Green Product Design Considering Consumer’s Income and Environmental Awareness

Na Liu 1* and Linghong Zhang 1
1 Business School, Shandong Normal University, Ji’nan 250014, China
*Corresponding author’s email: 2018020935@stu.sdnu.edu.cn

Abstract. With the enhancement of consumer environmental awareness, many companies are paying more attention to developing green products with higher environmental quality. In this paper, we study how the consumer’s valuation towards product’s qualities and consumer demand affect manufacturer’s product design and pricing regimes. Assuming there is a monopolist who manufacture products with traditional and environmental qualities and the market is divided into four segments according to consumer’s income level and environmental awareness, we give the optimal closed form solutions of the qualities and prices of products in mass-market and segment-market strategies. Additionally, we discuss the impacts of consumers’ valuation towards products’ qualities and market segments’ size on the total environmental qualities. We find that (i) various parameters, especially consumers’ valuation towards products’ qualities and market share of each segment affect the firm’s choice on market strategies and consequent environmental performance; (ii) green product development does not always increase and may decrease the degree of environmentally friendliness.

1. Introduction

Environmental degradation has generated increasing concerns among people who pay more attention to the environmental characteristics of products, such as the use of recycled materials, reduced toxicity and energy efficiency of the product. For example, Wang et al. found that environmental awareness affects the willingness to purchase energy-efficient appliances[1].

Considering the impact of consumer environmental awareness (CEA) (Zhang [2], Hong et al [3]), researchers have begun to study the green market segmentation. Zhu et al. developed and analyzed a product differential model on petrol vehicles and new energy vehicles for a monopolist who manufacture both vehicles and the market is categorized into two segments: primary consumers and replacement consumers[4]. For firms, it represents a significant marketing opportunity to develop environmental-friendly products targeting the needs. Meanwhile, since consumers self-select the product they purchase and products within a product can be cannibalized. Firms need to consider the issue carefully in designing their product line design.

Green product design, which has been widely studied in the literature, has been a significant practice for achieving sustainability. Du et al. studied firm’s green production decisions considering the competing of green and traditional products in the market which is separated by consumer’s green valuations [5]. Dey et al. assessed the power structures and strategic inventory effects on the green product types under three purchase strategies in a two-level supply chain [6].

This study mainly makes two contributions to the literature: First, we consider the market is divided into four segments according to both consumers’ income and environment awareness, while most of other papers studying how segmentation affects manufacturer’s production strategy did not...
consider using both to segment market. Second, the paper integrates the proportion of consumers with high environmental awareness and high income as significant parameters into the model and explore the impact of them on profit and greenness.

2. Literature review

Our work is closely related to the research on market segmentation and green product line design. Here we review the recent literature related to the two research streams.

2.1. Market segmentation

Abundant papers have been addressed the issue of Market segmentation. Some studies distinguished consumers based on their cognitions. Du et al. developed models to help make green production decisions in the market with two segments differing in consumer’s willingness-to-pay and premiums for product’s environmental quality in both monopolist and duopoly cases [5]. Zhang et al. developed mathematical models to investigate how development cost affects company’s product design when facing the ordinary consumers and green consumers, divided by differentiation of consumer environmental conscious and green valuations [7]. There are some studies related to the organic products. For example, Buder et al. investigated the segmentation framework by using real data and find critical factors affecting purchasing organic foods: price, insufficient availability and quality[8].

2.2. Green product line design

Green product line design has been widely explored in the literature. Some researches mainly examined price strategies or quality design of green product line. Mitra explored the optimal pricing and core acquisition strategy considering the buy-back mechanism [9]. Mantovani et al. proposed a vertically differentiated duopoly model to explore the effect of price competition on technological choice between end-of-pipe and cleaner production. They arrived at the conclusion that the intensity of competition, consumers’ income gap and consumer environmental consciousness can have significant effect on green producer’s choice [10]. Choi examined the optimal pricing and brand investment strategies of remanufactured fashion products. The analysis presented solution for remanufactured fashion products companies to make optimal decisions on Pricing and branding [11]. Abundant studies explored both price strategies and quality design towards green products. For example, Gao et al. considered a supply chain consisting a manufacturer who produces two types of environmentally friendly products under government interventions. They examined green product design in the supply chain and derived the optimal tax, green degree and price for the product[12].

