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Title Page: Green product design considering functional-product reference

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Abstract

Consumers' reference behaviors are largely ignored in previous research on green product design. This study investigates a green-product design problem in a two-echelon supply chain by considering consumers' reference behaviors, where the reference point is associated with a functional product that has a utility-based reference form. Tax regulation and the environmental awareness of consumers are also considered in investigating their effects on the green-product design and pricing strategies. Analytical results show that consumers' reference behaviors significantly influence the green-product design and pricing decisions. When faced with consumers who have different recognition levels of reference, the product design and pricing strategies should be adjusted. Tax regulation and consumer green awareness also affect the firms' decisions. Tax regulation can encourage firms to increase the greenness degree of their product only when the tax level or the green development cost is at a low level, while consumer green awareness always plays a positive role in green design. By comparing the results between different supply chain structures, we find that the retailer-led supply chain outperforms the manufacturer-led supply chain in environmental improvements. The best environmental performance is achieved when the supply chain is coordinated.

Key words: sustainable supply chain management; green product design; consumer reference behavior; consumer environmental awareness; environmental regulation; product

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Key words: sustainable supply chain management; green product design; consumer reference behavior; consumer environmental awareness; environmental regulation; product and supply chain coordination

1. Introduction

Our research is partially motivated by practices in green-product design of the environmentally friendly bulb of the Philips-Carrefour supply chain in Europe. French retailers like Carrefour comply with European acts on the eco-design of energy-using products by reducing the least efficient lighting and lamps from the market (see carrefour.com/corporate-social-responsibility). Energy suppliers have to contribute to energy-saving efforts under the White Certificates Scheme for energy savings (CEE). The French government promotes LED technologies with an energy rating of at least A+ under the EN 62471 standard, which brings challenges to main bulb manufacturers Philips (see philips.com). First, Philips needs to consider greenness with energy labeling, which is a color-coded performance scale from G to A+++. It also needs to consider the pricing of green products. Owing to the large price difference between green LED bulbs and functional bulbs (2-3 times as per the data of Carrefour in 2018), customers will compare green lamps with the reference, namely, traditionally functional lamps, which will influence demand. This situation makes it difficult and interesting for the Philips-Carrefour supply chain to make decisions on greenness and pricing when taking customer reference and government regulation into consideration.

This business problem is also encountered in other industries. In 2018, three hi-tech giants, Huawei, Baidu and Tencent, jointly initiated an environmentally friendly electrical car, the Weltmeister EX5. While they can choose greenness from traditional cars, hybrid cars, or pure electrical cars, they decided to go with high greenness: full charging in just 30 minutes and battery duration capability of 600 KM. Retailers and manufacturers in the Weltmeister supply chain also made the pricing decision for the green product, pricing it at just 200,000RMB and, subsequently, to just 150,000RMB after the environmental subsidy and tax refund awarded by the Chinese government according to its “2017 new-energy environmentally friendly car subsidy policy”. After Chinese customers compared the

Weltmeister EX5 with the reference, namely, traditional fossil fuel vehicles with similar functions (duration capability of 600 KM), the demand for this car increased to 200,000 for in the first batch in 2018. In another example, PepsiCo develops recyclable PET plastic softdrink bottles instead of corrugated materials to “green” their products (see greenbiz.com). Coca-Cola has also developed the first fully recyclable PET plastic bottle (cleantechnica.com). In another new case, by a French act CITE (Tax Credit Energy Transition), the French government will provide subsidy to green windows (double-glazing windows or even greener products to save energy) in 2018. Retailers (e.g., Leroy Merlin) and manufacturers (e.g., Brico Essentiel, Le roi de la fenetre) need to make greenness and pricing decisions by considering the likelihood that customers will compare green windows and single-glazing windows.

Design for the environment (DFE) was introduced to abate the lifetime environmental impact of products (Allenby and Fullerton, 1991; Kuo et al., 2001). Recently, DFE has been drawing increasing attention from both academic and practical communities because of the increasingly severe environmental issues and its great potential in environmental improvement. Firms are facing increasing pressures to provide environmentally friendly products because of environmental regulations from governments and consumers’ growing environmental consciousness. Some countries, such as the United States, France, Switzerland, and China, permit the use of “low-carbon” or “green” labels for authorized green products. The use of green labels is not only a regulation implemented by the government but is also a chance for firms to attract consumers. Firms are encouraged to develop and design their product by taking environmental features into consideration. Green design is important for firms to survive and be successful in green-market competitions.

However, there exist some research gaps in the studies on green product design and pricing. Consumers’ behaviors are critical factors affecting the green purchase

behaviors and product demand, which accordingly affect the product design and pricing decisions of firms. For example, consumers' environmental awareness (CEA) is becoming an important factor in product consumption, which is a market-driven factor that motivates firms to develop and design green products (Schlegelmilch et al., 1996; Hopkins and Roche, 2009). CEA is taken into account in the study on green-product design and pricing in previous literature (Chen, 2001; Su et al., 2012; Nouira et al., 2014; Zhu and He, 2017). However, the reference behaviors of consumers are largely ignored in previous green-product-design studies (Chen, 2001; Subramanian et al., 2009; Nouira et al., 2014; Zhu and He, 2017). Consumers' reference behaviors are also important features affecting their green purchase behaviors. When environmentally aware consumers choose between a green product and a functional one, they commonly compare these two products in price, functional quality, and environmental concerns.

This study aims to fill these research gaps in literature. We investigate the green-product design and pricing problem by considering the reference behaviors and environmental awareness of consumers. An environmental tax scheme is also considered in our research. Particularly, we focus on the following research questions: How does consumers' reference behaviors influence green-product design and pricing decisions? How does CEA influence green-product design and pricing decisions? How does the environmental tax scheme affect green-product design and pricing decisions?

To answer these research questions, a Stackelberg model is formulated to study green-product design and pricing strategies, where a retailer acts as the leader to determine the retail price of the green product, and a manufacturer acts as the follower to determine the product's greenness degree and wholesale price. In the market, there exists a functional product that competes with the green product. The valuation-based demand functions for the green and functional products are addressed by taking into account the consumers' green awareness and reference behaviors. The closed-form solutions are obtained by

optimally solving the proposed model, based on which interesting managerial insights are addressed to support the firms' decisions on green-product design and pricing. The results show that environmental regulations and consumer' behaviors (green awareness and reference behaviors) significantly affect the green design and pricing strategies of firms.

Observing the different business modes of green product design in practices (such as manufacturer-led green design like PepsiCo and Weltmeister EX5, and retailer-led green design like Carrefour and Walmart), we investigate the effects of supply chain structure power on firms' design, pricing strategies, and furthermore supply chain performance. The results show that the retailer-led supply chain performs better in environmental performance improvement than the manufacturer-led case. The best environmental performance is achieved when the supply chain is coordinated.

The main contributions of this study are as follows: *i*) We consider consumers' reference behaviors in green-product design decision, thus filling research gaps in the literature of green design. *ii*) We introduce a new reference form, namely, utility-based reference, to further enrich the research on consumers' reference behaviors in green design. *iii*) We study the effects of supply chain structures on the environmental performance of the supply chain by taking into consideration consumers' reference behaviors. The research results provide insights on supply-chain contracting that takes environmental performance as the objective.

2. Literature Review

Two streams of research are closely related to our work. First, we review green-product design in consideration of consumers' green awareness and environmental regulations. Second, our work is related to the research on reference behaviors that affect operations management. In this section, we review studies in each stream and identify the differences between our work and the existing research.

2.1. Green design

Product design has been widely studied under the framework “*Design for X (DFX)*”, where X is a specific activity, feature, or goal considered in product design phase (Arnette et al., 2014). Boothroyd and Dewhurst (1983) develop a method to design a product for efficient assembly, which is noted as the first research on DFX known as design for assembly. Some other DFX concepts are investigated in the existing literature, such as design for manufacture (Dewhurst and Blum, 1989; Knight, 1991; Goncalves-Coelho and Mouro, 2007; Mottonen et al., 2009; Holt and Barnes, 2011) and design for quality (Deming, 1982; Taguchi, 1986; Watson, 1993; Koch et al., 2004).

Except for economic targets, ecology/environmental features are discussed widely, known as *design for environment* as introduced by Allenby and Fullerton (1991). Researchers develop methods or rules for product design. We mainly focus on the research conducted from the perspective of operations management. Consumers’ green awareness is considered in green-product design. Taking environmental quality as the decision on green-product design, Chen (2001) use a quality-based model to analyze the green-product design decisions facing a segmentation market containing consumers with or without green awareness. Relaxing the assumption in Chen (2001) that environmental and functional attributes are conflicting, Su et al. (2012) study the product pricing and design (design for traditional quality and environmental quality) problems under Zero-Sum and Synergy technology. Different from Chen (2001), their result shows that Synergy technology can improve environmental performance. Some researchers focus on the impacts of consumers’ green awareness on green design (Nouira et al., 2014; Zhu and He, 2017), and their results show that it positively influences environmental performances. Hong et al. (2018a) examine a product design problem considering supply chain configuration where the environmental attribute of the product is related to the emissions generated from all production/operations stages in the supply chain. Our

study also considers the consumers' green awareness on green product design. However, we further take into account consumers' reference behavior, which is largely ignored in previous literature.

The literature discussed above investigates the green-product design problem from the perspective of consumers, while other studies examine the impact of environmental regulations on green design (Chen, 2001; Zhang et al., 2012; Gouda et al., 2016). Zhang et al. (2012) extend Chen (2001) by considering environmental and profitable benefits when designing a green product. They point out that a subsidy policy can benefit the economic and environmental performance of firms. Taking into account the extended producer responsibility legislation, Subramanian et al. (2009) study how the regulation affects a durable product design. An environmental regulation (i.e., tax policy) is considered in the green-product design in this study. Different from existing studies, the current study combines the effects of regulation and consumers' green awareness and reference behavior on green-product design and analyzes the differential impact of these factors.

2.2. Sustainable operations considering consumers' green awareness

Researchers pay attentions on the effects of consumer environmental awareness on firm's operations decisions (Shamdasani et al., 1993; Schuhwerk and Lefkoff-Hagius, 1995; Ginsberg and Bloom, 2004; Conrad, 2005; Su et al., 2012). Chen (2001) studies the design and marketing policies facing consumers with different preferences on the traditional and environmental attributes of products. Chitra (2007) shows that the level of consumer environmental awareness has a positive promotion on willing to pay for green products. Liu et al. (2012) study the decisions of supply chain players under competition. Consistent with Chitra (2007), their results show that green consumer benefits retailers and manufacturers that have superior eco-friendly operations. Su et al. (2012) investigate the green product's pricing and environmental design problems, where the effects

of technologies used in R&D are considered in their work. Similar to Su et al. (2012), Hovelaque and Bironneau (2015) study an EOQ model facing a both price and environment dependent demand, and the result encourages government to actively develop environmental strategies for social ecological performance. Xu et al. (2017) use contracts to coordinate a green supply chain in which the retailer sells product to environment-concerned consumers and manufacturer has ability to develop green attributes. Our study also focuses on the green product design problem where the environmentally conscious consumer demand is considered as discussed by Xu et al. (2017). However, we are different from the existing literature in that the reference behavior is considered in our study. We focus on a practical problem that environmentally conscious consumers also make comparison between the traditional and green products when purchasing a green product. Therefore, besides environmentally consciousness, consumers' reference behavior should be considered in green product design.

