Research Article

The Optimal Green Product Design with Cost Constraint and Sustainable Policies for the Manufacturer

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In this paper, we study how the manufacturer balances the investment between the green product and the ordinary product as consumer environmental awareness (CEA) increases. The green product and ordinary product have a basic commonality traditional quality but difference between the premium environmental quality and premium traditional quality. With the cost constraint, we present manufacturer's optimal strategy: producing one product or two products and the optimal traditional quality of the ordinary product or the optimal environmental quality of the green product. Then, we further study the effect of government subsidy and tax on manufacturer's strategies and analyze the effectiveness of the policies. Finally, we give some numerical examples and sensitivity analysis. The main findings are as follows: (1) manufacturer's cost constraint affects product's optimal quality but may not influence manufacturer's optimal product strategy; the manufacturer may not produce two products even through the budget is sufficient large; (2) the government policy could induce the manufacturer to invest green product but may be inefficient; the subsidy and tax policies are mutual exclusion; and either subsidy or tax could play a role in changing manufacturer's strategy. Some management insights are given.

1. Introduction

Environment pollution has attracted public attention including the consumers, industries, and governments. Green products which address environmental issues through product design and innovation are emerging from the demand pull of customers with new attitudes toward environmental values [1]. A study carried out by the European Commission in 2008 shows that 75% of Europeans are ready to buy environmentally friendly products even if they cost a little bit more compared to 31% in 2005 [2]. On the other hand, many environment policies imposed by governments around the world encourage the manufacturer to produce green product. Nevertheless, a transition to produce green products will require innovation and investment in a range of green technologies and radical changes to operation practices in the industry sector [3]. Green products always have higher prices than ordinary products, and traditional qualities of green products are often lower than those of ordinary products. With demand changes and

government policies, how manufacturers determine the investment between the ordinary products and green products becomes an urgent issue emerged in the area of green operations management to study.

Consider an automobile manufacturer who could undertake design measures to improve the environmental performance of the engine during use (e.g., greater energy efficiency that would translate into lower emissions), or improve the traditional qualities of the automobile (e.g., the maximum speed, acceleration, or style). Meanwhile, the government employs some policies to encourage the manufacturer to the R&D eco-friendly products. For example, the US government invested 250 billions to help the manufacturer to update the advanced equipment in 2013. In China, the government invested 2000 millions to Shanghai Automobile Company for Rowe 550's R&D in 2012. Toward controlling environmental damage, the US Environmental Protection Agency set limits on certain air pollutants in the 2011 Clean Air Act. In China, the subsidy peaked at 50,000

RMB and 60,000 RMB for consumers who purchase plug-in hybrid EV (electric vehicle) and pure EV, respectively. A profit-maximizing manufacturer would trade off investments required to implement these measures against the possibility of generating higher revenues.

With consumer environmental awareness and government policies stimulation, some ordinary manufacturers begin to produce green product to capture more market share. In December 2010, the traditional manufacturer—Nissan, General, and Chevy Volt introduced the electric car—Nissan Leaf, and General Motors' plug-in hybrid, and Chevy Volt—in the US market to capture new markets in search of higher profit [4]. However, the current trend of green product development is not without obstacles and pitfalls. First, manufacturers with the cost constraint will not have sufficient budget to develop green product, and they tend to invest more on developing ordinary product, especially when the ordinary product with high traditional quality still attracts more consumers. Second, consumers with weak environmental awareness tend to transfer to ordinary product. The green product with environmental quality always has a higher price because the cost coefficient of the green product is always higher than the traditional product. Third, there are more and more subsidy and tax policies for developing green product; however, the interactions among consumer preferences, product line decisions, and government environment policies are needed to better understand the impact of policies on green product development and environment quality.

Therefore, in this paper, we mainly investigate the following two questions:

- (1) How the cost constraint affects manufacturer's product line strategy? Whether to produce one product or two products, and how to design the traditional quality of the ordinary product and the environmental quality of the green product with cost constraint?
- (2) Whether the government subsidy and tax are efficient to stimulate the manufacturer to produce green product all the time? And when are the government subsidy and tax not efficient?

In this paper, we consider that one manufacturer could produce one product (ordinary product) or two products (ordinary product and green product). Considering the impact of consumer environmental awareness, we introduce environmental quality as a demand enhancement factor in the product demand function [5, 6]. The green product provides greater environmental benefits (or imposes smaller environmental costs) than the ordinary product but has a higher price. With the cost constraint, the manufacturer needs to determine to develop the ordinary product or green product and improve the traditional quality of the ordinary product or the environmental quality of the green product to maximum his profit. Furthermore, we analyze the effect of government subsidy and tax on manufacturer's strategy and give the optimal subsidy and tax.

This study contributes to the literature by investigating the impacts of cost constraint on manufacturer's product

strategy and government policies. We find the following: (1) Manufacturer's cost constraint affects product's optimal quality but may not influence manufacturer's optimal product strategy; the manufacturer may not produce two products even through the budget is sufficiently large, and the manufacturer may choose to invest two products even when the budget is very small; (2) The government policy could induce manufacturer to invest green product but may be inefficient when CEA and prices of the two products satisfy a certain condition; (3) The cost coefficient of environmental quality, CEA, and green product's price are significant factors to influence manufacturer's strategy. The government could take some measures to stimulate the technology innovation to decrease green product's cost, improve CEA, or subsidize consumers to change manufacturer's strategy; (4) The subsidy and tax policies are mutual exclusion; either subsidy or tax could play a role in changing manufacturer's strategy, and the optimal subsidy or tax are determined by the cost constraint and the manufacturer's profit.

This paper is organized as follows. Section 2 provides a review of the relevant literature. Section 3 analyzes two models with one product and two products. Section 4 discusses the impact of government policies on product strategy. Section 5 presents sensitivity analyses and numerical examples. Section 6 summarizes our main findings and concludes the paper by providing some directions for future research. All proofs are relegated to Appendix.

2. Literature Review

Our work is closely related to the growing focus on product line design of green product in operations management. There are two main streams of literature.

The first stream focuses on how manufacturers design their products facing segment market with diverse consumers to maximize his profit. With two distinct segments of consumers, Kim and Chhajed developed a model to examine when modular products should be introduced and how much modularity to offer when a market consists of a high segment and a low segment [7]. Desai et al. studied three product configurations for two products: unique, premium-common, and basic-common; they compared the prices of the two products and the firm's sales revenues under different configurations and provided a useful framework to develop an index that can rank order components in terms of their attractiveness for commonality [8]. Krishnan and Gupta explored the effect of platforms on the positioning (performance levels) of products offered in a market with diverse consumers; their results indicated that platforms are not appropriate for extreme levels of market diversity or high levels of nonplatform scale economies [9]. Syam and Kumar divided the customers into high- and low-cost segments and examined firms' incentive to offer customized products in addition to their standard products in a competitive environment [10]. Heese and Swaminathan analyzed a manufacturer who determined the component quality levels, the amount of effort to reduce production costs, and

whether to use common or different components for the two products to two different customer segments [11]. Hua et al. divided consumers into two groups (i.e., two market segments), and they present the optimal product design strategy by a Stackelberg model [12]. Kim et al. studied the case of a nondominating preference structure where each segment has an attribute it values more than the other segment does. They showed that the effect of commonality strategy is more diverse in this nondominating preference structure and that commonality can actually relieve cannibalization in the product line design [13]. Bala et al. studied how the global distribution of product development impacts the profit-maximizing product line with low-end and high-end customer segments [14]. Shi et al. investigated the impact of remanufacturable product design on market segmentation and trade-in prices [15]. The above literature mainly studies the optimal product configuration with diverse consumers; however, the environmental consumer and ordinary consumer are not considered in detail; in addition, the cost constraint is not incorporated. In this paper, we study the optimal ordinary product's and the green product's configurations as CEA increases in recent years. Further, we analyze the effects of government subsidy and tax on manufacturer's product design strategy.

