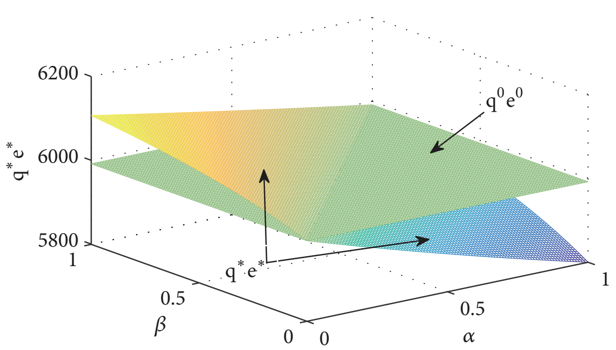


FIGURE 5: The impact of reference effect on total carbon emissions under the exogenous price.

Figures 8 and 9 demonstrate the impact of reference effect on the optimal production quantity under the endogenous price. In Figure 9, q^0 represents the optimal production without the reference effect under the endogenous price. We find the reference effect maintains a good consistency on manufacturer's optimal production quantity q^* whether the price is exogenous or endogenous; that is, (i) when $\alpha = \beta$, q^* is a fixed value and is equal to the value without considering the reference effect (Figure 8), (ii) when $\alpha \neq \beta$, q^* decreases with α (Figure 8(a)) and increases with β (Figure 8(b)), (iii) when $\alpha < \beta$, q^* is higher than the value without the reference effect (Figure 9), and (iv) when $\alpha > \beta$, the result is opposite (Figure 9).

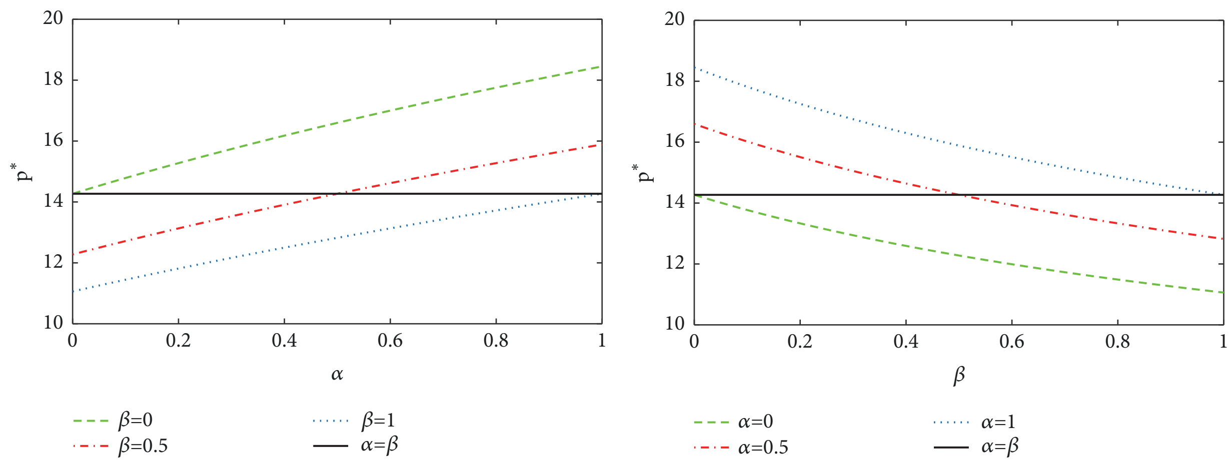
From Figure 10, we find that the optimal unit carbon emission decreases with α (Figure 10(a)) and increases with β (Figure 10(b)) under the endogenous price. That is, when a manufacturer has a pricing power, he has an internal drive to adjust carbon emissions. When $\alpha = \beta$, the optimal unit carbon emission is a fixed value and is equal to the value that does not consider the reference effect. In Figure 11, e^0 represents optimal unit carbon emissions without the reference effect under the endogenous price. We find that when $\alpha < \beta$, that is, when the manufacturer is more sensitive to the stockout loss, the optimal unit carbon emission is higher than the value that does not consider the reference effect. Conversely, when the manufacturer pays more attention to the clearance loss, i.e., $\alpha > \beta$, the optimal unit carbon emission is lower than the value without the reference effect.