2.3. Consumer reference behaviors

People always make social comparisons to estimate their self-worth (Festinger, 1954), which is a common phenomenon when consumers choose and purchase goods (Kim and Kim, 2015). Consumer reference behavior plays important roles in firms' operational decisions, such as in product pricing (Popescu and Wu, 2007; Kopalle et al., 2012; Zhang et al., 2014; Wang, 2016), product design (Liu et al., 2016) and supply chain management (He et al., 2016; Liu et al., 2016). Researchers investigate the effects of consumers' reference behaviors on operations management by considering different reference forms, such as pricing and quality.

Price reference is a common consumer reference behavior as widely discussed in the existing literature (Kalwani et al., 1990; Kalyanaram and Little, 1994; Moon et al., 2006; Kopalle et al., 2012; Wang, 2016). Kalyanaram and Winer (1995) and Greenleaf (1995) show that price reference significantly influences consumer demands, especially

when consumers are price-sensitive. Popescu and Wu (2007) study the dynamic pricing problem of a monopolist. Their result shows that reference effects are important factors in ensuring the profitable benefits of a firm. From the perspective of supply chain management, Kopalle et al. (2012) and Zhang et al. (2014) also indicate the importance of considering reference effects in optimizing the decisions of supply chain members. Some studies, such as that by Moon et al. (2006), further classify the price reference into different forms (i.e., memory-based and stimulus-based reference price) to investigate their different effects. While the above researchers find many results from their study on price reference, their research largely ignores the fact that quality comparison is common when consumers purchase goods.

Quality reference is another reference form (Bronnenberg and Wathieu, 1996; He et al., 2016). Bronnenberg and Wathieu (1996) investigate a brand promotion problem by considering quality and price effects. With respect to product quality, Gavious and Lowengart (2012) study the quality effects on firms' profits and compare the effects of price and quality reference. Some literature studies the quality effects on supply chain management. Liu et al. (2016) investigate the effects of quality reference on the manufacturer's product quality design strategy and the retailer's pricing strategy. Comparing the impacts of price and quality reference on a two-echelon supply chain, He et al. (2016) investigate the subsidy problem between a manufacturer and a retailer. Considering the consumer reference behavior, Hong et al. (2018b) investigate its effects on green product pricing, but the green design problem is not involved in their work. Our study is different from the existing literature in that the combined effects of price and quality are considered in the green product design and pricing problems.

In summary, this study attempts to fill research gaps in the investigations on reference effects on green-product design and pricing decisions by taking into consideration the non-green product reference, i.e., from a utility-reference perspective. By considering

consumer green awareness in green design, we are able to introduce the utility as the reference point.

3. The model

In this section, we formulate the problem by using a retailer-led Stackelberg game model and address the optimal solutions to investigate the green product design and pricing strategies. We then study the problem by considering a manufacturer-led case and a supply-chain coordination scenario. For notational convenience, we use the subscript “ R ” to refer to the retailer-led case, “ M ” for the manufacturer-led case, and “ RS ” for the revenue-sharing contract that coordinates the supply chain.

3.1. Mathematical formulation

We consider a two-echelon supply chain where a manufacturer makes green products and sells them to consumers through a retailer. The green product is new and environmentally friendly, while a functional product exists in the market and competes for market share with the green product. Comparing with the traditional production, the green one has less environmental impacts or is less detrimental to human health than the traditional equivalent product. In this paper, we do not focus on refurbished, remanufactured, repairable products. The environmental attribute of the green product is measured by the greenness degree (denoted as $0 < e \leq 1$), which is the level of greenness compared with that of the functional product (Chen, 2001; Zhang et al., 2017; Hong and Guo, 2018).

Consumers are environmentally conscious about homogeneously deriving environmental utility from the green product, but are heterogeneous in terms of their evaluations of the functional attributes of products. Note that we also consider the case that consumers are heterogeneous in deriving environmental utility from the green product. However, we obtain the similar results as those addressed in the homogeneous case and further confirm our main findings in different environments. We provide the main results with

heterogenous consumers in Appendix C, which can serve as a robust check for our main model.

The environmental utility is assumed to be ke (Chen, 2001; Yalabik and Fairchild, 2011), where k is the sensitivity of consumers to the green product's greenness. Let V be the functional utility a consumer derives from the functional product, where V is uniformly distributed on $[0, 1]$ (Ferrer and Swaminathan, 2006; Yenipazarli, 2016a). The functional utility a consumer derives from the green product is αV , where α is a coefficient indicating the difference in functional utility between the two products. The functional product is better in functional attribute if $0 < \alpha < 1$ and vice versa if $\alpha > 1$. Notice that we here omit the case $\alpha = 1$, i.e., the two products are the same in functional attributes.

In addition to the direct utilities, consumers derive a reference utility from comparing the products. We consider the utility of purchasing a functional product as the reference point. Let p_r and p denote the prices of the functional and green products, respectively. The reference effect is then defined as $u_r - u'_g$, where $u'_g = \alpha V - p$, and $u_r = V - p_r$ is the utility a consumer derives from the functional product (Klapper et al., 2005; Lu et al., 2014; Yenipazarli, 2016b). We use p to denote the green product's price for notational conciseness.

Let β be the consumers' recognition level of the reference, which is assumed to be $0 < \beta < \alpha$ to avoid trivial cases. That is, the utilities deriving from the reference behavior are always less than those from the product's functional quality. The utility derived from green products consists of four terms: positive utility from functional attribution (αV), negative utility from product price (p), positive utility from green attribute product price (ke), and negative utility from product reference ($\beta(u_r - u'_g)$). The utilities a consumer derives from the regular and green products are

Let β be a coefficient indicating a consumer's recognition level of the reference, and

be assumed to be $0 < \beta < \alpha$ in order to avoid trivial cases. That is, the utility derived from the reference behavior is less than that from the product's functional quality.

$$\begin{cases} u_r = V - p_r, \\ u_g = \alpha V - p + ke - \beta(u_r - u'_g). \end{cases}$$

These two products competes for market shares in the base of consumer choice. Consumers choose the functional product if $u_r \geq 0$ and $u_r > u_g$, and purchase the green product if $u_g \geq 0$ and $u_g \geq u_r$. Recalling V is uniformly distributed, we obtain the demand functions of the two products as follows. **Please find the detailed calculation and its proof in Appendix A.**

$$\begin{cases} q_r = 1 - \frac{(1 + \beta)(p_r - p) + ke}{1 - (\alpha + \alpha\beta - \beta)}, \\ q_g = \frac{(1 + \beta)(p_r - p) + ke}{1 - (\alpha + \alpha\beta - \beta)} - \frac{(1 + \beta)p - \beta p_r - ke}{\alpha + \alpha\beta - \beta}; \end{cases} \quad (0 < \alpha < 1) \quad (1)$$

and

$$\begin{cases} q_r = \frac{(1 + \beta)(p_r - p) + ke}{1 - (\alpha + \alpha\beta - \beta)} - p_r, \\ q_g = 1 - \frac{(1 + \beta)(p_r - p) + ke}{1 - (\alpha + \alpha\beta - \beta)}. \end{cases} \quad (\alpha > 1) \quad (2)$$

In the two-echelon supply chain with large retailers, such as Carrefour, Walmart, and Tesco, the retailer determines the retail price of the green product, while the manufacturer determines the wholesale price and greenness degree of the product. Note that the price of a functional product is assumed to be determined by the market (i.e., no firm has sufficient power to break the price equilibrium of the functional product). This case happens in the practice where the functional product has existed in the market for a long time and its price is formed in competition.

We first investigate the scenario where the retailer is the Stackelberg leader in the supply chain. Some large retailers, such as Carrefour and Walmart, implement their

sustainable operations strategies by requiring their suppliers (i.e., manufacturers) to produce green products. In addition, we consider the environmental tax regulation on emissions to investigate its effects on green-product pricing and design.

In the Stackelberg game, the retailer first determines the retail price (p_R) to maximize its profit. With ω_R as the whole price, the retailers decision problem is then formulated as follows:

$$\max \pi_R^r(p_R) = (p_R - \omega_R)q_R. \quad (3)$$

In response to the retailer, the manufacturer determines the whole price (ω_R) and green degree (e_R) of the green product to maximize its profit. We denote c as the unit product cost of the green product, γ as the cost rate of green technology development (Chen, 2001), and t as the tax on emissions, then manufacturer's decision problem is formulated as follows:

$$\max \pi_R^m(\omega_R, e_R) = (\omega_R - c)q_R - \gamma e_R^2 - t(1 - e_R)q_R, \quad (4)$$

where the term $(\omega_R - c)q_R$ is the product revenue deducts the production cost and γe_R^2 is the green development cost that is convex increasing in terms of product greenness (Chen, 2001; Swami and Shah, 2013; Hong and Guo, 2018), where γ is development cost coefficient. $t(1 - e_R)q_R$ is the tax that the manufacturer should pay, which is a linear function of emissions (Yalabik and Fairchild, 2011).

3.2. Results and analysis

The structure of the demand functions given in Eqs. (1) and (2) leads to the complexity in solving the Stackelberg model. The optimal decisions of the retailer and manufacturer are addressed in the following theorem. The proof and detailed solutions of the theorem are provided in Appendix A and B.