The second stream focuses on how manufacturers improve the environmental quality of the green product with CEA and government policies, such as subsidy and tax. The common methods to improve product environmental quality include increasing technology investment (e.g., clean-up level and emission level), improving social responsibility, introducing eco-labeling, and so on. For example, Amacher et al. showed that incentives for firms to invest in green technologies depend on their relative cost structure [16]. Chung and Wee explored how new green product design technology and remanufacturing affect the production inventory policy [17]. In two-echelon supply chain, Ni et al. addressed how to allocate corporate social responsibility between a supplier and a retailer under wholesale price contracts [18]. Liu et al. investigated the impacts among the supply chain players considering consumer environmental awareness and manufacturers' competition [6]. Xu et al. proposed revenue-sharing and two-part tariff contracts to coordinate the sustainable supply chain [19]. Considering government policies, Gonzalez and Fumero demonstrated how frequently used environmental policies influence the social welfare [20]. Tian presented how a regulatory increase in the minimum required level of environmental friendliness of imported good impacts home firm and consumer gain [21]. Bansal and Gangopadhyay investigated how subsidy policies and tax policies influence total pollution and aggregate welfare in the presence of environmentally aware consumers [22]. Lombardini-Riipinen studied how governments set the socially optimal emission and commodity tax policies when consumers are willing to pay a price premium for green variants of a product [23]. Yakita and Yamauchi explored the welfare effects of environmental R&D strategies of firms [24]. Zhang et al. examined how subsidy policies affect firms' design strategies of green products [25]. Yenipazarli

studied how the collaboration between the manufacturer and the retailer affects the eco-efficient innovation [26]. Ji et al. analyzed a detailed model which incorporates both cap-and-trade regulation and consumers' low-carbon preference [27]. Xu et al. investigated the decision and coordination in the dual-channel supply chain arising out of low-carbon preference and channel substitution under cap-and-trade regulation [28]. Hong et al. explored green product design by considering reference effects, and consumer environmental awareness and carbon tax were also considered in decision-making [29]. However, most of the above studies only focus on the green product, neglecting the competition between the ordinary product and the green product.

The literature most close to our paper is that of Chen's; this paper discussed the segment market including the traditional market and green market and explored the impacts of environmental standards on green product development [30]. Similar to Chen, Zhang et al. examined how subsidy policies affect firms' design strategies of green products [25]. Su et al. suggested how the two technologies, Zero-Sum and Synergy, impact the market structure strategy for green products [31]. Zhang et al. explored the impact of consumer environmental awareness on order quantities and channel coordination with traditional market and green market [5]. Zhang and Zhang studied the optimal subsidy and tax policies and firms' product selection (generic, green, or both), plus quality and pricing decisions [32]. Basiri and Heydari investigated the optimal retailer's sales efforts and green quality and channel coordination issue within a two-stage supply chain [33]. Chen et al. studied the optimal prices and green technology investment when there are competitions between two manufacturers who have different green technology investment cost coefficients [3]. Liu et al. investigates product design issue and its impact on the operations of a closed-loop supply chain consisting of a supplier, a manufacturer, and consumers [34]. Zheng et al. analyses cooperative and noncooperative game theoretically in a three-echelon closed-loop supply chain; the retailer's fairness concern is also considered in this game model [35]. However, the above studies did not consider the cost constraint into manufacturer's decision and discussed two products with completely different environmental qualities and traditional qualities. In this paper, we discuss two products that have the same basic traditional quality, but differ in the premium quality. The manufacturer determines how much to invest on the premium traditional quality and how much to invest on the environmental quality with the cost constraint. Then, we explore how subsidy and tax change manufacturers' investment strategies.

3. Model

The monopoly manufacturer could produce one product-ordinary product or two products-ordinary product and green product. The ordinary product and green product have the same basic commonality to satisfy the basic requirement of the product but have different premium qualities: the ordinary product has premium traditional

quality and the green product has premium environmental quality. With consumer's demand functions and cost constraint, the manufacturer needs to determine whether to produce one product or two products, how much to invest to the ordinary product to improve the traditional quality, and how much to invest to the green product to improve the environmental quality.

With cost constraint, we first study the optimal premium traditional quality of the ordinary product and the profit when the manufacturer only produces ordinary product; then, we give the optimal premium traditional quality of the ordinary product and the optimal premium environmental quality of the green product and the profit when the manufacturer produces ordinary and green products at the same time.

3.1. One Product. In this section, we assume that the manufacturer only produces ordinary product (denoted product 1) and the product have two attributes, price (denoted as p_1) and premium/improved traditional quality (denoted as q_t), influencing consumer demand. Product demand increases with the premium traditional quality and decreases with its price. Similar to Xie et al. [36], we consider that the demand function for product 1, denoted by D_1 , possesses the following structure:

$$D_1 = a - p_1 + \theta_t q_t, \quad (1)$$

where a_1 is the potential intrinsic demand and θ_t is the coefficient of the demand increment caused by traditional quality improvement.

Similar to Zhu and He [37], we model the R&D cost c_t as an increasing quadratic function, $c_t(q_t) = k_t q_t^2$. The R&D cost is independent of the production volume, and k_t is a strictly positive cost coefficient. The R&D cost increases and is convex with the improved quality level q_t . In this paper, we mainly study the development-intensive product, such as the electric vehicle and the solar power station, so the research and development cost of the development-intensive product is much larger than the product cost even though the traditional and the environmental qualities become very large, so we assume the variable cost (manufacturing costs) is zero in all further analysis; such variable costs are insignificant as compared to the development costs, and parameter transformations can be applied to suppress such variable costs into other parameters without affecting the properties of the profit functions [37]. Furthermore, in order to capture the manufacturer's cost constraint, we assume the total cost is c ; then, the manufacturer's objective function with the improved ordinary product is as follows:

$$\begin{aligned} \pi(q_t) &= p_1(a - p_1 + \theta_t q_t) - k_t q_t^2, \\ \text{s.t. } k_t q_t^2 &\leq c, \\ q_t &\geq 0. \end{aligned} \quad (2)$$

Theorem 1. *The optimal quality for the ordinary product with cost constraint c is*

- (1) When $c \geq c^*$, then $q_t = \theta_t p_1 / 2k_t$
- (2) When $c < c^*$, then $q_t = \sqrt{c/k_t}$, where $c^* = p_1^2 \theta_t^2 / 4k_t$

From Theorem 1, we can see that the optimal quality is related to the price, cost coefficient, and the consumer's sensitivity to the traditional quality (similar to Chen [30]; Kim et al. [13]) when the cost is sufficiently large [13, 30]; or else the optimal quality is determined by the cost constraint and the cost coefficient. The threshold point of the cost is determined by product price, cost coefficient, and consumers' sensitivity towards quality improvement; and the threshold point increases with p_1 and θ_t and decreases with k_t . Figure 1 shows that the optimal quality with cost constraint and the price.