Figures 12 and 13 illustrate the impact of reference effect on total carbon emissions under the endogenous price. In Figure 13, q^0e^0 represents total carbon emissions without the reference effect under the endogenous price. We find the reference effect also maintains a good consistency on total carbon emissions whether the price is exogenous or endogenous; that is, (i) when $\alpha \neq \beta$, total carbon emission q^*e^* decreases with α (Figure 12(a)) and increases with β (Figure 12(b)), (ii) when $\alpha < \beta$, q^*e^* is higher than the value without the reference effect (Figure 13), (iii) when $\alpha > \beta$, q^*e^* is lower than the value without the reference effect (Figure 13), and (iv) when $\alpha = \beta$, q^*e^* is a fixed value and is equal to the value without the reference effect (Figure 12).

6. Conclusions

This work considers a decision-making problem of the newsvendor system with the reference effect. Different from the classical model, the manufacturer's loss aversions are caused by the reference profit point under carbon emissions-sensitive random demand. Our ultimate goal is to maximize the expected total utility of the manufacturer and find out the changes in carbon emissions under different conditions. We explore the optimal production quantity and carbon emissions under price exogenous and price endogenous cases, respectively. When the price is endogenous, we introduce consumer strategic behavior which is more consistent with economic activities to explore the optimal price. Furthermore, we also discuss the impact of the reference effect on optimal decisions.

We find that there is always a unique optimal solution. Under exogenous price and endogenous price cases, the



(a) The degree of aversion on the clearance loss

(b) The degree of aversion on the stockout loss

FIGURE 6: The impact of reference effect on the optimal price under the endogenous price.

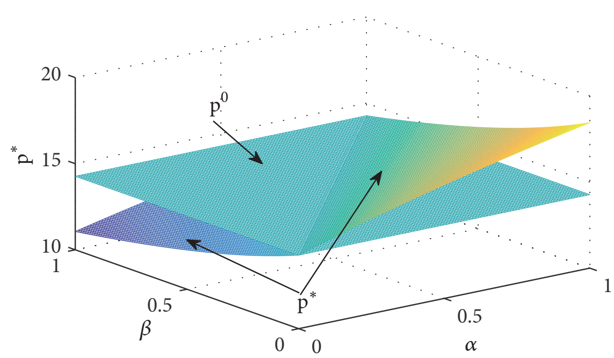


FIGURE 7: The impact of reference effect on the optimal price under the endogenous price.

optimal production quantity of the manufacturer is different from the optimal value of the classic model. Specifically, the manufacturer adjusts the optimal production due to the loss aversion caused by the manufacturer's reference profit point. When the manufacturer has a higher degree of aversion for the clearance loss α, he should reduce the production. Contrarily, when the manufacturer has a higher degree of aversion for the stockout loss β, he should increase the production. When the price is exogenous, the manufacturer's decision for unit carbon emissions is passive; that is, decision making is affected by the competitive environment. In this case, the government can carry out technical guidance to improve the manufacturer's efficiency in carbon emissions reduction. In the market-driven environment, this measure can effectively achieve the target of emission reduction. When the price is endogenous, the decision for unit carbon emissions is influenced by the manufacturer's reference effect. Specifically, the optimal unit carbon emission decreases with α but increases with β. The economic explanation for this is as follows: in order to avoid the clearance loss, the manufacturer reduces unit carbon emissions to attract consumers when facing the consumers who are sensitive to carbon emissions. If the manufacturer puts the consumers' loyalty at a high level, he will lack the enthusiasm to reduce carbon emissions to the stockout loss. The government should give appropriate subsidies to such manufacturers. We also find an economic explanation for government to launch a massive campaign to educate all citizens to improve their awareness of environmental protection; that is, the optimal unit carbon emission e^* falls as the demand sensitivity of unit carbon emissions k rises, all else being equal.