Theorem 1. *The Stackelberg equilibrium and the relative optimal decisions in a retailer-led case are*

$$p_R^* = \begin{cases} A_1, & 0 < \alpha < 1, \\ B_1, & \alpha > 1, \end{cases} \quad \omega_R^* = \begin{cases} A_2, & 0 < \alpha < 1, \\ B_2, & \alpha > 1; \end{cases} \quad e_R^* = \begin{cases} A_3, & 0 < \alpha < 1, \\ B_3, & \alpha > 1. \end{cases}$$

The relative profits of the retailer, the manufacturer, and the whole supply chain are

$$\pi_R^{r*} = \begin{cases} \frac{(1+\beta)^2 \gamma (t+c-\alpha p_r)^2}{2(4(1-\alpha)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma-(k+t+t\beta)^2)}, & 0 < \alpha < 1, \\ \frac{(1+\beta)^2 \gamma (1+t-\alpha+c-p_r)^2}{8(\alpha-1)(1+\beta)^2 \gamma - 2(k+t+t\beta)^2}, & \alpha > 1; \end{cases}$$

$$\pi_R^{m*} = \begin{cases} \frac{(1+\beta)^2 \gamma (t+c-\alpha p_r)^2}{4(4(1-\alpha)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma-(k+t+t\beta)^2)}, & 0 < \alpha < 1, \\ \frac{(1+\beta)^2 \gamma (1+t-\alpha+c-p_r)^2}{4(4(\alpha-1)(1+\beta)^2 \gamma - (k+t+t\beta)^2)}, & \alpha > 1; \end{cases}$$

$$\pi_R^{sc*} = \begin{cases} \frac{3(1+\beta)^2 \gamma (t+c-\alpha p_r)^2}{4(4(1-\alpha)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma-(k+t+t\beta)^2)}, & 0 < \alpha < 1, \\ \frac{3(1+\beta)^2 \gamma (1+t-\alpha+c_g-p_r)^2}{4(4(\alpha-1)(1+\beta)^2 \gamma - (k+t+t\beta)^2)}, & \alpha > 1. \end{cases}$$

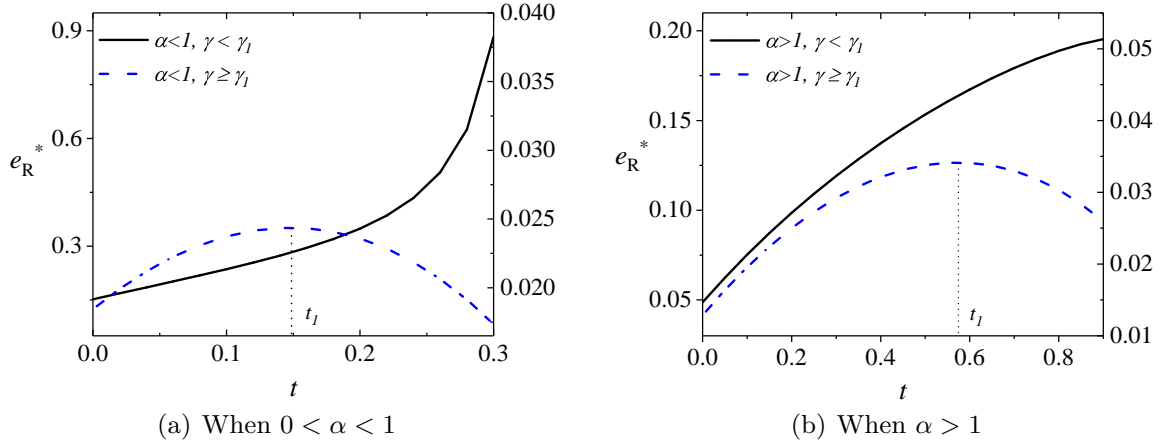
Observing the solutions above, we can find it easy that the consumer reference behavior has significant effects on the product and design pricing strategies. In what follows, we forward some propositions to show the pricing and green-design strategies of the retailer and manufacturer. We first provide two propositions to show the strategies on greenness degree with respect to the tax rate (t) and the consumers' recognition level of reference (β). The proofs and thresholds are provided in Appendixes D and E.

Proposition 1. *There exist some thresholds \hat{t}_1 and $\hat{\gamma}_1$, such that the optimal strategy of the green degree has the following properties:*

- 1) *If $\gamma < \hat{\gamma}_1$, e_R^* is increasing in t ;*
- 2) *else if $\gamma \geq \hat{\gamma}_1$ and $t \geq \hat{t}_1$, e_R^* is decreases with t .*

Proposition 1 shows that the tax level and green development cost influence the green design strategy of the product. When the tax level is at a low level (i.e., $t < \hat{t}_1$), the manufacturer bears less pressure on increasing the product's greenness degree e_R .

However, e_R will increase with the increase of t to reduce tax costs. When t is at a high level (i.e., $t \geq \hat{t}_1$), the green design strategy is also affected by the green development cost (γ). If the development cost is relatively low (i.e., $\gamma < \hat{\gamma}_1$), the manufacturer should increase e_R with the increase of t , because the tax cost is the major factor for his green design decision. By contrast, if the development cost is high (i.e., $\gamma \geq \hat{\gamma}_1$), the development cost will be the major factor. The manufacturer, therefore, decreases e_R to save on green development costs. That means the environmental performance can not be improved under a simple tax policy with high tax rate. For manufacturers facing a high R&D cost, a low-tax policy will reduce their costs, while their enthusiasm for green product design will be promoted. A numerical example shows these managerial insights and provides the results in Figure 1.



Note: (a) $\alpha = 0.8$, $\beta = 0.3$, $\gamma = 0.4$ ($\gamma < \hat{\gamma}_1$), $\gamma = 3$ ($\gamma \geq \hat{\gamma}_1$), $k = 0.2$, $c = 0.3$, and $p_r = 0.9$.

(b) $\alpha = 1.6$, $\beta = 0.3$, $\gamma = 0.4$ ($\gamma < \hat{\gamma}_1$), $\gamma = 3$ ($\gamma \geq \hat{\gamma}_1$), $k = 0.2$, $c = 0.3$, and $p_r = 0.9$.

Figure 1: Design strategy for a green product with respect to t

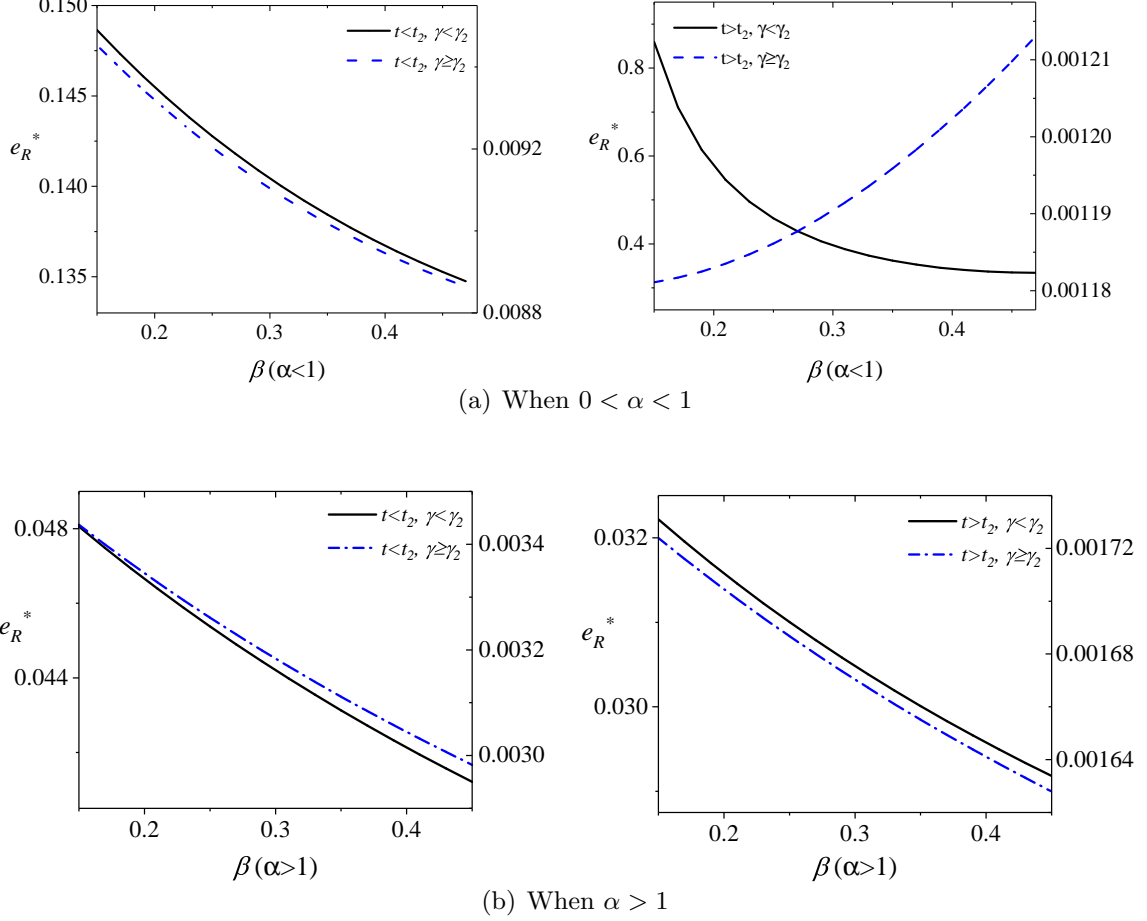
Proposition 2. *There exist some thresholds \hat{t}_2 and $\hat{\gamma}_2$ (detailed in the appendix), such that the optimal greenness degree has the following properties:*

- 1) When $0 < \alpha < 1$,
 - i) if $\gamma < \hat{\gamma}_2$, e_R^* is decreasing in β , and
 - ii) else if $\gamma \geq \hat{\gamma}_2$ and $t \geq \hat{t}_2$, e_R^* is increasing in β .
- 2) When $\alpha > 1$, e_R^* is decreasing in β .

Proposition 2 presents the effects of consumers' recognition level of reference (β) on the manufacturer's green design strategy. The results show that the green product's functional quality (α) is an important factor in green design. When the green product's functional quantity is lower than the regular one (i.e., $0 < \alpha < 1$), the effects of β on the green design strategy depend on the tax level t and green development cost (γ). When t is at a low level (i.e., $t < \hat{t}_2$), the manufacturer decreases e_R^* with the increase of β because it should decrease the green product's price (decreasing e_R^* simultaneously) to guarantee its market share under the increasing pressure of consumers' preferences on the products' cost-performance feature (i.e., the increase of β). When t is at a high level (i.e., $t \geq \hat{t}_2$), as discussed in Proposition 1, the green design strategy is also affected by the green development cost (γ). When $\gamma < \hat{\gamma}_2$, the manufacturer should decrease e_R^* with the increase of β . In such a case, e_R^* is at a high level due to the low development cost, which means the decrease of e_R^* can save considerable development costs (the marginal development cost increases in e_R). The manufacturer, therefore, lowers e_R^* (decreasing p_R^* simultaneously) to retain the green product's market share with the increase of β . When $\gamma \geq \hat{\gamma}_2$, e_R^* is at a low level, and the manufacturer should increase e_R^* when β increases. Although the increase of β erodes its market share, the manufacturer can maintain the market share by increasing e_R^* through emphasizing the greenness of the product. From the coming proposition 3, we know the retailer will reduce the retail price in this situation, which also offsets the negative impacts of increasing β on the market share. Therefore, the manufacturer's cost of increasing the product's greenness is virtually reduced. The increase of e_R^* makes it profitable because the profit from the market share's increase is more than its development cost's increase.