3.2. Two Products. As the consumer environmental awareness increases, many manufacturers begin to introduce green product (namely, product 2) to increase profit. In this section, we consider the scenario that the manufacturer produces two products—ordinary product and green product. The ordinary product has higher traditional quality than that of the green product; the green manufacturer has higher environmental quality than that of the ordinary product. For the ordinary product, the higher traditional quality of the ordinary product will attract more consumers who pay more attention to the traditional quality; however, the environmental quality increment of the green product will attract more green consumers. With the cost constraint, the manufacturer needs to determine the cost allocation between the ordinary product and the green product.

Similar to Section 3.1, we assume that the cost of offering an attribute to be convex in quality so that it is increasingly costly to offer better quality. We assume the cost function of the increment traditional quality for the ordinary product $c_t(q_t) = k_t q_t^2$, the cost function of the increment environmental quality for the green product $c_e(q_e) = k_e q_e^2$. And the variable costs of the two products are assumed to be zero similar to Section 3.1.

Similar to Zhang et al. [5] and Zhang and Wang [38], the demand functions for the ordinary product and green product are as follows:

$$\begin{aligned} D_1 &= a_1 - p_1 + \theta(p_2 - p_1) + \theta_t q_t - \theta'_e q_e, \\ D_2 &= a_2 - p_2 + \theta(p_1 - p_2) + \theta_e q_e - \theta'_t q_t, \end{aligned} \quad (3)$$

where a_i is the initial market potential for product i , p_i is the product i 's price, θ represents the sensitivity of switch over towards price difference, θ_t represents the consumers' sensitivity towards traditional quality improvement, θ'_e represents the demand switch over from the ordinary product to the green product because of the environmental quality improvement of the green product. Similarly, θ_e represents consumers' sensitivity toward green product's environmental quality improvement and can also be called consumer environmental awareness. The larger the CEA, the more the demand of the green product. θ'_t represents the demand switch over from green product to ordinary

FIGURE 1: Optimal quality q_t with c and p_1 .

product because of the higher traditional quality of the ordinary product. It is easy to obtain that $\theta_t \geq \theta'_t$ and $\theta_e \geq \theta'_e$ because the ordinary consumers pay much more attention to traditional quality than the green consumers and the green consumers focus more on environmental quality than the ordinary consumers.

Therefore, the manufacturer's profit function is

$$\begin{aligned} \pi(q_t, q_e) = & p_1 [a_1 - p_1 + \theta(p_2 - p_1) + \theta_t q_t - \theta'_e q_e] \\ & + p_2 [a_2 - p_2 + \theta(p_1 - p_2) + \theta_e q_e - \theta'_t q_t] \\ & - k_t q_t^2 - k_e q_e^2, \end{aligned}$$

$$\text{s.t. } k_t q_t^2 + k_e q_e^2 \leq c,$$

$$q_t, q_e \geq 0.$$

(4)

In order to ensure that the profit function is jointly concave on the decision variables, we need the following assumptions:

Assumption 1. The two products' prices satisfy $p_1 \theta_t - p_2 \theta'_t \geq 0$ and $p_2 \theta_e - p_1 \theta'_e \geq 0$.

Assumption 1 presents the conditions that the price and demand sensitivity coefficients towards quality improvement need to satisfy.

Theorem 2. The optimal qualities for the ordinary product and green product are

(1) If $c \geq c^{**}$, then

$$q_t^* = \frac{p_1 \theta_t - p_2 \theta'_t}{2k_t},$$

$$q_e^* = \frac{p_2 \theta_e - p_1 \theta'_e}{2k_e}.$$

(5)

(2) If $c < c^{**}$, then

$$\begin{aligned} q_t^* &= (p_1 \theta_t - p_2 \theta'_t) \sqrt{\frac{ck_e}{k_t [k_t (p_1 \theta'_e - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta'_t)^2]}}, \\ q_e^* &= (p_2 \theta_e - p_1 \theta'_e) \sqrt{\frac{ck_t}{k_e [k_t (p_1 \theta'_e - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta'_t)^2]}}, \end{aligned} \quad (6)$$

where $c^{**} = ((p_1 \theta'_e - p_2 \theta_e)^2 / 4k_e) + ((p_1 \theta_t - p_2 \theta'_t)^2 / 4k_t)$.

From Theorem 2, we can see that the optimal qualities and the threshold point are related to $p_1 \theta_t - p_2 \theta'_t$ and $p_2 \theta_e - p_1 \theta'_e$. When the cost is sufficiently large, the optimal qualities are not affected by the cost; or else the optimal qualities are determined by the total cost, cost coefficients, and the difference. Specially, when $p_1 = p_2$, $\theta_t = \theta_e$, and $\theta'_t = \theta'_e$, the ordinary product's and green product's optimal premium qualities are equal; and the cost coefficient of the product quality decreases corresponding product quality but increases the quality of the other product.

Table 1 summarizes the main results including the optimal qualities and manufacturer's profit obtained from Theorems 1 and 2. According to the threshold points of the cost, we divide the solutions into four scenarios.

Here,

$$\begin{aligned} G_1 &= (p_1 \theta_t - p_2 \theta'_t)^2 \sqrt{\frac{k_e}{k_t}} \sqrt{\frac{1}{[k_t (p_1 \theta'_e - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta'_t)^2]}}, \\ G_2 &= (p_2 \theta_e - p_1 \theta'_e)^2 \sqrt{\frac{k_t}{k_e}} \sqrt{\frac{1}{[k_t (p_1 \theta'_e - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta'_t)^2]}}. \end{aligned} \quad (7)$$

Theorems 1 and 2 present the optimal qualities of the ordinary product and green product. In order to obtain maximum profit, the manufacturer will compare the profit between producing one product and producing two products with finite cost. Therefore, we give the following proposition.

Proposition 1

(1) When $c \geq \max\{c^*, c^{**}\}$,

- (i) if $-p_1(a_2 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + ((p_1 \theta'_e - p_2 \theta_e)^2 / 4k_e) + (p_2^2 \theta_t'^2 - 2p_1 p_2 \theta_t \theta'_t / 4k_t) > 0$, then the manufacturer chooses to produce two products
- (ii) if $-p_1(a_2 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + ((p_1 \theta'_e - p_2 \theta_e)^2 / 4k_e) + (p_2^2 \theta_t'^2 - 2p_1 p_2 \theta_t \theta'_t / 4k_t) < 0$, then the manufacturer chooses to produce one product

(2) When $c^{**} \geq c \geq c^*$, there is at most one point $x_1 \in [c^*, c^{**}]$ satisfies $\pi_1^*(x_1) - \pi_2^*(x_1) = 0$, and

- (i) if $c^{**} \geq x_1 \geq c \geq c^*$, then the manufacturer produces one product

TABLE 1: Optimal qualities and profit.