We also carry out numerical studies to find more implications for manufacturer's decisions. We find that when $\alpha = \beta$, the manufacturer's optimal production is a fixed value and is equal to the value without the reference effect. When the manufacturer is more sensitive to the stockout loss, the manufacturer's optimal production is higher than the value without considering the reference effect. Conversely, when the manufacturer pays more attention to the clearance loss, the manufacturer's optimal output is lower than the value without the reference effect. When the price p is endogenous, the optimal unit carbon emission is equal to the value without the reference effect, if $\alpha = \beta$. When $\alpha < \beta$, the optimal unit carbon emission is higher than the value that does not consider the reference effect. Conversely, when $\alpha > \beta$, the optimal unit carbon emission is lower than the value without the reference effect.

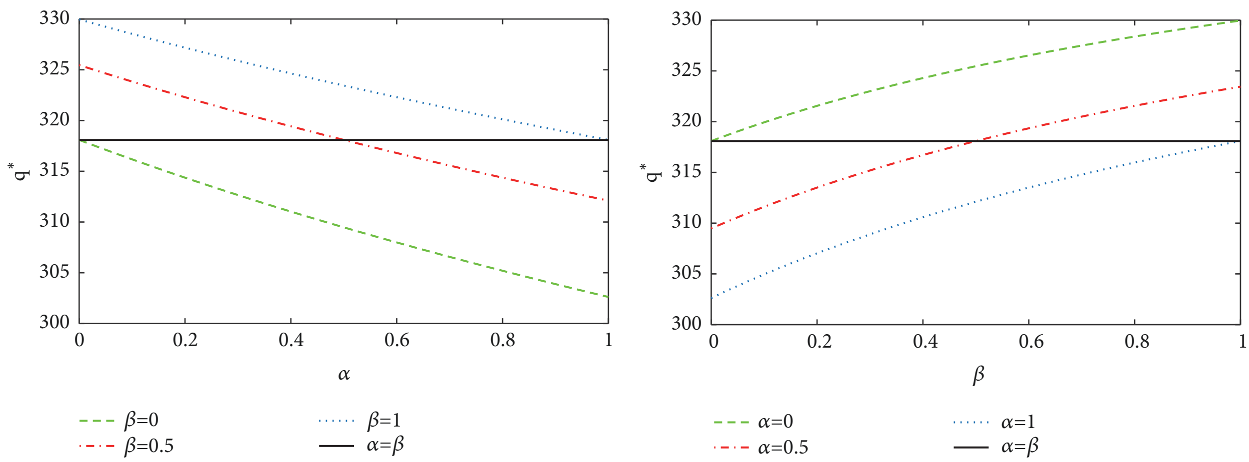
However, there are still some flaws in the study. The main disadvantage is that our work does not consider the carbon emissions policy. It is far sighted to take the carbon emissions policy into consideration in future work.

Appendix

A. Proof of Proposition 1

When the price is exogenous, we can get the first and twice order partial differential equations of $E(U)$ on the inventory factor z and the unit carbon emissions e from (16):

$$\begin{aligned}\frac{\partial E(U)}{\partial z} &= (1+\beta)(p-c+s)(1-F(z)) \\ &\quad -(1+\alpha)(c-v)F(z),\end{aligned} \tag{A.1}$$



(a) The degree of aversion on the clearance loss

(b) The degree of aversion on the stockout loss

FIGURE 8: The impact of reference effect on the optimal production under the endogenous price.

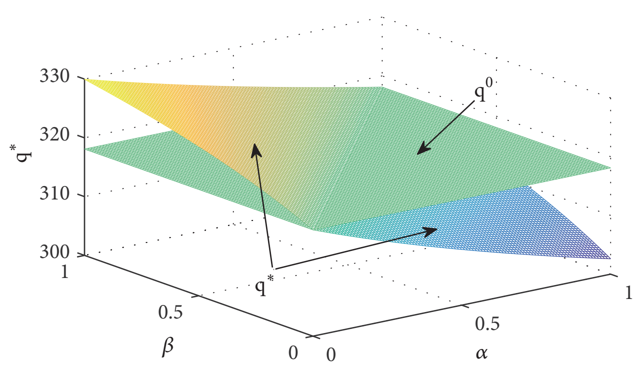


FIGURE 9: The impact of reference effect on the optimal production under the endogenous price.