When the functional quality of the green product is higher than that of the regular one (i.e., $\alpha > 1$), e_R^* always increases with the increase of β . The utility from the green product increases with the increase of β , and the manufacturer decreases the green

product's price to amplify its market share (decreasing e_R^* simultaneously). A numerical example is used to show these managerial insights, and the results are provided in [Figure 2](#).



Note: (a) $\alpha = 0.8$, $t = 0.1(t < \hat{t}_2)$, $t = 0.5(t \geq \hat{t}_2)$, $\gamma = 0.75(\gamma < \hat{\gamma}_2)$, $\gamma = 10(\gamma \geq \hat{\gamma}_2)$, $k = 0.2$, $c = 0.2$, and $p_r = 0.9$.

(b) $\alpha = 1.5$, $t = 0.1(t < \hat{t}_2)$, $t = 0.5(t \geq \hat{t}_2)$, $\gamma = 0.75(\gamma < \hat{\gamma}_2)$, $\gamma = 10(\gamma \geq \hat{\gamma}_2)$, $k = 0.2$, $c = 0.8$, and $p_r = 0.9$.

Figure 2: Design strategy for a green product with respect to β

In the following, we provide two propositions to show the optimal pricing strategies with respect to the consumers' greenness awareness (k) and recognition level of reference (β). The proofs and thresholds are provided in Appendixes F and G, respectively.

Proposition 3. *There exists thresholds $\hat{\beta}_1$, \hat{t}_3 , $\hat{\gamma}_3$ and $\hat{\gamma}_4$, such that the optimal pricing strategy has the following properties:*

1) When $0 < \alpha < 1$,

i) if $\gamma \geq \hat{\gamma}_3$, $t \geq \hat{t}_3$ and $\beta < \hat{\beta}_1$, p_R^* is decreasing in β ;

ii) if else, p_R^* is increasing with β .

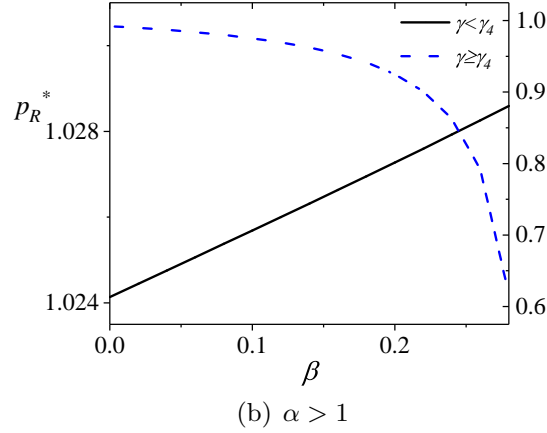
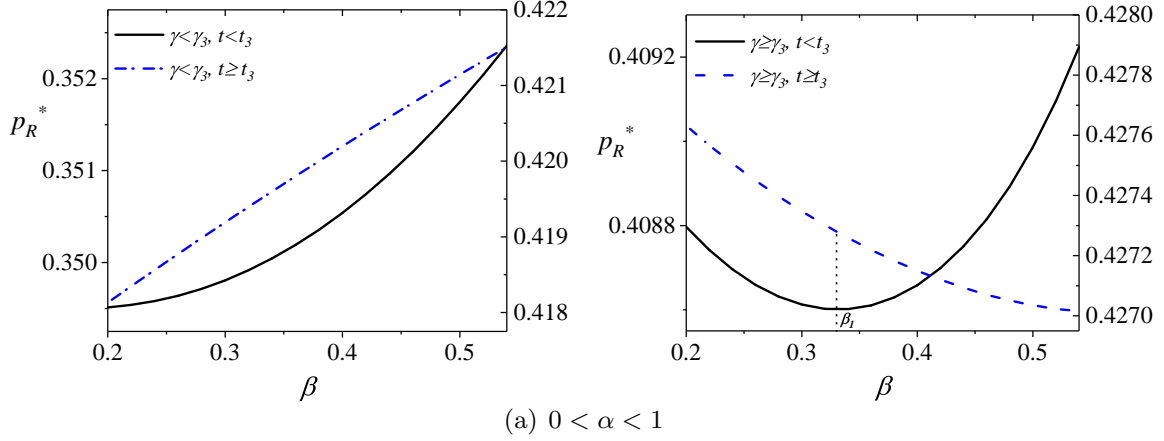
2) When $\alpha > 1$,

i) if $\gamma < \hat{\gamma}_4$, p_R^* is increasing with β , and

ii) if $\gamma \geq \hat{\gamma}_4$, p_R^* is decreasing with β .

Proposition 3 shows the effects of consumers' recognition level of reference (β) on the retailer's pricing strategy. Similar to its effects on the green design strategy, the effects of β on green design strategy depend on green development cost γ and the tax level t . The result shows that p_R^* always increases with the increase of β when the γ is at a low level. From Proposition 2, we know the manufacturer will reduce the green product's greenness at this situation (i.e., β increases). The manufacturer's strategy erodes the consumer's utility from the green attributes of the product. However, the retailer still can increase its profits through raising up its retail price since the greenness of the product is at a relatively high level.

When γ is at a high level, the retailer lowers down its price when consumers concern more on the functional attribute of the product (i.e., β increases). However, there exists an external factor, i.e., the tax rate, that could affect the retailer's pricing strategies. When the tax rate is at a low level (i.e., $t < \hat{t}_3$) and consumers seriously concerned about the difference of the functional utility of the two products (i.e., $\beta \geq \hat{\beta}_1$), the greenness of the product goes to a low level. The demand inevitably decreases, and the retailer has no choice but to increase the retail price to guarantee his profit. A numerical example is used to show these managerial insights, and the results are provided in [Figure 3](#).



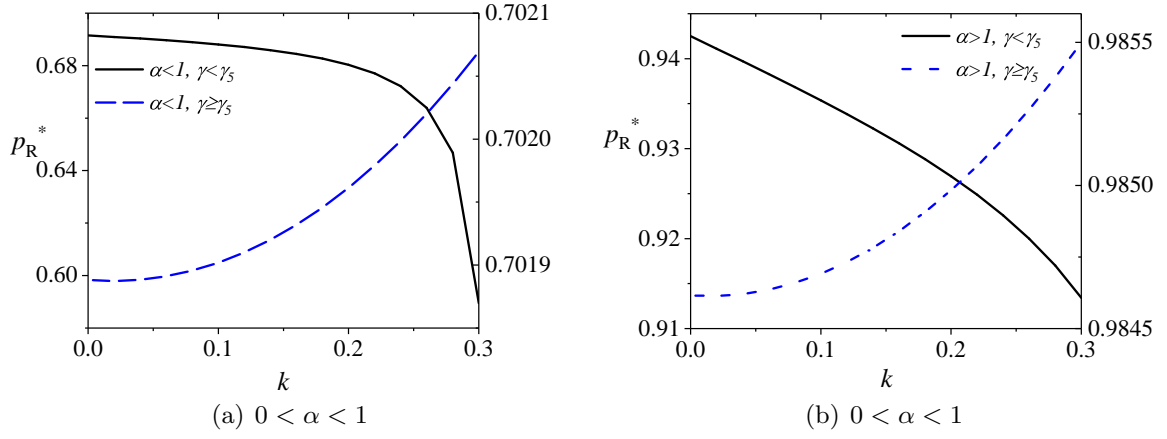
Note: (a) $\alpha = 0.5$, $t = 0.01 (t < \hat{t}_3)$, $t = 0.1 (t \geq \hat{t}_3)$, $\gamma = 0.008 (\gamma < \hat{\gamma}_3)$, $\gamma = 0.3 (\gamma \geq \hat{\gamma}_3)$, $k = 0.2$, $c = 0.25$, and $p_r = 0.9$;
(b) $\alpha = 1.2$, $t = 0.1$, $\gamma = 0.04 (\gamma < \hat{\gamma}_4)$, $\gamma = 0.08 (\gamma \geq \hat{\gamma}_4)$, $k = 0.2$, $c = 0.8$, and $p_r = 0.9$.
Figure 3: Pricing strategy with respect to β

Proposition 4. *The optimal product pricing and green design strategies have the following properties:*

- i) e_R^* is increasing in k .
- ii) There exists a threshold $\hat{\gamma}_3$, such that
 - if $\gamma < \hat{\gamma}_3$, p_R^* is decreasing in k , and
 - if $\gamma \geq \hat{\gamma}_3$, p_R^* is increasing in k .

Proposition 4 shows that the consumers' green awareness (k) always positively influences the product's greenness degree, while its effects on the pricing strategy depend on the green development cost. When the development cost is at a low level (i.e.,

$\gamma < \hat{\gamma}_5$), the manufacturer prefers to set a high green level to increase demand. The manufacturer adopts a high-yield and low-price strategy to ensure its profit. Hence, the retailer decreases its retail price with the increase of k . When the development cost is at a high level (i.e., $\gamma \geq \hat{\gamma}_5$), the manufacturer will choose the low green-product strategy. However, the product's greenness degree will increase with the increase of k , and the retailer will increase the retail price to obtain maximal profits. A numerical example is used to show these managerial insights, and the results are presented in Figure 4.



Note: (a) $\alpha = 0.8$, $\beta = 0.3$, $t = 0.4$, $\gamma = 0.7(\gamma < \hat{\gamma}_5)$, $\gamma = 8(\gamma \geq \hat{\gamma}_5)$, $c = 0.25$, and $p_r = 0.9$.
(b) $\alpha = 1.2$, $\beta = 0.3$, $t = 0.4$, $\gamma = 0.7(\gamma < \hat{\gamma}_5)$, $\gamma = 8(\gamma \geq \hat{\gamma}_5)$, $c = 0.25$, and $p_r = 0.9$.

Figure 4: Pricing strategy with respect to k

Observing from the analysis above, we find an interesting phenomenon that the government's tax policy goes failed when γ and t are at high levels and $0 < \alpha < 1$. That means a tax policy with high-level tax rate can not boost green production (i.e., can not encourage the manufacturer to make green product with a high-level greenness). However, as shown in Proposition 2 and Proposition 4, consumers' reference behavior has positive on environmental performance of the supply chain (i.e., inducing the manufacturer to design green product with relatively high greenness).

4. The impact of supply chain structure on green product design

This section studies a practical setting that either manufacturers or retailers should act as the leaders when designing green products, especially facing consumers with green-awareness and reference behaviors. In practices, there exist two business modes for green product design. One mode is that the manufacturer leads green product design, the typical example are PepsiCo's and Coca-Cola's green R&D on recyclable PET plastic softdrink bottles; and the other is that the retailer leads green product design, the examples are some retail giants, like Carrefour and Walmart, who require their suppliers (manufacturers) to provide green products for sales. That is, the supply chain structure may play impacts on green product design and its performances.