Cost constraint	One product	Two products
$c \geq \max\{c^*, c^{**}\}$	$q_t^* = \theta_t p_1 / 2k_t,$ $\pi_1^* = p_1(a - p_1) + (p_1^2 \theta_t^2 / 4k_t).$	$q_t^* = (p_1 \theta_t - p_2 \theta_t') / 2k_t, q_e^* = (p_2 \theta_e - p_1 \theta_e') / 2k_e,$ $\pi_2^* = p_1(a_1 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2,$ $+ ((p_1 \theta_e' - p_2 \theta_e)^2 / 4k_e) + ((p_1 \theta_t - p_2 \theta_t')^2 / 4k_t).$
$c^{**} \geq c \geq c^*$	$q_t^* = \theta_t p_1 / 2k_t,$ $\pi_1^* = p_1(a - p_1) + (p_1^2 \theta_t^2 / 4k_t).$	$q_t^* = (p_1 \theta_t - p_2 \theta_t') \sqrt{ck_e / (k_t [k_t (p_1 \theta_e' - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta_t')^2])},$ $q_e^* = (p_2 \theta_e - p_1 \theta_e') \sqrt{ck_t / (k_e [k_t (p_1 \theta_e' - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta_t')^2])},$ $\pi_2^* = p_1(a_1 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + (G_1 + G_2)\sqrt{c} - c.$
$c^* \geq c \geq c^{**}$	$q_t^* = \sqrt{c/k_t},$ $\pi_1^* = p_1(a - p_1 + \theta_t \sqrt{c/k_t}) - c.$	$q_t^* = p_1 \theta_t - p_2 \theta_t' / 2k_t, q_e^* = p_2 \theta_e - p_1 \theta_e' / 2k_e,$ $\pi_2^* = p_1(a_1 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2$ $+ ((p_1 \theta_e' - p_2 \theta_e)^2 / 4k_e) + ((p_1 \theta_t - p_2 \theta_t')^2 / 4k_t).$
$c < \min\{c^*, c^{**}\}$	$q_t^* = \sqrt{c/k_t},$ $\pi_1^* = p_1(a - p_1 + \theta_t \sqrt{c/k_t}) - c.$	$q_t^* = (p_1 \theta_t - p_2 \theta_t') \sqrt{ck_e / (k_t [k_t ((p_1 \theta_e' - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta_t')^2])},$ $q_e^* = (p_2 \theta_e - p_1 \theta_e') \sqrt{ck_t / (k_e [k_t (p_1 \theta_e' - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta_t')^2])},$ $\pi_2^* = p_1(a_1 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + (G_1 + G_2)\sqrt{c} - c.$

- (ii) if $c^{**} \geq c \geq x_1 \geq c^*$, then the manufacturer produces two products
- (iii) if $\pi_1^*(c^*) > \pi_2^*(c^{**})$, then the manufacturer produces one product
- (iv) if $\pi_1^*(c^*) < \pi_2^*(c^*)$, then the manufacturer produces two products

(3) When $c^* \geq c \geq c^{**}$, there is at most one point $x_2 \in [c^{**}, c^*]$ satisfies $\pi_1^*(x_2) - \pi_2^*(x_2) = 0$, and

- (i) if $c^* \geq c \geq x_2 \geq c^{**}$, then the manufacturer produces one product
- (ii) if $c^* \geq x_2 \geq c \geq c^{**}$, then the manufacturer produces two products
- (iii) if $\pi_1^*(c^*) < \pi_2^*(c^{**})$, then the manufacturer produces two products
- (iv) if $\pi_1^*(c^{**}) > \pi_2^*(c^{**})$, then the manufacturer produces one product

(4) When $c < \min\{c^*, c^{**}\}$,

- (i) if $J_1 + J_2 \sqrt{c} > 0$ for any $c < \min\{c^*, c^{**}\}$, then the manufacturer produces one product
- (ii) if $J_1 + J_2 \sqrt{c} < 0$ for any $c < \min\{c^*, c^{**}\}$, then the manufacturer produces two products
- (iii) when $J_1 < 0$, $J_2 > 0$ and $c > x_3$, where $x_3 \in [0, \min\{c^{**}, c^*\}]$ satisfies $\pi_1^*(x_3) - \pi_2^*(x_3) = 0$, then the manufacturer produces one product; when $J_1 < 0$, $J_2 > 0$ and $c < x_3$, then the manufacturer produces two products
- (iv) when $J_1 > 0$, $J_2 < 0$ and $c < x_3$, then the manufacturer produces one product; when $J_1 > 0$, $J_2 < 0$ and $c > x_3$, the manufacturer produces two products

Here, $J_1 = p_1(a_2 - p_1) - p_2(a_2 - p_2) + \theta(p_1 - p_2)^2$,
 $J_2 = (p_1 \theta_t / \sqrt{k_t}) - G_1 - G_2.$

Proposition 1 presents the optimal production strategy for the manufacturer with the changes of the cost, price, and other sensitivity coefficients. Interestingly, even though the

cost is sufficiently large, the manufacturer may only produce ordinary product, and the manufacturer may produce two products in spite of the cost being very small.

4. Government Policy

From Section 3, we obtain that the manufacturer may only produce ordinary product to maximize his profit. In order to induce the manufacturer to produce green product, the government always subsidizes the manufacturer who produces green product and tax manufacturer who produces ordinary product. In this section, we will examine the efficiency of the government policy and give the optimal subsidy and tax.

With the subsidy and tax, the manufacturer will determine to produce one product or two products by maximizing his profit. If the manufacturer chooses to produce two products without government policy, then the subsidy and tax policies are not necessary. Although the subsidy will assist the manufacturer to produce the green product with higher environmental quality, in this paper, we focus on the key point of changing the product strategy (from one product to two products) with the subsidy and tax policies.

We assume that the manufacturer will obtain R&D subsidy s if he produces green product and pays tax t if he produces ordinary product; if the manufacturer provides ordinary product and green product, he will obtain subsidy s and pay tax t at the same time.

Therefore, when the manufacturer provides one product, his profit function with the government policy is as follows:

$$\begin{aligned} \pi(q_t) &= p_1(a - p_1 + \theta_t q_t) - k_t q_t^2, \\ \text{s.t. } k_t q_t^2 &\leq c - t, \\ q_t &\geq 0. \end{aligned} \quad (8)$$

When the manufacturer provides two products, the manufacturer's profit function is

$$\begin{aligned}
\pi(q_t, q_e) &= p_1[a_1 - p_1 + \theta(p_2 - p_1) + \theta_t q_t - \theta'_e q_e] \\
&\quad + p_2[a_2 - p_2 + \theta(p_1 - p_2) + \theta_e q_e - \theta'_t q_t] - k_t q_t^2, \\
\text{s.t. } k_t q_t^2 + k_e q_e^2 &\leq c + s - t, \\
q_t, q_e &\geq 0.
\end{aligned} \tag{9}$$

Similar to Theorems 1 and 2, the optimal qualities can be obtained by replacing c with $c - t$ in Theorem 1 and replacing c with $c + s - t$ in Theorem 2. Thus, we directly give the manufacturer's strategy change by comparing the profit between with and without government policies. Therefore, we obtain the following proposition.