3. Problem assumptions and model description

We assume that there is a monopolist who serve products with two different attributes, environmental attributes and traditional attributes, which are behaved like “qualities” and thus are called environmental qualities (denote as \( q_e \)) and traditional qualities (denote as \( q_t \)).

We assume that there are \( N \) consumers in the market and the market is divided into four segments according to consumers’ income and environmental awareness. Figure 1 shows market segmentation. We further assume that the proportion of consumers with high environmental awareness and consumers with high income is \( n_1 \) and \( n_2 \) of the market respectively, then the proportion of consumers with low environmental awareness and consumers with low income are \( 1 - n_1 \) and \( 1 - n_2 \), i.e., \( n_1, n_2 \leq 1 \). Customers in segment I value a unit of product with qualities \( q_t \) and \( q_e \) at \( v_t^H q_t + v_e^H q_e \), where \( v_t^H \) and \( v_e^H \) are the positive marginal valuations on the two qualities. Similarly, customers in segment II value a unit of product with qualities \( q_t \) and \( q_e \) at \( v_t^H q_t + v_e^H q_e \), customers in segment III value that at \( v_t^L q_t + v_e^L q_e \) and customers in segment IV value that at \( v_t^L q_t + v_e^L q_e \). We also assume that each consumer will only buy a unit of the product or none.

The monopolist plans to supply the market with either a single or two product types. Similar to Chen [13], we model the variable production cost as an increasing quadratic function with respect to the levels of its two qualities, which is \( c_t q_t^2 + c_e q_e^2 \), where \( c_t \) and \( c_e \) are the variable manufacturing
cost coefficients and are strictly positive. We assume that there is a fixed cost \( F \) to introduce a product to the market, regardless of the product type. Figure 2 shows product types of this paper.

![Figure 1: Market segmentation](image1.png)  
**Figure 1. Market segmentation**

![Figure 2: Product types](image2.png)  
**Figure 2. Product types**

Based on the analysis above, we can specify the efficient qualities that maximize the differences between customers’ valuation and the monopolist’s production cost by standard calculus. For example, the efficient environmental and traditional qualities for segment I are \( \frac{v^h}{2c_e} \) and \( \frac{v^h}{2c_t} \) separately, which maximize \( v^e q^e_q^e + v^h q^h_q^h - \left( c_e q^e_q^e + c_t q^h_q^h \right) \). Table 1 summarizes the major notations.

| Variable | Meaning |
|----------|---------|
| \( N \) | market size |
| \( n_1, n_2 \) | the proportion of consumers with high environmental awareness and consumers with high income respectively |
| \( c_t, c_e \) | cost coefficient of production |
| \( v_t, v_e \) | the positive marginal valuations on traditional and environmental attributes respectively |
| \( F \) | fixed cost to introduce a product to the market |
| \( \pi \) | the expected monopolist’s profit |
| \( p_i \) | the product’s price |
| \( q_t \) | traditional qualities |
| \( q_e \) | environmental qualities |

### 4. Model formulation and solution

In this section, we explore the monopolist’s optimal product types selection issue. Given the information about market segmentation and production cost, the manufacturer shall adopt a product strategy which consists of product type(s) and corresponding qualities and prices. In this paper, we consider two product strategies, Mass-market and Segment-market. The former is to serve the entire market with a single product. There are two possibilities of the latter strategy: (i) introduce a single product to one market segment, (ii) introduce multiple products to according multiple market segments.

#### 4.1. Mass-market strategy

If the firm intends to serve the four segments with a single product, the manufacturer’s problem is

\[
\max \pi(q_e, q_t, p) = N(p - c_e q_e^2 - c_t q_t^2) - F
\]

subject to:

\[
\begin{align*}
    v^e q_e + v^h q_t & - p \geq 0, \\
    v^h q_e + v^t q_t & - p \geq 0, \\
    v^e q_e + v^l q_t & - p \geq 0, \\
    v^h q_e + v^l q_t & - p \geq 0, \\
    p, q_e, q_t & \geq 0.
\end{align*}
\]

The function (1) is the firm’s objective function, which is to maximize the difference between the revenues and the fixed cost for introducing the product. Participation constraints (2) to (5) are used to
Proposition 1. In Mass-market model, the optimal environmental qualities, traditional qualities and price are determined by:

\[ q_e^* = \frac{v_e^L}{2c_e}, \quad q_t^* = \frac{v_t^L}{2c_t} \quad \text{and} \quad p^* = \frac{v_e^L}{2c_e} + \frac{v_t^L}{2c_t} \]  

(7)

Proposition 1 means that if the firm wants to supply all the market with a single product, then what it shall do is to provide a product that could satisfy consumers with the lowest consumption level.