To investigate the effects of supply chain structure on green-product design, this section considers two other cases: the manufacturer acts as the Stackelberg leader, and the supply chain achieves coordination with a revenue-sharing contract. Different from the retailer-led case where the retailer takes advantage in determining the retail price, with the Stackelberg leadership, the manufacturer has the advantage in determining the greenness degree of products. With a revenue-sharing contract, the supply chain can achieve coordination. We investigate the effects of Stackelberg leadership and cooperation level on the firms' decisions and the supply chain's performance.

4.1. Manufacturer-led supply chain

We consider the manufacturer-led case, where the manufacturer first determines the wholesale price (ω_M) and the greenness degree (e_M) of the green product, and the retailer responds to the manufacturer's decisions and determines the retail price (p_M). The decision models for the two firms are the same as those addressed for the retailer-led case.

The optimal decisions of the two firms are addressed in the following theorem. The proof and the solutions are provided in Appendix H.

Theorem 2. *The Stackelberg equilibrium and the relative optimal decisions are as follows:*

$$p_M^* = \begin{cases} A_4, & (0 < \alpha < 1) \\ B_4, & (\alpha > 1) \end{cases} \quad \omega_M^* = \begin{cases} A_5, & (0 < \alpha < 1) \\ B_5, & (\alpha > 1) \end{cases} \quad e_M^* = \begin{cases} A_6, & (0 < \alpha < 1) \\ B_6, & (\alpha > 1) \end{cases}$$

The relative profits of the retailer, the manufacturer, and the whole supply chain are

$$\pi_M^{r*} = \begin{cases} \frac{4(1-\alpha)(1+\beta)^4(\alpha+(\alpha-1)\beta)\gamma^2(t+c_g-\alpha p_r)^2}{((k+t+t\beta)^2+8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2}, & 0 < \alpha < 1, \\ \frac{4(\alpha-1)(1+\beta)^4\gamma^2(1+t-\alpha+c_g-p_r)^2}{((k+t+t\beta)^2-8(\alpha-1)(1+\beta)^2\gamma)^2}, & \alpha > 1; \end{cases}$$

$$\pi_M^{m*} = \begin{cases} \frac{(1+\beta)^2\gamma(t+c_g-\alpha p_r)^2}{8(1-\alpha)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma-(k+t+t\beta)^2}, & 0 < \alpha < 1, \\ \frac{(1+\beta)^2\gamma(1+t-\alpha+c_g-p_r)^2}{8(\alpha-1)(1+\beta)^2\gamma-(k+t+t\beta)^2}, & \alpha > 1; \end{cases}$$

$$\pi_M^{sc*} = \begin{cases} \frac{(1+\beta)^2\gamma(12(1-\alpha)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma-(k+t+t\beta)^2)(t+c_g-\alpha p_r)^2}{((k+t+t\beta)^2+8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2}, & 0 < \alpha < 1, \\ \frac{(1+\beta)^2\gamma(12(\alpha-1)(1+\beta)^2\gamma-(k+t+t\beta)^2)(1+t-\alpha+c_g-p_r)^2}{((k+t+t\beta)^2-8(\alpha-1)(1+\beta)^2\gamma)^2}, & \alpha > 1. \end{cases}$$

By comparing the firms' strategies between the retailer-led and manufacturer-led cases, we obtain proportions to show the distinct strategies and performances. We use the software *Mathematica* to obtain the comparison of relationships among the terms discussed. Let $\hat{\gamma}_6 = \frac{k(k+t+t\beta)}{2(1-\alpha)(1+\beta)^2(\alpha-\beta+\alpha\beta)}$ and $\hat{\gamma}_7 = \frac{3(k+t+t\beta)^2}{8(1-\alpha)(1+\beta)^2(\alpha-\beta+\alpha\beta)}$ ($0 < \alpha < 1$); $\hat{\gamma}_6 = \frac{k(k+t+t\beta)}{2(\alpha-1)(1+\beta)^2}$ and $\hat{\gamma}_7 = \frac{3(k+t+t\beta)^2}{8(\alpha-1)(1+\beta)^2}$ ($\alpha > 0$). Then we have the following propositions.

Proposition 5. *A threshold $\hat{\gamma}_6$ exists, such that we have the following relationships:*

- i) $e_R^* > e_M^*$.
- ii) $q_R^* > q_M^*$.
- iii) $p_R^* > p_M^*$, if $\gamma < \hat{\gamma}_6$; and $p_R^* \leq p_M^*$, if $\gamma \geq \hat{\gamma}_6$.

Proposition 5 shows that the supply chain provides a greener product to consumers

in the retailer-led case than in the manufacturer-led case case, i.e., $e_R^* > e_M^*$. The retailer advantage of its Stackelberg leadership to carry out a high-yield strategy, (i.e., $q_R^* > q_M^*$). Such a strategy encourages the manufacturer to make a relatively green product to promote green consumptions. In other words, the retailer-led supply chain performs better in environmental improvements than the manufacturer-led one. In a retailer-led supply chain, the retailer takes its leadership and extracts as much as possible profits from the sales of green product by dominating the direction of green product designing strategy. When facing green-awareness consumers, the retailer would gain more green-product demands by increasing the greenness of the product. And the retailer could achieve this strategic intention as it is the leader of the supply chain. However, in a manufacturer-led supply chain, the manufacturer is the leader and would make a tradeoff between the revenue and green technology development cost when designing the green product. Under such a supply chain structure, the manufacturer could not extract all marginal profits by increasing the green product's sales volume. Thus, it will choose a relatively low green strategy when designing a green product, i.e., $e_R^* < e_M^*$.

The price of the green product in the retailer-led case is higher than that in the manufacturer-led case (i.e., $p_R^* > p_M^*$) when the green development cost is at a low level, (i.e., $\gamma < \hat{\gamma}_6$). The retailer could implement a high-price and high-yield strategy when the manufacturer's marginal green development cost is at a relatively low level. The manufacturer would follow the retailer's high-price and high-yield strategy by increasing the product's greenness degree. However, when the manufacturer's marginal development cost is at a high level, (i.e., $\gamma \geq \hat{\gamma}_6$), the retailer should adopt a low-price and high-yield strategy to ensure it is profitable.

Proposition 6. *A threshold $\hat{\gamma}_7$ exists, such that we have the following relationships:*

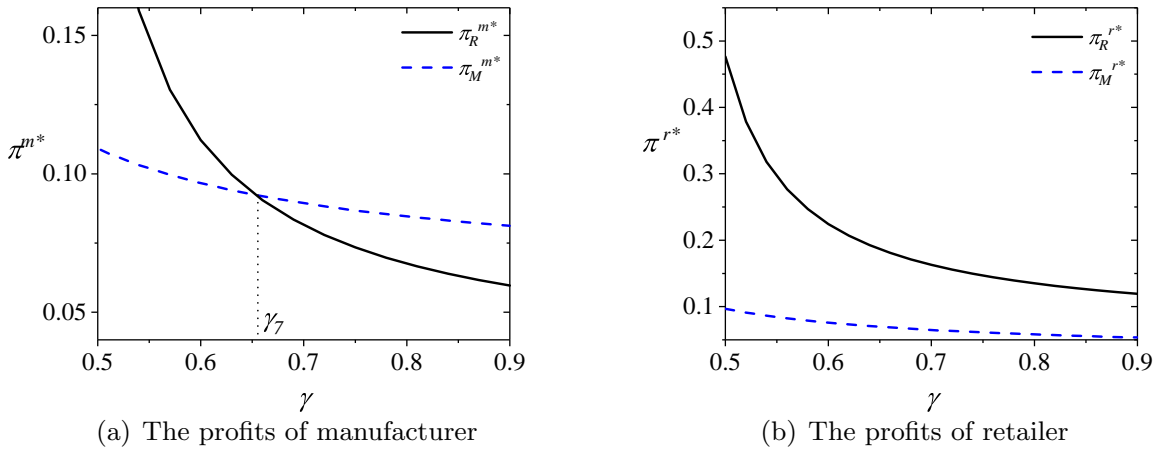
- i) *For the manufacturer, we have*
 - *if $\gamma < \hat{\gamma}_7$, $\pi_R^{m*} > \pi_M^{m*}$, and*

- if $\gamma \geq \hat{\gamma}_7$, $\pi_R^{m*} \leq \pi_M^{m*}$.

ii) For the retailer, we have $\pi_R^{r*} > \pi_M^{r*}$.

iii) For the supply chain, we have $\pi_R^{sc*} > \pi_M^{sc*}$.

Proposition 6 shows that the manufacturer does not always benefit from its leadership, while the retailer and the whole supply chain can benefit from the retailer's leadership. When the green development cost is at a low level (i.e., $\gamma < \hat{\gamma}_7$), the manufacturer is more profitable in the retailer-led case than in the manufacturer-led case (i.e., $\pi_R^{m*} > \pi_M^{m*}$). The product's greenness degree is at a high level when the manufacturer's marginal green development cost is at a relatively low level. In such a case, the manufacturer has little room to improve its profit by adjusting the greenness degree. However, the retailer can improve the supply chain performance through its Stackelberg leadership by adjusting its pricing strategy, from which the manufacturer can also benefit. When the green development cost is at a high level (i.e., $\gamma \geq \hat{\gamma}_7$), the manufacturer is more profitable in the manufacturer-led case than in retailer-led the case (i.e., $\pi_R^{m*} \leq \pi_M^{m*}$). This result is due to the relatively allowance for the greenness degree adjustment when it is at a low level and has a low marginal improvement cost. A numerical example is used to show the managerial insights, and the results are provided in Figure 5.



Note: $\alpha = 0.8$, $\beta = 0.3$, $k = 0.4$, $t = 0.2$, $c = 0.25$, and $p_r = 0.9$.

Figure 5: Comparisons on profits with different supply chain structures

4.2. Channel coordination with a revenue-sharing contract

In this section, we present a revenue-sharing contract to investigate the supply chain's performance when it achieves coordination. The optimal decisions of a centralized supply chain is obtained by the following model:

$$\max \pi_C(p, e) = (p - c)q - \gamma e^2 - t(1 - e)q. \quad (5)$$

By solving the problem, we obtain the optimal green degree and the retailer price. Based on the optimal solutions of the centralized supply chain, we propose a revenue-sharing contract to coordinate the supply chain. The retailer obtains ϕ proportion of the total revenue of the supply chain. The objective functions are

$$\pi_{RS}^r(p) = (\phi p - \omega)q, \quad (6)$$

$$\pi_{RS}^m(e) = (\omega - c)q - \gamma e^2 - t(1 - e)q + (1 - \phi)pq. \quad (7)$$

The contract addressed in the following theorem can coordinate the supply chain. The proof and the solutions are provided in Appendix I.