Proposition 2. *When parameters satisfy one of the following conditions, the government policy is unnecessary.*

- (1) If $c \geq \max\{c^*, c^{**}\}$ and $-p_1(a_2 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + ((p_1\theta'_e - p_2\theta_e)^2/4k_e) + (p_2^2\theta_t'^2 - 2p_1p_2\theta_t\theta_t'/4k_t) > 0$
- (2) If $c^{**} \geq c \geq x_1 \geq c^*$, $x_1 \in [c^*, c^{**}]$ satisfies $\pi_1^*(x_1) - \pi_2^*(x_1) = 0$
- (3) If $c^{**} \geq c \geq c^*$ and $\pi_1^*(c^*) < \pi_2^*(c^*)$
- (4) If $c^* \geq x_2 \geq c \geq c^{**}$, $x_2 \in [c^{**}, c^*]$ satisfies $\pi_1^*(x_2) - \pi_2^*(x_2) = 0$
- (5) If $c^* \geq c \geq c^{**}$ and $\pi_1^*(c^*) < \pi_2^*(c^{**})$
- (6) If $c < \min\{c^*, c^{**}\}$ and $J_1 + J_2\sqrt{c} < 0$ for any $c < \min\{c^*, c^{**}\}$
- (7) If $c < \min\{c^*, c^{**}\}$, $J_1 < 0$, $J_2 > 0$ and $c < x_3$, where $x_3 \in [0, \min\{c^{**}, c^*\}]$ satisfies $\pi_1^*(x_3) - \pi_2^*(x_3) = 0$ and
- (8) if $c < \min\{c^*, c^{**}\}$, $J_1 > 0$, $J_2 < 0$ and $c > x_3$ where $x_3 \in [0, \min\{c^{**}, c^*\}]$ satisfies $\pi_1^*(x_3) - \pi_2^*(x_3) = 0$

Proposition 2 presents all the cases that the manufacturer produces two products when there is no subsidy and tax; in these scenarios, the government do not need to provide subsidy or tax to induce the manufacturer to produce green product.

When manufacturer's optimal strategy is not restricted by the cost, then the government policy is inefficient especially when the manufacturer's optimal strategy is providing one product. In other words, no matter how much the subsidy and tax the government gives, the manufacturer will not change the product strategy. In this situation, the government may need to find other ways to induce the manufacturer to produce green product, such as grant subsidies to the green consumer, improving consumers' environmental awareness, or improving the green technology level etc. Proposition 3 presents when the subsidy and tax are inefficient.

Proposition 3. *When manufacturer's cost and other parameters satisfy one of the following conditions, the government policy is inefficient:*

- (1) if $c \geq \max\{c^*, c^{**}\}$ and $-p_1(a_2 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + ((p_1\theta'_e - p_2\theta_e)^2/4k_e) + (p_2^2\theta_t'^2 - 2p_1p_2\theta_t\theta_t'/4k_t) < 0$

- (2) if $c^{**} \geq c \geq c^*$ and $\pi_1^*(c^*) > \pi_2^*(c^{**})$
- (3) if $c^* \geq c \geq c^{**}$ and $\pi_1^*(c^{**}) > \pi_2^*(c^*)$
- (4) if $c < \min\{c^*, c^{**}\}$ and $J_1 + J_2\sqrt{c} > 0$ for any $c < \min\{c^*, c^{**}\}$

Only when the manufacturer is producing one product and facing the cost constraint, government subsidy or tax will affect manufacturer's product strategy. The optimal subsidy/tax is determined by the key points of the cost and profit with different scenarios. And the inappropriate subsidy will not only encourage the manufacturer to produce green product but also harm the environment when the manufacturer invests more money on ordinary product.

Proposition 4. *When manufacturer's cost and other parameters satisfy one of the following conditions, then the government policy is efficient, and the optimal subsidy and tax satisfy the following conditions:*

- (1) when $c^{**} \geq c \geq c^*$ and $c^{**} \geq x_1 \geq c \geq c^*$, the optimal subsidy $s = x_1 - c + 1$
- (2) when $c^* \geq c \geq c^{**}$ and $c^* \geq x_2 \geq c^{**}$, the optimal tax $t = c - x_2 + 1$
- (3) when $c < \min\{c^*, c^{**}\}$, $J_1 < 0$, $J_2 > 0$ and $c > x_3$, where $x_3 \in [0, \min\{c^{**}, c^*\}]$ satisfies $\pi_1^*(x_3) - \pi_2^*(x_3) = 0$, the optimal tax $t = c - x_3 + 1$
- (4) when $c < \min\{c^*, c^{**}\}$, $J_1 > 0$, $J_2 < 0$ and $c < x_3$, where $x_3 \in [0, \min\{c^{**}, c^*\}]$ satisfies $\pi_1^*(x_3) - \pi_2^*(x_3) = 0$, then the optimal subsidy $s = x_3 - c + 1$

Proposition 4 gives all the scenarios that the subsidy and tax influence manufacturer's product strategy and present the optimal government policy that encourages the manufacturer to change his product strategy from one product to two products. Among these scenarios, the government policy is efficient to benefit the environment. Note that in order to distinguish $c > x$ and $c \geq x$ (or $c < x$ and $c \leq x$), we let the subsidy and tax to be strictly larger than the boundary point. For example, it is $s = x_1 - c + 1$ and not $s = x_1 - c$ in Proposition 4(1).

5. Numerical Example

To better illustrate our theoretical results, we present the numerical analyses in this section. We first give some numerical examples to analyze the change of manufacturer's optimal strategies and the government policy with manufacturer's cost constraint. Then, we explore the change of qualities and profits when parameters change.

5.1. Optimal Product Strategy and Government Policy

Example 1. In this example, we examine the optimal qualities when the manufacturer produces one product and two products. Let $a = 100$, $a_1 = 60$, $a_2 = 40$, $k_t = 1$, $k_e = 1.5$, $\theta = 1$, $\theta_t = 2$, $\theta_e = 1.5$, $\theta'_t = 0.2$, $\theta'_e = 0.1$, $p_1 = 10$, and $p_2 = 16$. These parameters are consistent with our

assumptions and industrial practices. The green product provides greater environmental benefits than the ordinary product but has a higher cost and price.

Figures 2 and 3 shows that the optimal product qualities and profit increase with cost. And the qualities with two products are less than that with one product even though the cost is sufficiently large. The environmental quality is less than the traditional qualities because of the higher cost and less demand. In this example, $c^* = 100$ and $c^{**} = 158$, and when $c > 100$, the manufacturer chooses to produce two products; when $0 < c < 100$, the manufacturer produces one product. Therefore, the government could subsidize manufacturer's R&D cost to a threshold point ($c < 100$ in this example) so that the manufacturer chooses to produce two products.

Example 2. In this example, we examine the scenario when the government subsidy is inefficient. Let $a = 100$, $a_1 = 60$, $a_2 = 40$, $k_t = 1$, $k_e = 1.5$, $\theta = 1$, $\theta_t = 2$, $\theta_e = 1$, $\theta'_t = 0.2$, $\theta'_e = 0.1$, $p_1 = 10$, and $p_2 = 16$.