$$\begin{aligned}\frac{\partial^2 E(U)}{\partial z^2} &\\ &= -\left(\left(1+\beta\right)\left(p-c+s\right)+\left(1+\alpha\right)\left(c-v\right)\right) f\left(z\right) \\ &< 0,\end{aligned} \tag{A.2}$$

$$\frac{\partial E(U)}{\partial e} = 2h\left(e_0 - e\right) - k\left(p-c\right), \tag{A.3}$$

$$\frac{\partial^2 E(U)}{\partial e^2} = -2h < 0, \tag{A.4}$$

$$\frac{\partial^2 E(U)}{\partial z \partial e} = \frac{\partial^2 E(U)}{\partial e \partial z} = 0. \tag{A.5}$$

Thus, the Hessian matrix is

$$\begin{aligned}&\begin{vmatrix} \dfrac{\partial^2 E(U)}{\partial z^2} & \dfrac{\partial^2 E(U)}{\partial z \partial e} \\ \dfrac{\partial^2 E(U)}{\partial e \partial z} & \dfrac{\partial^2 E(U)}{\partial e^2} \end{vmatrix} \\ &\quad = 2h\left(\left(1+\beta\right)\left(p-c+s\right)+\left(1+\alpha\right)\left(c-v\right)\right) f\left(z\right) \\ &\quad > 0.\end{aligned} \tag{A.6}$$

So, the total utility function of the manufacturer $E(U)$ is jointly strict concave in z and e. That is, there are unique z and e which maximize $E(U)$. Let $\partial E(U)/\partial z = 0, \partial E(U)/\partial e = 0$; we have

$$\begin{aligned}&\left(1+\beta\right)\left(p-c+s\right)\left(1-F\left(z\right)\right)-\left(1+\alpha\right)\left(c-v\right)F\left(z\right) \\ &\quad = 0, \\ &2h\left(e_0-e\right)-k\left(p-c\right)=0.\end{aligned} \tag{A.7}$$

From (A.7), we can get

$$F\left(z^*\right) = \frac{\left(1+\beta\right)\left(p-c+s\right)}{\left(1+\alpha\right)\left(c-v\right)+\left(1+\beta\right)\left(p-c+s\right)}, \tag{A.8}$$

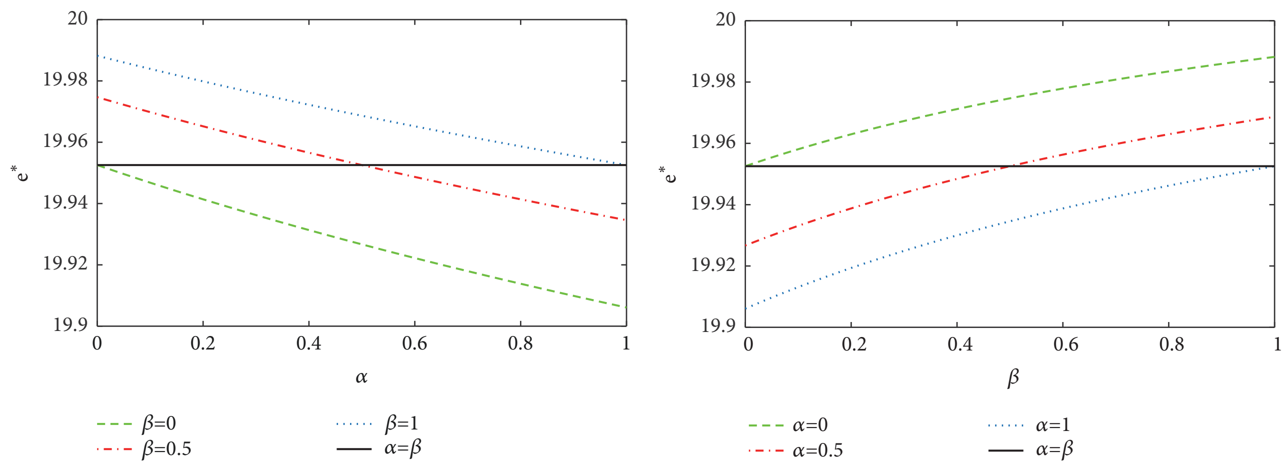
$$e^* = e_0 - \frac{k\left(p-c\right)}{2h}. \tag{A.9}$$