Theorem 3. *The supply chain achieves coordination through a revenue-sharing contract in the following contract terms:*

$$\begin{cases} \omega_{RS} = \phi(c + \gamma e^2/q + t(1 - e)), \\ \phi \in [\frac{1}{2}, \frac{3}{4}], \end{cases}$$

where q is the retailer's ordering quantity, and e is the green product's greenness degree.

The related optimal decisions and profit are

$$p_{RS}^* = \begin{cases} A_7, & 0 < \alpha < 1, \\ B_7, & \alpha > 1; \end{cases} \quad e_{RS}^* = \begin{cases} A_8, & 0 < \alpha < 1, \\ B_8, & \alpha > 1; \end{cases}$$

$$\pi_{RS}^{sc*} = \begin{cases} \frac{(1+\beta)^2 \gamma (t+c-\alpha p_r)^2}{4(1-\alpha)(1+\beta)^2 (\alpha+(\alpha-1)\beta) \gamma - (k+t+t\beta)^2}, & 0 < \alpha < 1, \\ \frac{(1+\beta)^2 \gamma (1+t-\alpha+c-p_r)^2}{4(\alpha-1)(1+\beta)^2 \gamma - (k+t+t\beta)^2}, & \alpha > 1. \end{cases}$$

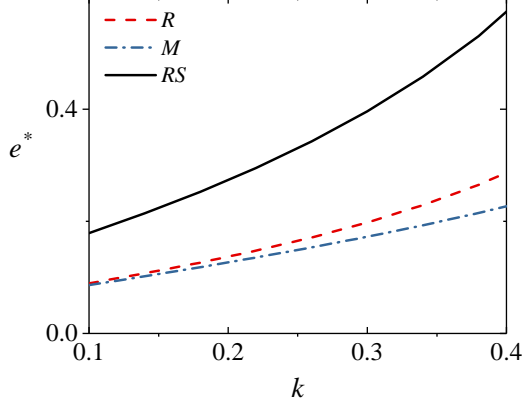
Comparing the green design strategies in three supply-chain cases, we have the following proposition to show the environmental performance of the supply chain.

Proposition 7. *The green product's greenness degree under the three cases follows the relationship $e_{RS}^* > e_R^* > e_M^*$.*

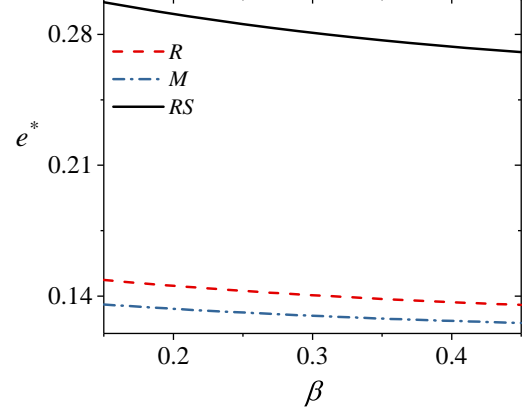
Proposition 7 shows that the cooperation among partners can improve the supply chain's environmental performance as follows: $e_{RS}^* > e_R^*$ and $e_{RS}^* > e_M^*$. Among the three power structures, the revenue-sharing contract can coordinate the supply chain with the highest level of cooperation. All of the supply chain's decisions are integrated as a whole when the supply chain achieves coordination, thus inducing the most effective decisions and the greenest product design. Therefore, cooperation on environmental improvement in the supply chain should be encouraged because consumers are becoming more environmentally conscious (Hong and Guo, 2018). The results also show retail-led supply chain can achieve better environmental improvement than a manufacturer-led one (i.e., $e_R^* > e_M^*$), as discussed after Proposition 5. A numerical example is used to show these managerial insights and, and the results are provided [Figure 6](#).

5. Conclusion

This study investigated the green-product design strategies for a two-echelon supply chain, where the manufacturer determines the product's greenness degree and the retailer determines the retail price. The green product competes with a functional product that has a similar functional feature. We considered the effects of consumers' reference behavior and environmental awareness on the green design and pricing decisions.



(a) The design strategies respect to k



(b) The design strategies respect to β

Note: (a) $\alpha = 0.8$, $\beta = 0.4$, $\gamma = 0.75$, $t = 0.1$, $c = 0.2$, and $p_r = 0.9$;

(b) $\alpha = 0.8$, $\gamma = 0.75$, $k = 0.2$, $t = 0.1$, $c = 0.2$, and $p_r = 0.9$.

Figure 6: Comparisons on green design with different supply chain structures

Particularly, we introduced a new reference form with utility reference to characterize the reference behaviors of consumers. We formulated Stackelberg game models to study the green-product design strategies under three structures: manufacturer-led, retailer-led and supply chain coordination structures.

The analytical results showed that environmental tax regulation and consumers' reference behaviors and green awareness play significant but distinct roles in the green-product design and pricing strategies. Tax regulation can encourage firms to increase the product's greenness degree only when the tax level or the green development cost is at a low level, while consumer's green awareness always positively affects green product design. When the green product's functional quantity is higher than that of functional product, the manufacturer always increases the product's greenness degree if the recognition level of consumer reference increases; when the green product's functional quantity is lower than that of the functional product, the manufacturer's green design strategy does not depend only on the recognition level, but also on the tax rate and green development cost. By comparing the results among the supply chain structures, we found that the retailer-led supply chain performs better in environmental improvement than the manufacturer-led case. The best environmental performance is achieved when the supply chain is

coordinated.

The green product considered in our research setting is a general concept, which is relative to a traditional product that is functionally similar but different in environmental attributes. We focus on a new green product and call the traditional product by functional product. Specifically, the green product has less environmental impacts or is less detrimental to human health than the functional one. In this paper, we donot focus on refurbished, remanufactured, repairable products in modeling description to avoid confusing and overplaying. However, it is interesting to explore green product design considering the reference effect of functional product for refurbished, remanufactured, repairable products in the future research.

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Appendix

Appendix A. Proof of demand-function

Proof. Let $A = \alpha + \alpha\beta - \beta$. We obtain a condition that will be used later: when $0 < \alpha < 1, A < 1$; when $\alpha > 1, A > 1$. By definition, we know that $q_r = P\{u_r > u, u_r \geq 0\}$ and $q = P\{u \geq u_r, u \geq 0\}$. Next, we give the specific formulas for q_r and q .

(I) When $0 < \alpha < 1$, $q_r = P\{V - p_r > \alpha V - p + ke - \beta(u_r - u'), V - p_r \geq 0\}$; and $q = P\{u \geq u_r, u \geq 0\} = P\{\alpha V - p + ke - \beta(u_r - u') \geq V - p_r, \alpha V - p + ke - \beta(u_r - u') \geq 0\}$. To ensure both manufacturers are in the market, it is necessary to keep $\Delta V_1 > 0$ and $\Delta V_2 > 0$, where $\Delta V_1 = ((1 + \beta)(p - \alpha p_r) + ke)/(1 - \alpha)(1 + \beta)(\alpha + \beta(\alpha - 1)) > 0$ and $\Delta V_2 = ((1 + \beta)(p - \alpha p_r) + ke)/(1 - \alpha)(1 + \beta) > 0$. We then obtain the condition $k > (1 + \beta)(p - \alpha p_r)/e$.

Given that V is uniformly distributed on $[0, 1]$, the demand function can be rewritten as

$$\begin{cases} q_r = 1 - \frac{(1 + \beta)(p_r - p) + ke}{1 - (\alpha + \alpha\beta - \beta)}, \\ q = \frac{(1 + \beta)(p_r - p) + ke}{1 - (\alpha + \alpha\beta - \beta)} - \frac{(1 + \beta)p - \beta p_r - ke}{\alpha + \alpha\beta - \beta}. \end{cases} \quad (0 < \alpha < 1)$$

(II) When $\alpha > 1$, the demand function can be obtained in the same way.

This condition $k > (1 + \beta)(p - \alpha p_r)/e$ is necessary. Specifically, when the product function is poor, the green product can coexist with the functional product only if the CEA is high, the green product can be in coexistence with the functional product. When $\alpha > 1$, a similar condition is $k < (1 + \beta)(p - \alpha p_r)/e$. ■

Appendix B. The proof of Theorem 1

Proof. When $0 < \alpha < 1$, we solve the maximization problem of the manufacturer $\max \pi_R^m(\omega, e) = (\omega - c)q - \gamma e^2 - t(1 - e)q$ first. The Hessian is negative definite and the profit function π_R^m is concave in (ω, e) if and only if $(k + t + t\beta)^2 + 4(\alpha - 1)(1 + \beta)^2(\alpha + (\alpha - 1)\beta)\gamma < 0$. When this concavity condition holds, solving the

FOCs simultaneously yields $\omega = t + c + \frac{(1+\beta)(kt+(1+\beta)(t^2+2(\alpha-1)(\alpha+(\alpha-1)\beta)\gamma))(\alpha p_r - p)}{k(k+t+t\beta)+2(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma}$; $e = \frac{(1+\beta)(k+t+t\beta)(p-\alpha p_r)}{k(k+t+t\beta)+2(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma}$. Then, substituting the optimal values of (ω, e) into the retailer's profit function $\max \pi_R^r(p) = (p - \omega)q$, and it is concave in p . We get the optimal values of p , ω , and e . To ensure the firm's profit is more than zero, we can obtain a condition that equals the concavity condition. Additionally, because of $k > (1 + \beta)(p - \alpha p_r)/e$, we have $t + c_g - \alpha p_r < 0$. Note that this condition would be used as follows: When $\alpha > 1$, the concavity condition is $(k + t + t\beta)^2 - 4(\alpha - 1)(1 + \beta)^2\gamma^2 < 0$, and $1 + t - \alpha + c - p_r < 0$. The method is similar with $0 < \alpha < 1$.