Similar to the conclusion that we obtained from Figure 2, Figure 4 shows that the optimal product qualities increase with cost when the government subsidy is inefficient. This means the manufacturer should choose to produce one traditional product. Figure 5 shows that the manufacturer's profit with two products is lower than that with ordinary product even though the cost is sufficiently large. From the parameter values in Example 2, we can see that consumer's sensitivity towards the environmental quality is lower than in Example 1; in other words, consumers' environmental awareness affects manufacturer's product strategies. In this scenario, the subsidizing manufacturer is inefficient; however, the government could improve consumers' environmental awareness or subsidize consumers who purchase green product to change manufacturer's strategy.

Example 3. In this example, we explore the manufacturer's optimal strategy when the green product has a higher cost coefficient but only has a slightly higher price compared with Example 2. Let $a = 100$, $a_1 = 60$, $a_2 = 40$, $k_t = 1$, $k_e = 1.5$, $\theta = 1$, $\theta_t = 2$, $\theta_e = 1$, $\theta'_t = 0.2$, $\theta'_e = 0.1$, $p_1 = 5$, and $p_2 = 6$.

Figures 6 and 7 show that without government policy, the manufacturer's optimal strategy is producing two products. In this scenario, the green product only has a slightly higher price than the ordinary product; hence, the manufacturer invests more on the ordinary product, and the environmental quality of the green product is very small. In this case, even though the manufacturer chooses to produce two products, the green product's environmental quality is very small, and thus, the green product has less impact on environment quality. Therefore, the government could improve environment quality by improving consumers' environmental awareness or the R&D technology of the green product when the cost coefficient of the green technology is very high and the consumer's environmental quality is much lower.

Example 4. In this example, we explore the scenario when the green product's cost coefficient and price are much lower

FIGURE 2: Optimal qualities as a function of c . Notes: q_{1t} represents the optimal traditional quality when the manufacturer provides one product; q_{2t} and q_{2e} represent the optimal traditional quality and environmental quality when the manufacturer provides two products.

FIGURE 3: Profits as a function of c .

FIGURE 4: Optimal qualities as a function of c .

than those of the ordinary product, and consumer's sensitivity towards environmental quality is lower than consumer's sensitivity towards traditional quality. This scenario

FIGURE 5: Profits as a function of c . FIGURE 6: Optimal qualities as a function of c . FIGURE 7: Profits as a function of c .

represents that the green technology has developed very well, but consumers pay less attention to the environmental quality of the product than the traditional quality of the product. Let $a = 100$, $a_1 = 60$, $a_2 = 40$, $k_t = 1$, $k_e = 0.5$, $\theta = 1$, $\theta_t = 2$, $\theta_e = 1.5$, $\theta'_t = 0.2$, $\theta'_e = 0.1$, $p_1 = 10$, and $p_2 = 8$.

Figure 8 shows that the optimal environmental quality of green product is higher than the traditional quality of

ordinary product. In other words, when the cost inefficient of environment quality is much less than that of traditional quality, the manufacturer tends to improve much more environment quality of the product. Hence, the degree of technological maturity is the key point to induce the manufacturer to produce green product. Figure 9 shows that the optimal profits increase with cost. And we obtain that the manufacturer's profit with two products is lower than that with ordinary product when the green product's cost coefficient and price are much lower than those of the ordinary product.

5.2. Sensitivity Analysis. In this section, we present the sensitivity analysis of consumer sensitivity towards environmental quality, the cost coefficient of the environmental quality, and the price of green product.

5.2.1. Impact of Consumer Sensitivity towards Environmental Quality on Qualities and Profits. Let $a = 100$, $c = 100$, $a_1 = 60$, $a_2 = 40$, $k_t = 1$, $k_e = 1.5$, $\theta = 1$, $\theta_t = 2$, $\theta'_t = 0.2$, $p_1 = 10$, and $p_2 = 16$. Because the demand switch over toward the environmental quality difference θ'_e is related to the consumers' environmental awareness θ_e , we assume that $\theta'_e = 0.1\theta_e$ to illustrate the effect of the consumers' environmental awareness on manufacturer's product strategy.

From Figures 10 and 11, we could see that the environmental quality of the green product increases with θ_e but the traditional quality of ordinary product decreases when the manufacturer produces two products, and the environmental quality exceeds traditional quality when $\theta_e > 1.7$. When the manufacturer provides one product, then the optimal traditional quality keeps a constant with θ_e . The manufacturer's profit increases with θ_e when the manufacturer produces two products, and the profit with two products is larger than that with one product when $\theta_e > 1.5$. Therefore, consumers' environmental awareness is a main factor to influence manufacturer's product strategy.

5.2.2. Impact of Cost Coefficient of Environmental Quality on Qualities and Profits. In this section, we present the changes of product qualities and manufacturer's profits with cost coefficient of environmental quality. Let $a = 100$, $c = 100$, $a_1 = 60$, $a_2 = 40$, $k_t = 1$, $\theta = 1$, $\theta_t = 2$, $\theta'_t = 0.2$, $\theta_e = 1.5$, $\theta'_t = 0.1$, $p_1 = 10$, $p_2 = 16$, and $k_e \in [1, 3]$.

Figures 12 and 13 show that the environmental quality of green product and manufacturer's profit decrease with k_e . When $k_e < 1.4$, the environmental quality is larger than traditional quality and the manufacturer's profit with two products is larger than that with one product; when $k_e \geq 1.4$, the environmental quality is less than traditional quality and the manufacturer's profit with two products is lower than that with one product. Therefore, the cost coefficient of improving environmental quality could influence manufacturer's strategy significantly.

5.2.3. Impact of Price of Green Product on Qualities and Profits. In this section, we show the changes of product

FIGURE 8: Optimal qualities as a function of c . FIGURE 11: Profits as a function of θ_e . FIGURE 9: Profits as a function of c . FIGURE 12: Optimal qualities as a function of k_e . FIGURE 10: Optimal qualities as a function of θ_e . FIGURE 13: Profits as a function of k_e .

qualities and manufacturer's profits with green product's price. Let $a = 100$, $c = 100$, $a_1 = 55$, $a_2 = 45$, $k_t = 1$, $k_e = 1.5$, $\theta = 1$, $\theta_t = 2$, $\theta'_t = 0.2$, $\theta_e = 1.5$, $\theta'_e = 0.1$, $p_1 = 10$, and $p_2 \in [10, 30]$.

Figure 14 shows that the environmental quality increases when the price of green product increases, but the traditional quality decreases when the manufacturer provides two products. However, manufacturer's profit first goes up then goes down with p_2 (Figure 15) because the demand decreases with p_2 and when $14 < p_2 < 23$, the manufacturer will produce two products. It means that higher price or lower

FIGURE 14: Optimal qualities and profits as a function of p_2 . FIGURE 15: Profits as a function of p_2 .

price of the green product may not induce the manufacturer to produce two products. Appropriate pricing of the green product will benefit not only the manufacturer but also the environment.

6. Conclusions

This study explores how the manufacturer effectively balances the finite investment between the green product and the ordinary product with consumers' environmental awareness. Our study points out some important managerial insights.

