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GREEN INNOVATION AND PRODUCT LINE DECISIONS UNDER ENVIRONMENTAL STANDARD UPGRADING

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Abstract. With the continuous improvement of product environmental standards, using or selling older generation products will increase additional environmental costs, resulting in a decrease in consumer preference for older generation products or products on hand. This paper investigates the impact of specific product environmental standards implementation on enterprise product line extension and pricing strategies. We find that if the production cost is low or the consumers' green sensitivity is high enough, the manufacturer's green production can be better than the designated standard. When the unit production cost of new products is within a certain range, the manufacturer's profit will increase, otherwise it will decrease. In addition, we present the manufacturer's product line update strategy in different market segments defined by different cost thresholds, which indicate the cases where the manufacturer will be forced to withdraw from the market. Moreover, we examine the correlation between consumer quality preference and market demand, and discover that an elevation in consumer preference for product functional quality does not necessarily result in a corresponding increase in product demand. Finally, we investigate the relationship between the manufacturer's actual green product decision and the specified environmental standard, and give the decision areas where the manufacturer's actual green decision is higher (or lower) than or equal to the specified green standard. The results suggest that blindly improving environmental standards by policymakers does not necessarily lead to an improvement in manufacturers' green decisions.

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1. Introduction

In recent years, striking a balance between economic development and environmental protection has become a prominent topic in both academic research and practical applications [11, 16]. In Europe, the European Commission's Euro VI proposal sets forth new emission standards for trucks and buses, while discussions on implementing the Euro VII emission standard are ongoing. This trend is not limited to Europe, as countries such as China, the United States, and other regions continue to push for the enhancement of environmental protection

Keywords. Green innovation, product green standard, new product introduction, replacement consumer.

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standards. For instance, Singapore has adopted the Euro VI emission standard for new diesel vehicles since 2018[1]. In China, the National Phase VIa has been fully implemented on July 1, 2020, and National Phase VIb has also been fully implemented on July 1, 2023. On the other hand, enterprises strive to generate higher profits by actively launching new products with improved functionality. Furthermore, as consumers' environmental awareness continues to grow, they are increasingly drawn towards purchasing green and low-carbon products [29,39,45]. In order to meet the demands of environmental regulations and cater to consumers' strong preference for green products, manufacturers often design and introduce green value-added offerings [30,36]. For instance, an increasing number of traditional automotive companies have begun to launch new energy vehicles or hybrid vehicles[2].

In the context of environmental standard upgrades, if the manufacturer's products do not meet environmental standards, then consuming products such as cars will bring additional costs to potential consumers when using the product, such as paying additional environmental taxes and car scrapped in advance etc. [1,8]. Correspondingly, the valuation of second-hand products will also decrease after purchasing the products, and this will have an impact on potential purchase decisions for consumers who are preparing for replacing their used product in hand. In this case, companies face technological upgrade tests and whether the green decision is up to the standard directly affects the purchase intention of potential consumers.

Most existing studies have either explored the impact of new product introduction on supply chain performance or the production decisions of manufacturers under environmental regulations. To our knowledge, there is limited literature considering the negative effects of environmental standard upgrades on the sales of older generation products and the holders of these products, as well as the manufacturer's product line decision-making and green level design strategy under such circumstances. However, the actual impact of these environmental standard upgrades on the production and sales of tangible products is a real concern. Inspired by real world cases and the existing research gaps, in this paper, we try to answer the following questions that may be of interest to related companies and consumers:

(1) How will changes in consumer preferences affect the manufacturer's decisions on production, pricing strategies, and product green decisions in the context of upgrading environmental standards? Under what conditions will the manufacturer completely abandon the production of older generation products?
(2) How will the upgrade of environmental standards affect the manufacturer's profit? How does the manufacturer's actual green decisions for the next-generation product relate to the predetermined environmental standards?

In order to solve the above questions, this paper considers a monopoly manufacturer produces both products, namely the old-generation products and the new-generation products (higher-functional green products). On investigating consumer preferences for product renewal decisions, we consider both the primary consumers who purchased the product for the first time and the potential replacement consumers. In the scenarios of with and without environmental standard upgrades, we give the optimal decisions for manufacturers to sell new and old products at the same time, and analyze the impact of environmental standard upgrades through the comparison of equilibrium solutions. Secondly, we investigate key parameters such as the unit production cost of the product on the manufacturer's product line strategies in the segmented markets. In addition, we analyze the situation where the manufacturer upgraded the product but the green R&D level is not up to the standard, and compared the relationship between environmental standard and manufacturer' actual realized green decisions. The main contributions of this paper can be summarized as follows:

(1) We delve into the phenomenon of product preference devaluation resulting from the elevation of environmental standards and the introduction of new products to existing buyers and holders of older products. This analysis offers a fresh and practical perspective that is currently lacking in existing literature.