4.2. Segment-market strategy

In this section, we assume the firm intends to adopt segment-market strategy. There are four market segments and the firm can decide whether to serve a single segment with an appropriate product or introduce multiple products to corresponding segments. In this subsection, we limit our study scope and focus on serving two segments with appropriate products combination.

4.2.1. Segment-market strategy with a single product. we examine the case where the firm produce a single product aimed to segment I. Considering that the low-qualities product could cannibalize the demand from product with high qualities, serving only the segment II or III or IV is impossible because whenever the three segments buy, so does the segment I. Then the monopolist’s problem can be written as:

\[
\max \pi(q_e, q_t, p) = n_1n_2N(p - c_eq_e^{H2} - c_tq_t^{H2}) - F
\]  

(8)

subject to:

\[ v_e^Hq_e^H + v_t^Hq_t^H - p \geq 0, \]
\[ p, q_e^H, q_t^H \geq 0. \]  

(9)

Differentiating the function (8) with respect to \( q_e^H \) and \( q_t^H \) respectively.

Proposition 2. If the firm adopts Segment-market Strategy and target a single segment to introduce an appropriate product, the optimal qualities and price are given as follows:

\[ q_e^{H*} = \frac{v_e^H}{2c_e}, \quad q_t^{H*} = \frac{v_t^H}{2c_t} \quad \text{and} \quad p^* = \frac{v_e^H}{2c_e} + \frac{v_t^H}{2c_t} \]  

(11)

Proposition 2 means that if the firm intends to choose a single product to serve one segment, its optimal decision is to serve the highest segment with efficient qualities and set the price equal to the customer’s valuation in that segment.

4.2.2. Segment-market strategy with two products. we examine the case where the firm adopts Segment-market strategy and intends to serve two segments with two appropriate products, then there will be two available combinations: (I, II) and (I, III). As serving only the segment II or III or IV is impossible, serving only segments (I, IV) is also not possible because whenever segment IV buys-whenever \( p_4 \leq v_e^Lq_e^L + v_t^Lq_t^L \) so do the segment II and III, the same goes for (II,III), (II, IV) and (III, IV). The monopolist target a product line of qualities \( (q_e^H, q_t^H), (q_e^L, q_t^L) \) at price \( p_1, p_2 \) to the segment land II separately. Then the monopolist’s problem is:

\[
\max \pi(q_e^H, q_e^L, q_t^H, q_t^L, p_1, p_2) = n_1n_2N(p_1 - c_eq_e^{H2} - c_tq_t^{L2}) \\
+ (1 - n_1)n_2N(p_2 - c_eq_e^{L2} - c_tq_t^{H2}) - 2F
\]  

(12)

subject to:

\[ v_e^Hq_e^H + v_t^Hq_t^H - p_1 \geq v_e^Hq_e^L + v_t^Hq_t^L - p_2, \]
\[ v_e^Lq_e^L + v_t^Hq_t^H - p_2 \geq v_e^Lq_e^H + v_t^Hq_t^L - p_1, \]
\[ v_e^Hq_e^L + v_t^Lq_t^H - p_1 \geq 0, \]
\[ v_e^Lq_e^H + v_t^Lq_t^L - p_2 \geq 0, \]
\[ q_e^H, q_e^L, q_t^H, q_t^L, p_1, p_2 \geq 0. \]  

(13)

(14)

(15)

(16)

(17)
Like constraints (2) to (5), constraints (15) and (16) are participation constraints. Besides, the constraints (13) and (14) are the “self-selection” constraints for the segment I and II, which are served to ensure that each segment voluntarily chooses the product-price combination directed to them.