6.1. Managerial Implications. This study has five main managerial implications. Firstly, the manufacturer's optimal product strategy may not produce two products even through the budget is sufficient large, and the manufacturer may choose to invest two products when the budget is very small, and the optimal product strategy still depends on price, consumers' environmental awareness, cost coefficient, and so on. Secondly, not all the government policies are efficient to encourage the manufacturer to provide green product: the government policy will not

affect manufacturer's product strategy when the manufacturer's product strategy is not influenced by the cost; the government policy is redundant when the market could push the manufacturer to produce green product. Thirdly, the cost coefficients of improving environmental quality and CEA are significant factors to influence manufacturer's strategy. When the government policies are not efficient, the government could take some measures to stimulate the technology innovation to decrease green product's cost or improve CEA or subsidize consumers who purchase green product to change manufacturer's strategy. Fourthly, green product's price affects manufacturer's product strategy significantly. The government could subsidize green product to influence the green product's price, so that the manufacturer produces green product. Finally, the subsidy and tax policies are mutual exclusion; either subsidy or tax could play a role in changing manufacturer's strategy, and the optimal subsidy or tax are determined by the cost constraint and the manufacturer's profit.

6.2. Limitations. Our model has certain limitations; it presents opportunities for future research. The model focuses on product design; therefore, the cost is mainly related to the R&D cost; not including the variable cost in manufacturing, one may consider the variable cost and R&D cost simultaneously. Further, most studies focus on subsidizing consumers; hence, we could further combine more types of subsidy or tax policies to examine the effectiveness of the government policy.

Appendix

Proof of Theorem 1. Define the Lagrange function

$$L(q_t, \lambda) = p_1(a - p_1 + \theta_t q_t) - k_t q_t^2 + \lambda(c - k_t q_t^2). \quad (\text{A.1})$$

It is obvious that $\pi(q_t)$ is concave with q_t , with KKT condition; the optimal solution could be determined by the following equations:

$$\begin{cases} \frac{\partial \pi}{\partial q_t} = 0, \\ \lambda(c - k_t q_t^2) = 0, \\ c - k_t q_t^2 \geq 0, \\ \lambda \geq 0. \end{cases} \quad (\text{A.2})$$

Let $\partial \pi / \partial q_t = 0$, then $q_t' = \theta_t p_1 / 2k_t$ and $q_t' \geq 0$; substitute $q_t' = \theta_t p_1 / 2k_t$ into $c = k_t q_t^2$. Then, the authors obtain $c^* = p_1^2 \theta_t^2 / 4k_t$.

If $c \geq c^*$ and $\lambda = 0$, then the optimal quality is $q_t^* = \theta_t p_1 / 2k_t$. If $c < c^*$, then the optimal quality is determined by $k_t q_t^2 = c$; thus, the optimal quality is $q_t^* = \sqrt{c/k_t}$. $\square$

Proof of Theorem 2

$$\begin{aligned} \pi(q_t, q_e) = & p_1(a_1 - p_1 + \theta(p_2 - p_1) + \theta_t q_t - \theta'_e q_e) \\ & + p_2(a_2 - p_2 + \theta(p_1 - p_2) + \theta_e q_e - \theta'_t q_t) \\ & - k_t q_t^2 - k_e q_e^2, \end{aligned}$$

$$\text{s.t. } k_t q_t^2 + k_e q_e^2 \leq c,$$

$$q_t, q_e \geq 0.$$

(A.3)

Define the Lagrange function $L(q_t, q_e, \lambda) = p_1[a_1 - p_1 + \theta(p_2 - p_1) + \theta_t q_t - \theta'_e q_e] + p_2[a_2 - p_2 + \theta(p_1 - p_2) + \theta_e q_e - \theta'_t q_t] - k_t q_t^2 - k_e q_e^2 + \mu(c - k_t q_t^2 - k_e q_e^2)$. It is obvious that $\pi(q_t, q_e)$ is quasi-concave with q_t and q_e , with KKT condition, and the optimal solution could be determined by the following equations:

$$\begin{cases} \frac{\partial \pi}{\partial q_t} = 0, \\ \frac{\partial \pi}{\partial q_e} = 0, \\ \mu(c - k_t q_t^2 - k_e q_e^2) = 0, \\ c - k_t q_t^2 - k_e q_e^2 \geq 0, \\ \mu \geq 0. \end{cases} \quad (\text{A.4})$$

Let $\partial \pi / \partial q_t = 0$ and $\partial \pi / \partial q_e = 0$, then

$$\begin{aligned} q'_t &= \frac{p_1 \theta_t - p_2 \theta'_t}{2k_t}, \\ q'_e &= \frac{p_2 \theta_e - p_1 \theta'_e}{2k_e}, \end{aligned} \quad (\text{A.5})$$

$$q'_t, q'_e \geq 0.$$

Substitute q'_t and q'_e into $c' = k_t q_t^2 + k_e q_e^2$. Then, the authors obtain $c^{**} = ((p_1 \theta'_e - p_2 \theta_e)^2 / 4k_e) + ((p_1 \theta_t - p_2 \theta'_t)^2 / 4k_t)$.

(1) If $c \geq c^{**}$ and $\mu = 0$, then the optimal qualities are

$$\begin{aligned} q'_t &= \frac{p_1 \theta_t - p_2 \theta'_t}{2k_t}, \\ q'_e &= \frac{p_2 \theta_e - p_1 \theta'_e}{2k_e}. \end{aligned} \quad (\text{A.6})$$

(2) If $c < c^{**}$, then the optimal qualities satisfy $k_t q_t^2 + k_e q_e^2 = c$, and then, we obtain $q_e = \sqrt{(c - k_t q_t^2) / k_e}$.

Substitute $q_e = \sqrt{(c - k_t q_t^2) / k_e}$ into $\pi(q_t, q_e)$; then, the $\pi(q_t, q_e)$ is transformed into $\pi(q_t)$ (the function of q_t):

$\pi(q_t)|_{q_e=\sqrt{(c-k_t q_t^2)/k_e}} = p_1(a_1 - p_1 + \theta(p_2 - p_1) + \theta_t q_t - \theta'_e q_e) + p_2(a_2 - p_2 + \theta(p_1 - p_2) + \theta_e q_e - \theta'_t q_t) - k_t q_t^2 - k_e q_e^2$; then, the optimal quality q_t could be derived by $\partial \pi(q_t)|_{q_e=\sqrt{(c-k_t q_t^2)/k_e}} / \partial q_t = 0$ (because of the concavity of $\pi(q_t)|_{q_e=\sqrt{(c-k_t q_t^2)/k_e}}$)

Thus,

$$\begin{aligned} q_t &= (p_1 \theta_t - p_2 \theta'_t) \sqrt{\frac{ck_e}{k_t [k_t (p_1 \theta'_e - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta'_t)^2]}}, \\ q_e &= (p_2 \theta_e - p_1 \theta'_e) \sqrt{\frac{ck_t}{k_e [k_t (p_1 \theta'_e - p_2 \theta_e)^2 + k_e (p_1 \theta_t - p_2 \theta'_t)^2]}}. \end{aligned} \quad (\text{A.7})$$