The specific formulas are shown here:

$$\begin{aligned}
A_1 &= \frac{(k(k+t+t\beta)+2(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)(c+t+\alpha(k^2+3kt(1+\beta)+2(1+\beta)^2(t^2+3(\alpha-1)(\alpha+(\alpha-1)\beta)\gamma)))p_r}{2((k+t+t\beta)^2+4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)}; \\
B_1 &= \frac{(k+t+t\beta)(k(t+\alpha-1)+2t(\alpha-1)(1+\beta))-2(\alpha-1)(t+3\alpha-3)(1+\beta)^2\gamma+(k(k+t+t\beta)-2(\alpha-1)(1+\beta)^2\gamma)c+(k^2+3kt(1+\beta)+2(1+\beta)^2(t^2+3\gamma(1-\alpha)))p_r}{(2(k+t+t\beta)^2-8(\alpha-1)(1+\beta)^2\gamma)}; \\
A_2 &= t + c + \frac{(1+\beta)(kt+(1+\beta)(t^2+2(\alpha-1)(\alpha+(\alpha-1)\beta)\gamma))(\alpha p_r - t - c)}{2(k+t+t\beta)^2+8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma}; \\
B_2 &= \frac{(t(k+t+t\beta)(2k+(t+\alpha-1)(1+\beta))-2(\alpha-1)(3t+\alpha-1)(1+\beta)^2\gamma+(2k^2+3kt(1+\beta)+(1+\beta)^2(t^2+6\gamma(1-\alpha)))c+(1+\beta)(t(k+t+t\beta)-2(\alpha-1)(1+\beta)\gamma)p_r)}{(2(k+t+t\beta)^2-8(\alpha-1)(1+\beta)^2\gamma)}; \\
A_3 &= \frac{((1+\beta)(k+t+t\beta)(t+c-\alpha p_r))}{(2((k+t+t\beta)^2+4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma))}; \\
B_3 &= \frac{((1+\beta)(k+t+t\beta)(1+t-\alpha+c-p_r))}{(2(k+t+t\beta)^2-8(\alpha-1)(1+\beta)^2\gamma)}. \quad \blacksquare
\end{aligned}$$

Appendix C. The heterogeneous case and its results

Considering the heterogeneity of consumers' environmental utility from the green product, the environmental utility is assumed to be $k_i e$ (Chen, 2001; Yalabik and Fairchild, 2011), where k_i with a probability P_i ($i = h, l$) is the sensitivity of consumers to the green product's greenness. We use a two-point distribution to describe the environmental awareness of consumers, k_h with a probability θ for the consumer with strong environmental awareness and k_l with a probability $1 - \theta$ for the weak one. Similar to the situation in Section 3, the utilities a consumer derives from the regular and green products are

$$\begin{cases} u_r = V - p_r, \\ u_g = \alpha V - p + k_i e - \beta(u_r - u'_g). \quad i = h, l \end{cases}$$

Similarly to the homogeneous case, we obtain the conditions as $k_i > (1 + \beta)(p - \alpha p_r)/e$ ($0 < \alpha < 1$) and $k_i < (1 + \beta)(p - \alpha p_r)/e$ ($\alpha > 1$). The demand functions of the two

products are as follows:

$$\begin{cases} q_r = \sum_i P_i \left(1 - \frac{(1+\beta)(p_r - p) + k_i e}{1 - (\alpha + \alpha\beta - \beta)}\right), \\ q = \sum_i P_i \left(\frac{(1+\beta)p_r - (1+\beta)p + k_i e}{1 - (\alpha + \alpha\beta - \beta)} - \frac{(1+\beta)p - \beta p_r - k_i e}{\alpha + \alpha\beta - \beta}\right); \end{cases} \quad (0 < \alpha < 1) \quad (\text{C.1})$$

and

$$\begin{cases} q_r = \sum_i P_i \left(\frac{(1+\beta)(p - p_r) - k_i e}{(\alpha + \alpha\beta - \beta) - 1} - p_r\right), \\ q = \sum_i P_i \left(1 - \frac{(1+\beta)(p - p_r) - k_i e}{(\alpha + \alpha\beta - \beta) - 1}\right). \end{cases} \quad (\alpha > 1) \quad (\text{C.2})$$

Define $K = \theta k_l + (1 - \theta)k_h$ as the expected consumers' greenness awareness in whole market. Solving the model, we obtain the optimal solutions as follows:

$$p_M^* = \begin{cases} A'_1, & (0 < \alpha < 1) \\ B'_1; & (\alpha > 1) \end{cases} \quad \omega_M^* = \begin{cases} A'_2, & (0 < \alpha < 1) \\ B'_2; & (\alpha > 1) \end{cases} \quad e_M^* = \begin{cases} A'_3, & (0 < \alpha < 1) \\ B'_3. & (\alpha > 1) \end{cases}$$

The specific formulas are given below:

$$\begin{aligned} A'_1 &= \frac{(K(K+t+t\beta) + 2(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)(c+t) + \alpha(K^2 + 3Kt(1+\beta) + 2(1+\beta)^2(t^2 + 3(\alpha-1)(\alpha+(\alpha-1)\beta)\gamma))p_r}{2((K+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)}; \\ B'_1 &= \frac{(K+t+t\beta)(K(t+\alpha-1) + 2t(\alpha-1)(1+\beta) - 2(\alpha-1)(t+3\alpha-3)(1+\beta)^2\gamma) + (K(K+t+t\beta) - 2(\alpha-1)(1+\beta)^2\gamma)c + (K^2 + 3Kt(1+\beta) + 2(1+\beta)^2(t^2 + 3\gamma(1-\alpha)))p_r}{(2(K+t+t\beta)^2 - 8(\alpha-1)(1+\beta)^2\gamma)}; \\ A'_2 &= t + c + \frac{(1+\beta)(Kt + (1+\beta)(t^2 + 2(\alpha-1)(\alpha+(\alpha-1)\beta)\gamma))(ap_r - t - c)}{2(K+t+t\beta)^2 + 8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma}; \\ B'_2 &= \frac{(K+t+t\beta)(2K + (t+\alpha-1)(1+\beta) - 2(\alpha-1)(3t+\alpha-1)(1+\beta)^2\gamma) + (2K^2 + 3Kt(1+\beta) + (1+\beta)^2(t^2 + 6\gamma(1-\alpha)))c + (1+\beta)(K(K+t+t\beta) - 2(\alpha-1)(1+\beta)\gamma)p_r}{(2(K+t+t\beta)^2 - 8(\alpha-1)(1+\beta)^2\gamma)}; \\ A'_3 &= \frac{((1+\beta)(K+t+t\beta)(t+c-ap_r))}{(2((K+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma))}; \\ B'_3 &= \frac{((1+\beta)(K+t+t\beta)(1+t-\alpha+c-p_r))}{(2(K+t+t\beta)^2 - 8(\alpha-1)(1+\beta)^2\gamma)}. \end{aligned}$$

Appendix D. The proof of Proposition 1

Proof. The optimal design strategy depends on e_R^* 's monotonicity in t .

(I) When $0 < \alpha < 1$, the first derivatives of e_R^* in t is

$$\frac{\partial e_R^*}{\partial t} = \frac{(1+\beta)(k(k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)(k+2t(1+\beta))\gamma - (1+\beta)((k+t+t\beta)^2 - 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)(c-ap_r))}{2((k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2}.$$

Let $\sigma_1 = 2((k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2$. We have $\sigma_1 > 0$ and $c - ap_r < 0$ because of $t + c - ap_r < 0$. Let $\eta_1 = k(k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)(k+2t(1+\beta))\gamma - (1+\beta)((k+t+t\beta)^2 - 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)(c-ap_r) = 0$.

We have a threshold $\hat{\gamma}_1 = \frac{(k+t+t\beta)^2(-k+(1+\beta)(c-\alpha p_r))}{4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)(k+2t(1+\beta)+(1+\beta)(c-\alpha p_r))}$, $0 < \alpha < 1$. There is another threshold $\hat{t}_1 = \frac{(1+\beta)(\alpha p_r - c) - k}{2(1+\beta)}$, $0 < \alpha < 1$, which determines η_3 's monotonicity in γ : when $t < \hat{t}_1$, η_1 is increasing in γ ; and when $t \geq \hat{t}_1$, η_3 is decreasing in γ . We find that

i) when $t < \hat{t}_1$, $\hat{\gamma}_1 < 0$, so e_R^* is increasing in t ; and

ii) when $t \geq \hat{t}_1$, if $\gamma < \hat{\gamma}_1$, e_R^* is increasing in t ; and if $\gamma \geq \hat{\gamma}_1$, e_R^* is decreasing in t .

(II) When $\alpha > 1$, the proposition is similar to the former but only the value of the thresholds changes: $\hat{t}_1 = \frac{(\alpha-1-c+p_r)(1+\beta)-k}{2(1+\beta)}$ and $\hat{\gamma}_1 = \frac{(k+t+t\beta)^2(k+(\alpha-1-c+p_r)(1+\beta))}{4(\alpha-1)(1+\beta)^2(k+(1+2t-\alpha)(1+\beta)+(1+\beta)c-(1+\beta)p_r)}$. ■

Appendix E. The proof of Proposition 2

Proof. The optimal design strategy depends on e_R^* 's monotonicity in β .

(I) When $0 < \alpha < 1$, the first derivatives of e_R^* in β is

$\frac{\partial e_R^*}{\partial \beta} = \frac{(k(k+t+t\beta)^2 - 4(\alpha-1)(1+\beta)^2(t(\alpha-1)(1+\beta)^2 + k(-1-2\beta+2\alpha(1+\beta))))\gamma(t+c-\alpha p_r)}{2((k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2}$. Let $\sigma_1 = 2((k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2$. We have $\sigma_1 > 0$ and $t+c-\alpha p_r < 0$. Let $\eta_2 = k(k+t+t\beta)^2 - 4(\alpha-1)(1+\beta)^2(t(\alpha-1)(1+\beta)^2 + k(-1-2\beta+2\alpha(1+\beta)))\gamma$, and η_2 is a function of γ . The coefficient of γ in η_2 is decreasing in t . Let the coefficient $-4(\alpha-1)(1+\beta)^2(t(\alpha-1)(1+\beta)^2 + k(-1-2\beta+2\alpha(1+\beta))) = 0$. We have $\hat{t}_2 = \frac{k(1+2\beta-2\alpha(1+\beta))}{(\alpha-1)(1+\beta)^2}$. Thus, i) when $t < \hat{t}_2$, η_2 is increasing in γ ; and ii) when $t \geq \hat{t}_2$, η_2 is decreasing in γ . Let $\eta_2 = 0$, and so we have $\hat{\gamma}_2 = \frac{k(k+t+t\beta)^2}{4(\alpha-1)(1+\beta)^2(t(\alpha-1)(1+\beta)^2 + k(2\alpha(1+\beta)-2\beta-1))}$.

We find that

i) when $t < \hat{t}_2$, $\hat{\gamma}_2 < 0$, and e_R^* is always decreasing in β ; and

ii) when $t \geq \hat{t}_2$, e_R^* is decreasing in β , if $\gamma < \hat{\gamma}_2$; and e_R^* is increasing in β , if $\gamma \geq \hat{\gamma}_2$.