B. Proof of Proposition 2

When $\alpha = \beta$, from (20), we can get

$$\begin{aligned} q^* &= a - bp - k\left(e_0 - \frac{k\left(p-c\right)}{2h}\right) \\ &\quad + F^{-1}\left(\frac{p-c+s}{p-v+s}\right). \end{aligned} \tag{B.1}$$

So, if $\alpha = \beta$, the optimal production quantity is not related to the above loss aversion behavior, and it is the same as the optimal production quantity of the loss-neutral manufacturer.



(a) The degree of aversion on the clearance loss (b) The degree of aversion on the stockout loss

FIGURE 10: The impact of reference effect on optimal unit carbon emissions under the endogenous price.

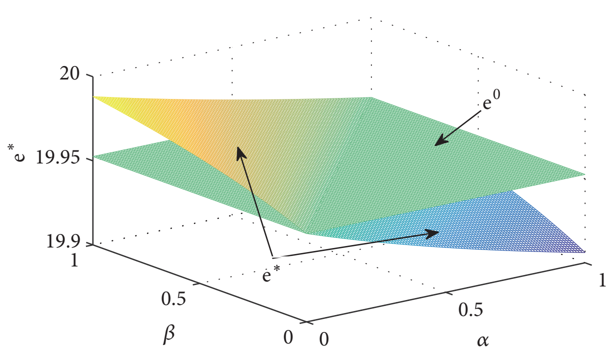


FIGURE 11: The impact of reference effect on optimal unit carbon emissions under the endogenous price.

C. Proof of Proposition 3

The proof of the positive and negative properties of $\partial q^*/\partial\alpha$ is equivalent to show the positive and negative properties of $\partial F(z^*)/\partial\alpha$.

$$\frac{\partial F(z^*)}{\partial\alpha} = \frac{-(1+\beta)(c-v)(p-c+s)}{[(1+\alpha)(c-v)+(1+\beta)(p-c+s)]^2} < 0. \tag{C.1}$$

So, $\partial q^*/\partial\alpha < 0$, that is, the manufacturer's optimal production quantity decreases with α.

The proof of the positive and negative properties of $\partial q^*/\partial\beta$ is equivalent to show the positive and negative properties of $\partial F(z^*)/\partial\beta$.

$$\frac{\partial F(z^*)}{\partial\beta} = \frac{(1+\alpha)(p-c+s)(c-v)}{[(1+\alpha)(c-v)+(1+\beta)(p-c+s)]^2} > 0. \tag{C.2}$$

So, $\partial q^*/\partial\beta > 0$, that is, the manufacturer's optimal production quantity increases with β.

D. Proofs of Propositions 4 and 5

According to the definition of rational expectation equilibrium (Desai et al., 2004), the solution of rational expectation equilibrium (p, z, r, δ_r, ξ_{prob}) must meet the following conditions: (i) $r = u-(u-v)\xi_{prob}$; (ii) $p=\delta_r$; (iii) z, e are a solution of $\operatorname{argmax}_{z,e}E(U)$; (iv) $\xi_{prob}=F(z)$; and (v) $\delta_r = r$.

From the above analysis we can get

$$p = u-(u-v)F(z). \tag{D.1}$$

Combined with Appendix A, we can get

$$\begin{aligned} &p = u-(u-v)F(z),\\ &(1+\beta)(p-c+s)(1-F(z))-(1+\alpha)(c-v)F(z)\\ &\quad = 0,\\ &2h(e_0-e)-k(p-c)=0. \end{aligned} \tag{D.2}$$

Given p, $E(U)$ is jointly strict concave in z and e. So there are unique z and e which maximize $E[U(z,e,p)]$. Solving (D.2), we can derive the optimal condition of the inventory factor $F(z^*)$, the optimal retail price p^*, and the optimal carbon emission e^* of the manufacturer, respectively:

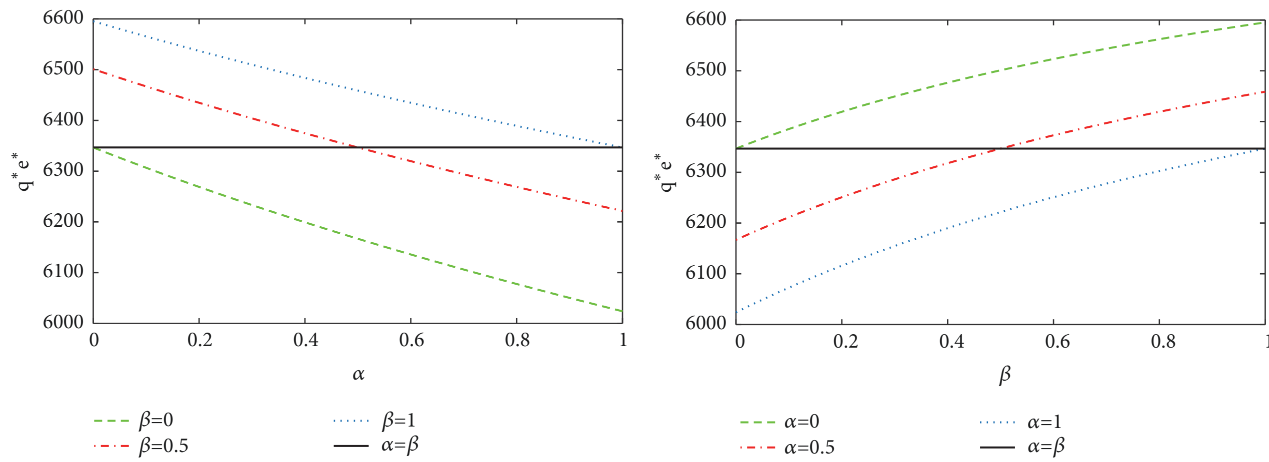
$$F(z^*) = \frac{(1+\beta)(2u-c-v+s)+(1+\alpha)(c-v)\pm\varphi(\alpha,\beta)}{2(1+\beta)(u-v)}, \tag{D.3}$$

where $\varphi(\alpha,\beta) = (((1+\beta)(v+s-c)+(1+\alpha)(c-v))^2+4(1+\alpha)(1+\beta)(c-v)(u-v))^{1/2}$,

$$p^* = u-(u-v)F(z^*), \tag{D.4}$$

$$e^* = e_0 - \frac{k(p^*-c)}{2h}. \tag{D.5}$$

When the price p is endogenous and consumers have strategic behavior, $F(z^*)$ decreases in α and increases with



(a) The degree of aversion on the clearance loss

(b) The degree of aversion on the stockout loss

FIGURE 12: The impact of reference effect on total carbon emissions under the endogenous price.

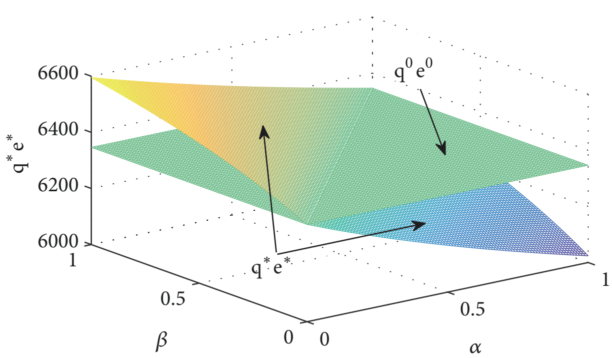


FIGURE 13: The impact of reference effect on total carbon emissions under the endogenous price.

β (see Appendix E). When $\alpha = 1$ and $\beta = 0$, we can get $\varphi(1,0) = (((v+s-c)+2(c-v))^2 + 8(c-v)(u-v))^{1/2}$. Due to $(c-v)(u-v) > 0$, $\varphi(1,0) > (v+s-c)+2(c-v)$. Therefore, we can obtain $((2u-c-v+s)+2(c-v)+((v+s-c)+2(c-v)))/(2(u-v)) = ((u-v)+(s+c-v))/(u-v) > 1$. That is, $((1+\beta)(2u-c-v+s)+(1+\alpha)(c-v)+\varphi(\alpha,\beta))/(2(1+\beta)(u-v))$ is always greater than 1. Because of $F(z) \in (0,1)$, we remove the solution that is not in line with the requirement.