□

Proof of Proposition 1

- (1) When $c \geq \max\{c^*, c^{**}\}$, $\pi_1^* = p_1(a_1 - p_1) + (p_1^2 \theta_t^2 / 4k_t)$ and $\pi_2^* = p_1(a_1 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + ((p_1 \theta'_e - p_2 \theta_e)^2 / 4k_e) + ((p_1 \theta_t - p_2 \theta'_t)^2 / 4k_t)$; hence, if $\pi_1^* > \pi_2^*$, the manufacturer produces one product or else produces two products.
- (2) When $c^{**} \geq c \geq c^*$, π_2^* increases with c and π_1^* is constant with c ; hence, there is at most one point $c = x_1 \in [c^*, c^{**}]$ that satisfies $\pi_1^*(x_1) - \pi_2^*(x_1) = 0$:
 - (i) If $c^{**} \geq x_1 \geq c \geq c^*$, $\pi_1^*(c) > \pi_2^*(c)$, then the manufacturer chooses to produce one product.
 - (ii) If $c^{**} \geq c \geq x_1 \geq c^*$, $\pi_1^*(c) < \pi_2^*(c)$, then the manufacturer chooses to produce two products.
 - (iii) If $\pi_1^*(c^*) > \pi_2^*(c^{**})$, then $\pi_1^*(x) > \pi_2^*(x)$ for any $x \in [c^*, c^{**}]$. Further, $\pi_1^*(x) > \pi_2^*(x)$ for any $x \in [c^*, +\infty]$, because $\pi_2^*(x) = \pi_2^*(c^{**}) < \pi_1^*(c^*)$, $\pi_1^*(x) = \pi_1^*(c^*)$ if $x \in [c^{**}, +\infty]$. So manufacturer chooses to produce one product.
 - (iv) If $\pi_1^*(c^*) < \pi_2^*(c^*)$, then $\pi_1^*(x) < \pi_2^*(x)$ for any $x \in [c^*, c^{**}]$. Further, $\pi_1^*(x) < \pi_2^*(x)$ for any $x \in [c^*, +\infty]$, because $\pi_2^*(x) = \pi_2^*(c^{**}) > \pi_2^*(c^*)$, $\pi_1^*(x) = \pi_1^*(c^*)$ if $x \in [c^{**}, +\infty]$. So manufacturer chooses to produce two products.
- (3) Similar to (2).
- (4) When $c < \min\{c^*, c^{**}\}$,

$$\begin{aligned} \pi_1^* - \pi_2^* &= p_1 \left(a - p_1 + \theta_t \sqrt{\frac{c}{k_t}} \right) - c - p_1(a_1 - p_1) \\ &\quad - p_2(a_2 - p_2) + \theta(p_1 - p_2)^2 - (G_1 + G_2)\sqrt{c} + c \\ &= J_1 + J_2\sqrt{c}, \end{aligned} \quad (\text{A.8})$$

where $J_1 = p_1(a_2 - p_1) - p_2(a_2 - p_2) + \theta(p_1 - p_2)^2$ and $J_2 = (p_1 \theta_t / \sqrt{k_t}) - G_1 - G_2$.

$$G_1 = (p_1\theta_t - p_2\theta'_t)^2 \sqrt{\frac{k_e}{k_t}} \sqrt{\frac{1}{[k_t(p_1\theta'_e - p_2\theta_e)^2 + k_e(p_1\theta_t - p_2\theta'_t)^2]}}$$

$$G_2 = (p_2\theta_e - p_1\theta'_e)^2 \sqrt{\frac{k_t}{k_e}} \sqrt{\frac{1}{[k_t(p_1\theta'_e - p_2\theta_e)^2 + k_e(p_1\theta_t - p_2\theta'_t)^2]}}$$
(A.9)

If $\pi_1^* - \pi_2^* > 0$ for any $c < \min\{c^*, c^{**}\}$, then the manufacturer chooses to produce one product.

If $\pi_1^* - \pi_2^* < 0$ for any $c < \min\{c^*, c^{**}\}$, then the manufacturer chooses to produce two products.

Or else, let $x_3 = J_1^2/J_2^2$ satisfies $\pi_1^* - \pi_2^* = J_1 + J_2\sqrt{c} = 0$; then, when $J_1 < 0, J_2 > 0$; if $c > x_3$ and $\pi_1^* - \pi_2^* > 0$; then, the manufacturer produces one product; if $c < x_3$ and $\pi_1^* - \pi_2^* < 0$, the manufacturer produces two products.

When $J_1 > 0, J_2 < 0$; if $c < x_3$ and $\pi_1^* - \pi_2^* > 0$; then, the manufacturer produces one product; if $c > x_3$ and $\pi_1^* - \pi_2^* < 0$, the manufacturer produces two products. $\square$

Proof of Proposition 2. It is obvious to obtain the results. $\square$

Proof of Proposition 3

- (1) When $c \geq \max\{c^*, c^{**}\}$, $\pi_1^* = p_1(a_1 - p_1) + (p_1^2\theta_t^2/4k_t)$ and $\pi_2^* = p_1(a_1 - p_1) + p_2(a_2 - p_2) - \theta(p_1 - p_2)^2 + ((p_1\theta'_e - p_2\theta_e)^2/4k_e) + ((p_1\theta_t - p_2\theta'_t)^2/4k_t)$; hence, if $\pi_1^* > \pi_2^*$, the manufacturer produces one product or else produces two products. And π_1^* and π_2^* are constant with c and the change of c will not change manufacturer's strategy.
- (2) If $c^{**} \geq c \geq c^*$ and $\pi_1^*(c^*) > \pi_2^*(c^{**})$, then $\pi_1^*(x) > \pi_2^*(x)$ for any $x \in [c^*, +\infty]$ because $\pi_2^*(x) = \pi_2^*(c^{**}) < \pi_1^*(c^*)$, $\pi_1^*(x) = \pi_1^*(c^*)$ if $x \in [c^{**}, +\infty]$. So grant subsidies to the manufacturer will not change their product strategy.
- (3) Similar to (2).
- (4) If $\pi_1^* - \pi_2^* > 0$, that is, $J_1 + J_2\sqrt{c} > 0$, for any $c < \min\{c^*, c^{**}\}$; then, the manufacturer chooses to produce one product. And the change of c will not change manufacturer's strategy.

And if there is some subsidy, the manufacturer will invest more on traditional product; thus, it is harmful to the environment. $\square$

Proof of Proposition 4

- (1) If $c^{**} \geq x_1 \geq c \geq c^*$ then subsidize the manufacturer $s = x_1 - c + 1$; then, the new cost constraint $c' = x_1 + 1$, and the manufacturer turns to produce two products according to Proposition 1 (2)(ii).
- (2) If $c^* \geq c \geq x_2 \geq c^{**}$, then tax the manufacturer $t = c - x_2 + 1$; then, the new cost constraint $c' = x_2 - 1$, and the manufacturer turns to produce two products according to Proposition 1 (3)(ii).
- (3) When $J_1 < 0, J_2 > 0$; if $c > x_3$, tax $t = c - x_3 + 1$; then, the new cost constraint $c' = x_3 - 1$, and the

manufacturer turns to produce two products according to Proposition 1 (4)(iii).

- (4) When $J_1 > 0, J_2 < 0$; if $c < x_3$, then subsidize the manufacturer $s = x_3 - c + 1$; then, the new cost constraint $c' = x_3 + 1$, and the manufacturer turns to produce two products according to Proposition 1 (4)(iv). $\square$

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

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

Authors' Contributions

Linghing Zhang conceived and designed the research question. Linghong Zhang and Hao Zhou contributed significantly to the analysis and manuscript preparation. Hao Zhou performed the model analyses and wrote the manuscript. Linghong Zhang helped perform the analysis with constructive discussions. All authors read and approved the manuscript.

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