[1] https://www.businesstimes.com.sg/transport/singapore-to-adopt-euro-vi-emission-standard-for-new-diesel-vehicles-from-2018.

[2] Car companies like Audi and BMW are expanding their product lines to produce new energy vehicles. See: http://finance.sina.com.cn/stock/relnews/hk/2019-11-28/doc-iihnzhfz2325546.shtml and https://nev.ofweek.com/2019-12/ART-71000-8400-30420498.html.

(2) We examine the influence of production costs and consumer green sensitivity on manufacturers' decision to engage in green production, and propose product renewal strategies for manufacturers based on different cost thresholds. These cost thresholds indicate the circumstances under which manufacturers will be compelled to exit the market, offering guidance for manufacturers to optimize their production and pricing decisions in practice when faced with environmental standard upgrades.
(3) We also identify the decision areas for manufacturers' actual green decisions that are higher than, lower than, or equal to the specified green standards. Our findings highlight that blindly raising environmental standards by policymakers does not necessarily result in better manufacturers' green decisions. The research results offer a theoretical basis for policymakers to establish more reasonable environmental standards.

The remainder of this paper is organized as follows. Section 2 presents the literature related to our work. Section 3 provides details of the modeling framework and equilibrium results are derived in Section 4. Section 5 shows a comparative analysis on the impact of implementing environmental standard upgrading on demands, product innovation and profit. In Section 6, we extend our analysis on product line design and the manufacturer's actual green decision under specific environmental standard. Finally, concluding remarks are summarized in Section 7.

2. Literature review

In this section, we focus on three streams of related literature: (1) Benefits and challenges in new product introduction; (2) Marketing issues of green product innovation; and (3) Product replacement with trade-ins.

2.1. Benefits and challenges in new product introduction

Sorescu *et al.* [37] believed that new product introduction (NPI) could be an important part of enterprise innovation, and NPI plays key roles in improving firm profit and preventing product lines from being obsolete. Lobel *et al.* [24] believed that technology firm used to launch new generations products frequently. Results showed that whether or not to release a new generation of the product with new technology levels depend on a fixed launch cost. Further, Nuscheler *et al.* [31] demonstrated that NPI could be risky and expensive, and they show that a successful NPI often depends on skillful management teams. Quddus [33] believed that unlike traditional gasoline vehicles (GV), the power source of new energy vehicles (NEV) is electricity, which has lower use cost and is more environment-friendly. However, the high production cost and sales price also hinder the promotion of new energy vehicles to a certain extent. Mirzagoltabar *et al.* [28] explored the impact of new product development on economic, environmental and social performances in a sustainable dual channel closed-loop supply chain taking the lighting industry as an example. Dou and Choi [5] discussed whether the implementation of trade in and green technology innovation is conducive to the environment. Their research results show that retailer collection schemes using green technology can bring the highest level of supply chain profits and social welfare, but may produce more emissions.

Baum *et al.* [2] pointed out that NPI positively regulates consumers' purchasing intention and recommendation. Palmer and Truong [32] analyzed the question of whether introducing environmental beneficial new products with better environmental performance would bring a higher profit for a firm in a polluting industry. Khan and Wuest [17] demonstrated that the implication of a upgradable product may require additional capabilities and resources, and they pointed out that conventional manufacturer firms do not have such abilities. Flankegård *et al.* [6] examined the challenges and mitigation mechanisms of suppliers' participation in product development from the perspective of the supplier. Hou *et al.* [14] studied the impact of the introduction of new energy vehicles on corporate profits and social welfare. Results show that when considering the network effect, the introduction of electric vehicles can increase the manufacturer's profits and social welfare only when the fixed cost of the new product line is low enough.

2.2. Marketing issues of green product innovation

Environmental issues have attracted more and more attention from individuals, enterprises, governments and non-governmental organizations [27]. Kong *et al.* [18] believed green consumerism had received increasing attention with the fact that consumer awareness of green products had increased. Such as bio-diversity reduction, air pollution, resource depletion, water-pollution, especially greenhouse gas emission, severe smog and haze crises. Therefore Wei *et al.* [40] indicated more and more firms had spent significant financial resources to develop and produce green products.