So, we can obtain

$$F(z^*) = \frac{(1+\beta)(2u-c-v+s)+(1+\alpha)(c-v)-\varphi(\alpha,\beta)}{2(u-v)}, \tag{D.6}$$

E. Proof of Propositions 6 and 7

In order to determine the impact of the manufacturer's aversion on the clearance loss and the shortage loss of his decisions, we introduce the Cramer's Rule. According to (22), we can get the first order partial derivatives of all variables with respect to α; that is,

$$\begin{aligned} &\frac{\partial p}{\partial \alpha} + (u-v)\frac{\partial F(z)}{\partial \alpha} = 0, \\ &(1+\beta)(1-F(z))\frac{\partial p}{\partial \alpha} \\ &\quad - ((1+\beta)(p-c+s)+(1+\alpha)(c-v))\frac{\partial F(z)}{\partial \alpha} \\ &\quad = (c-v)F(z). \end{aligned} \tag{E.1}$$

From (E.1), we can get

$$\frac{\partial p}{\partial \alpha} = \frac{\begin{vmatrix} 0 & u-v \\ (c-v)F(z) & -((1+\beta)(p-c+s)+(1+\alpha)(c-v)) \end{vmatrix}}{\begin{vmatrix} 1 & u-v \\ (1+\beta)(1-F(z)) & -((1+\beta)(p-c+s)+(1+\alpha)(c-v)) \end{vmatrix}} > 0, \tag{E.2}$$

$$\frac{\partial F(z)}{\partial \alpha} = \frac{\begin{vmatrix} 1 & 0 \\ (1+\beta)(1-F(z)) & (c-v)F(z) \end{vmatrix}}{\begin{vmatrix} 1 & u-v \\ (1+\beta)(1-F(z)) & -((1+\beta)(p-c+s)+(1+\alpha)(c-v)) \end{vmatrix}} < 0. \tag{E.3}$$

Similarly, according to (22), we can get the first order partial derivatives of all variables with respect to β; that is,

$$\begin{aligned} &\frac{\partial p}{\partial \beta} + (u-v)\frac{\partial F(z)}{\partial \beta} = 0, \\ &(1+\beta)(1-F(z))\frac{\partial p}{\partial \beta} \\ &\quad - ((1+\beta)(p-c+s)+(1+\alpha)(c-v))\frac{\partial F(z)}{\partial \beta} \\ &\quad = -(p-c+s)(1-F(z)). \end{aligned} \tag{E.4}$$

From (E.4), we can get

$$\frac{\partial p}{\partial \beta} = \frac{\begin{vmatrix} 0 & u-v \\ -(p-c+s)(1-F(z)) & -((1+\beta)(p-c+s)+(1+\alpha)(c-v)) \end{vmatrix}}{\begin{vmatrix} 1 & u-v \\ (1+\beta)(1-F(z)) & -((1+\beta)(p-c+s)+(1+\alpha)(c-v)) \end{vmatrix}} < 0, \tag{E.5}$$

$$\frac{\partial F(z)}{\partial \beta} = \frac{\begin{vmatrix} 1 & 0 \\ (1+\beta)(1-F(z)) & -(p-c+s)(1-F(z)) \end{vmatrix}}{\begin{vmatrix} 1 & u-v \\ (1+\beta)(1-F(z)) & -((1+\beta)(p-c+s)+(1+\alpha)(c-v)) \end{vmatrix}} > 0. \tag{E.6}$$

So, when the price p is endogenous and consumers have strategic behavior, the manufacturer's optimal production quantity decreases with α and increases with β. And the optimal unit price increases with α and decreases with β.

Due to $e^* = e_0 - k(p^* - c)/2h$, the optimal unit carbon emission decreases with α and increases with β.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was financially supported by the National Social Science Foundation of China (Grant No. 17BGL083).

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