If the monopolist intends to extract all the segment I’s consumer surplus by binding constraint (15) (set \( p_1 = v_e^H q_e^H + v_I^H q_I^H \), then the customers in the segment I will switch to the product II and thus get a positive surplus, since \( p_1 \leq v_e^H q_e^H + v_I^H q_I^H \leq v_e^H q_e^H + v_I^H q_I^H \). Nevertheless, nothing could prevent the monopolist from extracting the segment II’s entire consumer surplus. Hence, the constraint (16) binds \( p_2 = v_e^H q_e^H + v_I^H q_I^H \). Notice that the constraints (13) and (14) can be written as \( p_1 - p_2 \leq v_e^H (q_e^H - q_e^L) \) and \( p_1 - p_2 \geq v_e^H (q_e^H - q_e^L) \), respectively. Since \( v_e^H > v_e^L \), constraints (13) and (14) cannot bind both or else \( q_e^H = q_e^L \) (i.e., only one product is introduced). The consumers in the segment I are more willing to pay high qualities, thus constraint (13) is binding.

**Proposition 3.** When the firm adopts Segment-market Strategy and targets segments I and II to introduce two appropriate products, the optimal qualities and associated prices are given by:

(i) if \( v_e^H - n_1 v_e^L \geq 0 \),

\[
q_e^H^* = \frac{v_e^H}{2c_e}, \quad q_I^H^* = \frac{v_I^H}{2c_I}, \quad q_e^L^* = \frac{v_e^L - n_1 v_e^H}{2(1-n_1)c_e} \quad \text{and} \quad p_1^* = \frac{v_e^H}{2c_e} + \frac{v_I^H}{2c_I} - \frac{(v_e^H - v_e^L)(v_e^L - n_1 v_e^H)}{2(1-n_1)c_e} + \frac{v_I^H}{2c_I} \quad (18)
\]

(ii) if \( v_e^H - n_1 v_e^L \leq 0 \),

\[
q_e^H^* = \frac{v_e^H}{2c_e}, \quad q_I^H^* = \frac{v_I^H}{2c_I}, \quad q_e^L^* = 0 \quad \text{and} \quad p_1^* = \frac{v_e^H}{2c_e} + \frac{v_I^H}{2c_I} \quad (20)
\]

Proposition 3 indicates that the optimal qualities for segment I equal to the segment’s efficient qualities and the optimal environmental qualities for segment II equal to the difference between the segment’s efficient environmental equalities \( q_e^H^* \) and \( q_I^H^* \) when \( v_e^L \) is higher than \( n_1 v_e^H \). Notice that \( \frac{n_1}{1-n_1} \) is the ratio between the size of segment I and segment II. The optimal price for segment II equals to the customers’ valuation of the product targeted to it. Additionally, the optimal price for segment I is lower than customers’ valuation of the product when \( v_e^L \) is greater than \( n_1 v_e^H \) and while \( v_e^L \) is less than or equals to \( n_1 v_e^H \), the optimal price for segment I equals to the customers’ valuation.

Then we consider the case where the monopolist target a product combination of qualities \((q_e^H, q_I^H, q_e^L, q_I^L)\) at price \( p_1, p_3 \) to the segment I and III separately. Then the firm’s problem is as follows:

\[
\max \pi(q_e^H, q_I^H, q_e^L, q_I^L, p_1, p_3) = n_1 n_2 N(p_1 - c_e q_e^H^2 - c_I q_I^L^2) + \frac{n_1}{1-n_1} N(p_3 - c_e q_e^L^2 - c_I q_I^H^2) - 2F \quad (22)
\]

subject to

\[
\begin{align*}
v_e^H q_e^H + v_I^H q_I^H - p_1 & \geq v_e^H q_e^H + v_I^H q_I^H - p_3, \quad (23) \\
v_e^H q_e^H + v_I^H q_I^H - p_3 & \geq v_e^H q_e^H + v_I^H q_I^H - p_1, \quad (24) \\
v_e^H q_e^L + v_I^H q_I^L - p_1 & \geq 0, \quad (25) \\
v_e^H q_e^L + v_I^H q_I^L - p_3 & \geq 0, \quad (26) \\
q_e^H, q_I^H, q_e^L, q_I^L, p_1, p_3 & \geq 0. \quad (27)
\end{align*}
\]