Cost is the core obstacle of green product R&D and market introduction. Zhang *et al.* [51] pointed out that the innovation cost of green products was generally higher than that of general products, they showed that when a manufacturer who produces only ordinary products and is starting to produce green products, additional production costs such as tool costs for new machines and green R&D expenditures would be paid. Li *et al.* [19] found that when green technology is invested and subsidized, manufacturers and retailers tend to cooperate in green marketing. However, existing studies had pointed out that consumers' willingness to buy green products was related to the price difference between green products and ordinary products. Hong *et al.* [12] studied the optimal pricing strategies of green products by taking into account consumer environmental awareness and regular product reference. Results showed that asymmetric information in the supply chain could greatly affect the pricing of green products. Lin *et al.* [22] explored the moderating effect of marketing capability and R&D intensity on the impact of green innovation strategy on brand value. They demonstrated that marketing ability and R&D intensity are positively correlated with brand value. Li *et al.* [20] studied the contract design of green product supply chain considering marketing efforts in the era of circular economy. They found that in the case of high or low marketing effort effect, the improvement of product greening level can benefit enterprises.

2.3. Product replacement with trade-ins

The uncertainty level of the new product's incremental value is high, consumers are more willing to purchase the current product with trade-ins programs and thus trade-ins programs could be beneficial for the firm [48]. Xu *et al.* [42] analyzed and compared the impacts of trade-ins and price discounts on consumers' replacement purchases. Results demonstrated that under the scenario of a high substitutability level, the implication of trade-ins performs better than price discounts. Xiao *et al.* [41] constructed traditional channel and dual-channel models in the case of trade-in and non-trade-in, and believed that the determination of the best channel is related to customers' acceptance of online channel.

Rao *et al.* [34] studied the trade-ins strategy in a durable product market. Their analysis showed that producers should consider trade-in programs as a matter of routine. Zhu *et al.* [54] derived that the implementation of trade-ins could bring competitive advantage for the firm in a competitive duopoly market in terms of profit and market share. Under the framework of B2C platform, Cao *et al.* [3] showed that the implementation of trade-ins may induce the decision maker to set a lower trade-in rebate, and the platform would obtain a larger profit in return. Yi *et al.* [46] studied the trade-in strategies of automobile manufacturers and analyzed the optimal price and output under different strategies.

In the scenario of a trade old for new and a trade old for remanufactured program, Ma *et al.* [25] investigated the optimal pricing decisions of a monopoly firm. Their results demonstrated that simultaneously adopting the two programs do not necessarily improve the firm's profit and different trade-ins schemes should be designed under different conditions. Ma *et al.* [26] discussed the influence of dual reference effect and policy subsidy on the trade-in pricing of remanufactured products based on reference price effect and reference quality effect, and found that when reference price parameter and reference quality parameter are within a certain range, manufacturers can benefit from them. Zhao *et al.* [52] examined the impact of trade-in services on the quality selection of original equipment manufacturers in the context of competition with third-party remanufacturers and the results show that OEM always improve product quality and can benefit from the implementation of trade-in programs. Table 1 presents the differences between this paper and existing relevant literature.

TABLE 1. Comparisons of related research and this paper.

Related research	Consumer preference	Government policy /Environmental regulation	Trade-in	Product line design	Environmental standard upgrade
Dou and Choi [5]	✓	✓	✓		
Giri *et al.* [7]; Zhou *et al.* [53]; Hong *et al.* [13]; Yalabik and Fairchild [44]	✓	✓			
Hou *et al.* [14]	✓	✓		✓	
Han and Liu [10]; Liu *et al.* [23]	✓			✓	
Ma *et al.* [26]	✓	✓	✓	✓	
Xiao *et al.*, [41]; Cao *et al.* [3]			✓		
Yi *et al.* [46]			✓	✓	
Yu *et al.* [49]; Li *et al.* [20]	✓				
Lobel *et al.* [24]; Zhang *et al.* [51]	✓			✓	
Ino and Matsumura [15]; Li *et al.* [21]; Guo *et al.* [9]					✓
This paper	✓	✓	✓	✓	✓

2.4. Literature summary and research gap

In the existing literature, the profits generated by NPI for manufacturers has been widely recognized. However, the production of new products also brings additional production preparation costs to manufacturers. Enterprises not only update and launch new products with better product quality and functions, but also consider the green investment of products. Based on real-world issues, this study models and analyzes how manufacturers make corresponding pricing and green decisions under policies, taking into account the introduction of product environmental standards and the concessionary depreciation caused by new product introduction for old product buyers and holders. Additionally, to the best of our knowledge, most of the current research on the topic of environmental standard upgrades is conducted from a macro perspective using empirical methods, with few studies examining the impact of environmental standard upgrades on decision-making in supply chain members from a micro perspective. This study fills this gap in the literature.

3. Model setup

3.1. Model description

In this study, we consider a monopolistic manufacturer that sells two successive generation products, *i.e.*, the older generation product (denoted as product A) and the new generation product (product B). It is assumed that product B is superior in both quality and greenness as compared to product A. The manufacturer focuses on two market segments, *i.e.*, the primary segment (denoted as "P") with consumers who are first time buyers, and the replacement segment (denoted as "R") with consumers who have used product in hand. We comparatively study two scenarios, *i.e.*, with environmental standard upgrading (superscript "NU") and without environmental standard upgrading (superscript "EU").