(II) When $\alpha > 1$, the first derivatives of e_R^* in β is

$\frac{\partial e_R^*}{\partial \beta} = \frac{k((k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2\gamma)(1+t-\alpha+c-p_r)}{2((k+t+t\beta)^2 - 4(\alpha-1)(1+\beta)^2\gamma)^2} = \eta_3/\sigma_2$, where $\eta_3 < 0$ and $\sigma_2 > 0$. Thus e_R^* is decreasing in β . ■

Appendix F. The proof of Proposition 3

Proof. The optimal pricing strategy depends on p_R^* 's monotonicity in β .

$$(I) \text{ When } 0 < \alpha < 1, \frac{\partial p_R^*}{\partial \beta} = -\frac{(kt(k+t+t\beta)^2 - 2(\alpha-1)(1+\beta)(t^2(\alpha-1)(1+\beta)^3 + k^2(1+3\beta-3\alpha(1+\beta)))\gamma)(t+c_g-\alpha p_r)}{2((k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2}.$$

Let $\eta_5 = kt(k+t+t\beta)^2 - 2(\alpha-1)(1+\beta)(t^2(\alpha-1)(1+\beta)^3 + k^2(1+3\beta-3\alpha(1+\beta)))\gamma$. We find that η_5 's monotonicity in γ is dependent on $\eta_6 = t^2(\alpha-1)(1+\beta)^3 + k^2(1+3\beta-3\alpha(1+\beta))$.

Let $\hat{\beta}_1 = \frac{1-3\alpha}{3(\alpha-1)}$, and so we have the following:

i) When $\beta < \hat{\beta}_1$, then $\eta_6 < 0$, and η_5 is increasing in γ . Let $\eta_5 = 0$, we get a threshold $\hat{\gamma}_3 = \frac{kt(k+t+t\beta)^2}{2(\alpha-1)(1+\beta)(t^2(\alpha-1)(1+\beta)^3 + k^2(1+3\beta-3\alpha(1+\beta)))}$ of γ : if $\gamma < \hat{\gamma}_3$, p_R^* is increasing in β ; otherwise, p_R^* is decreasing in β .

ii) When $\beta \geq \hat{\beta}_1$, let $\eta_6 = 0$ and we can obtain a threshold $\hat{t}_3 = k\sqrt{\frac{3\alpha(1+\beta)-3\beta-1}{(\alpha-1)(1+\beta)^3}}$ of t : if $t \geq \hat{t}_3$, then $\eta_6 < 0$ and the proposition is the same as the former; if $t < \hat{t}_3$, then $\eta_6 > 0$ and η_5 is decreasing in γ : when $\gamma < \hat{\gamma}_3$, p_R^* is decreasing in β ; otherwise, p_R^* is increasing in β .

(II) When $\alpha > 1$, $\frac{\partial p_R^*}{\partial \beta} = -\frac{k(t(k+t+t\beta)^2 - 4k(\alpha-1)(1+\beta)\gamma)(1+t-\alpha+c_g-p_r)}{2((k+t+t\beta)^2 - 4(\alpha-1)(1+\beta)^2\gamma)^2}$. Let $\eta_7 = t(k+t+t\beta)^2 - 4k(\alpha-1)(1+\beta)\gamma = 0$. We have a threshold $\hat{\gamma}_4 = \frac{t(k+t+t\beta)^2}{4k(\alpha-1)(1+\beta)}$ of γ , such that i) when $\gamma < \hat{\gamma}_4$, p_R^* is increasing in β ; and when $\gamma \geq \hat{\gamma}_4$, p_R^* is decreasing in β . ■

Appendix G. The proof of Proposition 4

Proof. The optimal pricing strategy depends on p_R^* 's monotonicity in k .

(I) When $0 < \alpha < 1$, the first derivatives of p_R^* in k is

$$\frac{\partial p_R^*}{\partial k} = \frac{(1+\beta)(t(k+t+t\beta)^2 + 4k(\alpha-1)(1+\beta)(\alpha+(\alpha-1)\beta)\gamma)(t+c_g-\alpha p_r)}{2((k+t+t\beta)^2 + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)^2}.$$

Let $\eta_4 = t(k+t+t\beta)^2 + 4k(\alpha-1)(1+\beta)(\alpha+(\alpha-1)\beta)\gamma$, and it is decreasing in γ . Let $\eta_4 = 0$, and so we have a threshold

$$\hat{\gamma}_5 = \frac{t(k+t+t\beta)^2}{4k(1-\alpha)(1+\beta)(\alpha+\alpha\beta-\beta)}, 0 < \alpha < 1.$$

i) When $\gamma < \hat{\gamma}_5$, then $\eta_4 > 0$, so p_R^* is decreasing in k .

ii) When $\gamma \geq \hat{\gamma}_5$, then $\eta_4 \leq 0$, so p_R^* is increasing in k .

(II) When $\alpha > 1$, the proposition is similar to the former but only the value of threshold changes: $\hat{\gamma}_5 = \frac{t(k+t+t\beta)^2}{4k(\alpha-1)(1+\beta)}, \alpha > 1$. ■

Appendix H. The proof of Theorem 2

Proof. When $0 < \alpha < 1$, we solve the retailer's problem first. The objective function of the retailer is concave in p because $\partial_p \partial_p \pi_M^r = \frac{2}{(\alpha-1)(\alpha+(\alpha-1)\beta)} < 0$, so we have $p = \frac{ke + \alpha(1+\beta)p_r + (1+\beta)\omega}{2(1+\beta)}$. Then, substituting the optimal values of p into the manufacturer's profit function shows it is joint concave in (ω, e) when $(k+t+t\beta)^2 + 8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma < 0$. When this concavity condition holds, solving the FOCs simultaneously yields ω_M^* and e_M^* . To ensure the firm's profit is more than zero, we can obtain a condition that equals the concavity condition. When $\alpha > 1$, the solving process is the same. The specific formulas are shown here:

$$A_4 = \frac{(k(k+t+t\beta) + 2(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)(t+c) + \alpha(1+\beta)(t(k+t+t\beta) + 6(\alpha-1)(1+\beta)(\alpha+(\alpha-1)\beta)\gamma)p_r}{(k+t+t\beta)^2 + 8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma};$$

$$B_4 = \frac{t(k+t+t\beta)(k+(\alpha-1)(1+\beta)) - 2(\alpha-1)(t+3\alpha-3)(1+\beta)^2\gamma + (k(k+t+t\beta) - 2(\alpha-1)(1+\beta)^2\gamma)c + (1+\beta)(t(k+t+t\beta) - 6(\alpha-1)(1+\beta)\gamma)p_r}{(k+t+t\beta)^2 - 8(\alpha-1)(1+\beta)^2\gamma};$$

$$A_5 = \frac{(k(k+t+t\beta) + 4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)(t+c) + \alpha(1+\beta)(t(k+t+t\beta) + 4(\alpha-1)(1+\beta)(\alpha+(\alpha-1)\beta)\gamma)p_r}{(k+t+t\beta)^2 + 8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma};$$

$$B_5 = \frac{t(k+t+t\beta)(k+(\alpha-1)(1+\beta)) - 4(\alpha-1)(t+\alpha-1)(1+\beta)^2\gamma + (k(k+t+t\beta) - 4(\alpha-1)(1+\beta)^2\gamma)c + (1+\beta)(t(k+t+t\beta) - 4(\alpha-1)(1+\beta)\gamma)p_r}{(k+t+t\beta)^2 - 8(\alpha-1)(1+\beta)^2\gamma};$$

$$A_6 = \frac{(1+\beta)(k+t+t\beta)(t+c - \alpha p_r)}{(k+t+t\beta)^2 + 8(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma};$$

$$B_6 = \frac{(1+\beta)(k+t+t\beta)(1+t-\alpha+c-p_r)}{(k+t+t\beta)^2 - 8(\alpha-1)(1+\beta)^2\gamma}. \quad \blacksquare$$

Appendix I. The proof of Theorem 3

Proof. First, we solve the problem under the centralized supply chain. When $0 < \alpha < 1$, the Hessian is $-\frac{(k+t+t\beta)^2 + 4(-1+\alpha)(1+\beta)^2(\alpha+(-1+\alpha)\beta)\gamma}{(-1+\alpha)^2(1+\beta)^2(\alpha+(-1+\alpha)\beta)^2}$, same as the former model, to make sure the profit is more than zero. We have $(k+t+t\beta)^2 + 4(-1+\alpha)(1+\beta)^2(\alpha+(-1+\alpha)\beta)\gamma < 0$. Note that this condition guarantees that the Hessian is negative definite. Then we have the optimal retail price(A7) and green degree(A8). When $\alpha > 1$, we solve the problem in a similar way.

We then adopt a revenue-sharing contract to coordinate the supply chain. In this scenario, the firms' profit functions are

$$\pi_{RS}^r(p) = (\phi p - \omega)q \quad (\text{I.1})$$

$$\pi_{RS}^m(e) = (\omega - c)q - \gamma e^2 - t(1-e)q + (1-\phi)pq \quad (\text{I.2})$$

Given the wholesale price $\omega = \phi(c + \gamma e^2/q + t(1 - e))$, the profit function of the retailer (I.1) can be rewritten as $\pi_{RS}^r(p) = \phi((p - c)q - \gamma e^2 - t(1 - e)q) = \phi\pi_C(p, e)$, and the manufacturer's profit is $\pi_{RS}^m = (1 - \phi)\pi_C(p, e)$, which means the optimal solution of the centralized supply chain maximizes both firms' profit. The specific formulas are shown here:

$$A_7 = \frac{(k(k+t+t\beta)+2(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma)(t+c)+\alpha(1+\beta)(t(k+t+t\beta)+2(\alpha-1)(1+\beta)(\alpha+(\alpha-1)\beta)\gamma)p_r}{(k+t+t\beta)^2+4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma};$$

$$B_7 = \frac{t(k+t+t\beta)(k+(\alpha-1)(1+\beta))-2(\alpha-1)(t+\alpha-1)(1+\beta)^2\gamma+(k(k+t+t\beta)-2(\alpha-1)(1+\beta)^2\gamma)c+(1+\beta)(t(k+t+t\beta)-2(\alpha-1)(1+\beta)\gamma)p_r}{(k+t+t\beta)^2-4(\alpha-1)(1+\beta)^2\gamma};$$

$$A_8 = \frac{(1+\beta)(k+t+t\beta)(t+c-\alpha p_r)}{(k+t+t\beta)^2+4(\alpha-1)(1+\beta)^2(\alpha+(\alpha-1)\beta)\gamma};$$

$$B_8 = \frac{(1+\beta)(k+t+t\beta)(1+t-\alpha+c-p_r)}{(k+t+t\beta)^2-4(\alpha-1)(1+\beta)^2\gamma}. \quad \blacksquare$$