Like the constraints in segment-market strategy of segment I and II, constraints (23) and (24) are participation constraints and constraints (21) and (22) are the “self-selection” constraints for the segment I and III. Similar to the analysis in segment-market strategy of segment I and II, the constraint (26) should be bound \( p_3 = v_e^H q_e^H + v_I^H q_I^H \). Since the consumers in segment I are more likely to pay higher qualities, constraint (23) is binding.
Proposition 4. If the firm adopts Segment-market Strategy and chooses segment I and III to introduce two according products, the optimal qualities and associated prices are given by:

(i) if \( v^H_1 - n_2 v^H_t > 0 \),

\[
q_e^H = \frac{v^H_e}{2c_e}, q_t^H = \frac{v^H_t}{2c_t}, q^I = \frac{v^I_t - n_2 v^H_t}{2(1-n_2)c_t} \quad \text{and}
\]
\[
p^I_1 = \frac{v^I_t^2 + v^H_t^2}{2c_t} - \frac{(v^I_t - v^H_t)(v^I_t - n_2 v^H_t)}{2(1-n_2)c_t},
\]
\[
p^I_2 = \frac{v^I_t^2 - n_2 v^I_t^H v^H_t}{2(1-n_2)c_t} + \frac{v^H_t^2}{2c_e}
\]

(ii) if \( v^I_1 - n_2 v^H_t \leq 0 \),

\[
q_e^H = \frac{v^H_e}{2c_e}, q_t^H = \frac{v^H_t}{2c_t}, q^I = 0 \quad \text{and}
\]
\[
p^I_1 = \frac{v^H_e^2}{2c_e} + \frac{v^H_t^2}{2c_t}, p^I_2 = \frac{v^H_e^2}{2c_e}
\]

The proposition indicates that the optimal qualities for segment I equal to the segment’s efficient qualities. If \( v^I_1 \) is greater than \( n_2 v^H_t \), the optimal traditional qualities for segment III is lower than the segment’s efficient traditional qualities \((q^I)\) by \( \frac{n_2(v^I_1 - v^H_t)}{2(1-n_2)c_t} \). Notice that \( \frac{n_2}{1-n_2} \) is the ratio between segment I and segment III. If \( v^I_1 \) is less than or equal to \( n_2 v^H_t \), the monopolist will serve segment III product only with environmental attribute. The optimal price for segment III equals to the customers’ valuation of the product and the optimal price for segment I is lower than customers’ valuation when \( v^I_1 \) is greater than \( n_2 v^H_t \) and while \( v^I_1 \) is less than or equal to \( n_2 v^H_t \), the optimal price for segment I equals to the customers’ valuation.

Proposition 5. We explore the relative environmental impact of the above by calculating the product line’s total environmental qualities, which are denoted by \( E_{IIV}, E_{I}, E_{I,II}, E_{I,III} \):

\[
E_{IIV} = \frac{Nv^L_e}{2c_e}, \quad E_I = \frac{n_1n_2Nv^H_e}{2c_e}, \quad E_{I,II} = \frac{n_1Nv^H_t}{2c_e}
\]

\[
E_{I,III} = \begin{cases} 
\frac{n_2Nv^L_e}{2c_e}, & v^I_1 > n_1v^H_t > 0 \\
\frac{n_1n_2Nv^H_t}{2c_e}, & v^I_1 - n_1v^H_t \leq 0 
\end{cases}
\]

The total environmental qualities for the strategies equal to the sum of products of the demand by the green qualities of product line in their respective segments.

Proposition 6. (i) if \( \frac{v^H_t}{v^I_1} \leq \frac{n_2}{n_1} \), \( E_{IIV} > E_{I,II} \geq E_{I,III} > E_I \).

(ii) if \( \frac{n_2}{n_1} > \frac{v^H_t}{v^I_1} \leq \frac{1}{n_1} \), \( E_{IIV} \geq E_{I,II} \geq E_{I,III} > E_{I} \).

(iii) if \( \frac{1}{n_1} > \frac{v^H_t}{v^I_1} \leq \frac{1}{n_1n_2} \), \( E_{I,II} > E_{IIV} \geq E_{I} = E_{I,III} \).

(iv) if \( \frac{v^H_t}{v^I_1} > \frac{1}{n_1n_2} \), \( E_{I,III} > E_{I} = E_{I,II} > E_{IIV} \).

Proposition 6 presents the sequence of environmental impact of each strategy with the relationship between \( \frac{v^H_t}{v^I_1} \) and segment market size. We also can see that the green level of segment-market strategy with two products is no less than the segment-market strategy with a single product.

5. Conclusions
This study examines optimal quality design and price strategies when faced four market segments, which are divided by consumer’s income level and environmental awareness. In addition, our study analyses the optimal solutions and according total environmental qualities in four models. Here are some interesting managerial insights.
First, several parameters, especially consumers’ valuation towards products’ qualities and market size of each segment affect the firm’s choice on market strategies and consequent environmental performance; Second, green product development does not always increase and may decrease the degree of environmentally friendliness. Segment-market strategy with two products is greener than segment-market strategy with a single product, However, segment-market strategy with two products is not always greener than mass-market strategy.

References
[1] Z. H. Wang, X. M. Wang, and D. X. Guo, "Policy implications of the purchasing intentions towards energy-efficient appliances among China's urban residents: Do subsidies work?," Energy Policy, vol. 102, pp. 430-439, Mar 2017.
[2] Y. Zhang, C. Xiao, and G. Zhou, "Willingness to pay a price premium for energy-saving appliances: Role of perceived value and energy efficiency labeling," Journal of Cleaner Production, vol. 242, 2020.
[3] Z. F. Hong, H. Wang, and Y. M. Gong, "Green product design considering functional-product reference," International Journal of Production Economics, vol. 210, pp. 155-168, Apr 2019.
[4] X. X. Zhu, M. L. Ren, G. D. Wu, J. Pei, and P. M. Pardalos, "Promoting new energy vehicles consumption: The effect of implementing carbon regulation on automobile industry in China," Computers & Industrial Engineering, vol. 135, pp. 211-226, Sep 2019.
[5] S. F. Du, W. Z. Tang, J. J. Zhao, and T. F. Nie, "Sell to whom? Firm's green production in competition facing market segmentation," (in English), Annals of Operations Research, vol. 270, no. 1-2, pp. 125-154, Nov 2016.
[6] K. Dey, S. Roy, and S. Saha, "The impact of strategic inventory and procurement strategies on green product design in a two-period supply chain," International Journal of Production Research, vol. 57, no. 7, pp. 1915-1948, Apr 2019.
[7] Y. B. Zhang, M. Hafezi, X. Zhao, and V. Shi, "The impact of development cost on product line design and its environmental performance," International Journal of Production Economics, vol. 184, pp. 122-130, Feb 2017.
[8] F. Buder, C. Feldmann, and U. Hamm, "Why regular buyers of organic food still buy many conventional products Product-specific purchase barriers for organic food consumers," British Food Journal, vol. 116, no. 3, pp. 390-404, 2014.
[9] S. Mitra, "Optimal pricing and core acquisition strategy for a hybrid manufacturing/remanufacturing system," International Journal of Production Research, vol. 54, no. 5, pp. 1285-1302, Mar 2016.
[10] A. Mantovani, O. Tarola, and C. Vergari, "End-of-pipe or cleaner production? How to go green in presence of income inequality and pro-environmental behavior," (in English), Journal of Cleaner Production, Article vol. 160, pp. 71-82, Sep 2017.
[11] T. M. Choi, "Pricing and branding for remanufactured fashion products," Journal of Cleaner Production, vol. 165, pp. 1385-1394, Nov 2017.
[12] J. Z. Gao, Z. D. Xiao, H. X. Wei, and G. H. Zhou, "Active or passive? Sustainable manufacturing in the direct-channel green supply chain: A perspective of two types of green product designs," Transportation Research Part D-Transport and Environment, vol. 65, pp. 332-354, Dec 2018.
[13] C. L. Chen, "Design for the environment: A quality-based model for green product development," Management Science, Article vol. 47, no. 2, pp. 250-263, Feb 2001.