To cope with the upgrading of environmental standards, the manufacturer needs to strategically develop his/her product innovation and NPI strategies. That is, product greenness, pricing and market coverage strategies. As product A is the type of product to be phased out, we will focus on the situation where the manufacturer only increase the green level of the new generation product B. To simplify the comparison of products A and B, we assume that the green level of A is 0. To ease the expressions, we simplify segments "P" and "R" to be equal

TABLE 2. Notations.

Parameters	Explanations
θ	Consumers' preference of older generation product A
α	Functional difference between the two products
k	Consumers' sensitivity for the new product's greenness
h	Consumers' valuation on their used products in hand when a new product is introduced. $(0<h<1)$
β	Consumers' depreciation of product A
l	The depreciation of used product in hand of consumers in segment "R" under "EU"
s	Residual value of older generation product A
Decision variables	
p_A	The selling price of product A
p_B	The selling price of new product B
p_T	The trade-in rebate
e	The green level of new product B

in market size. The simplications do not change the results of important findings. The Notations are given in Table 2.

3.2. Demand structure

In this section, we first derive the consumers' strategic choice without environmental standard upgrading. The consumer utility function is adopted to capture consumers' heterogeneity, and it is widely used to represent the quantitative relationship between the utility obtained by consumers in consumption and the goods consumed [4, 38]. On the primary segment, the utility of purchasing a primary product is $U_A^{P-\mathrm{NU}}=\theta-p_A$, and the utility of purchasing a upgraded product is $U_B^{P-\mathrm{NU}}=(1+\alpha)\theta-p_B+ke$. Consumers are heterogeneous in evaluating the products' functional attributes, and θ is normally distributed in the interval $[0,1]$. Parameter α differentiate the functional difference of the two products. In this paper, we assume that the environmental utility equals ke (Similar assumption can be found in [13, 44, 55]). A consumer will purchase product B if $U_B^{P-\mathrm{NU}}\geq 0$ and $U_B^{P-\mathrm{NU}}\geq U_A^{P-\mathrm{NU}}$ hold at the same time. Similarly, product A is preferred if $U_A^{P-\mathrm{NU}}\geq 0$ and $U_A^{P-\mathrm{NU}}\geq U_B^{P-\mathrm{NU}}$ are satisfied. It is noted that we focus on the scenario where the demand for both products in each segment is positive. On the replacement segment, the utility of purchasing a upgraded product is $U_B^{R-\mathrm{NU}}=(1+\alpha)\theta-p_B+p_T-h\theta+ke$, and the utility of purchasing a primary product is $U_A^{R-\mathrm{NU}}=\theta-p_A+p_T-h\theta$. Similar to Hong *et al.* [13] and Zhu *et al.* [55], by solving the indifferent purchasing point of consumer valuation, we derive the demands in the presence of prices as follows:

$$D_A^{P-\mathrm{NU}}=\int_{p_A}^{\frac{p_B-p_A-ke}{\alpha}}\mathrm{d}\theta=\frac{p_B-p_A-ke}{\alpha}-p_A,\quad D_B^{P-\mathrm{NU}}=\int_{\frac{p_B-p_A-ke}{\alpha}}^{1}\mathrm{d}\theta=1-\frac{p_B-p_A-ke}{\alpha}$$

$$D_A^{R-\mathrm{NU}}=\int_{\frac{p_A-p_T}{1-h}}^{\frac{p_B-p_A-ke}{\alpha}}\mathrm{d}\theta=\frac{p_B-p_A-ke}{\alpha}-\frac{p_A-p_T}{1-h},\quad D_B^{R-\mathrm{NU}}=\int_{\frac{p_B-p_A-ke}{\alpha}}^{1}\mathrm{d}\theta=1-\frac{p_B-p_A-ke}{\alpha}.$$

With environmental standard upgrading, potential consumers have reduced their preference for product A. Specially, older generation product owners have also reduced their preference for holding products in hand. Therefore, on segment "P", the utility of purchasing product A is $U_A^{P-\mathrm{EU}}=(1-\beta)\theta-p_A$, and the utility of purchasing a upgraded product B is $U_B^{P-\mathrm{EU}}=(1+\alpha)\theta-p_B+ke$. On segment "R", the utility of purchasing a upgraded product B is $U_B^{R-\mathrm{EU}}=(1+\alpha)\theta-p_B+p_T-l\theta+ke$, and the utility of purchasing a primary product A is $U_A^{R-\mathrm{EU}}=(1-\beta)\theta-p_A+p_T-l\theta$. Be different to the scenario of "NU", in "EU", we use β to illustrate the consumers' depreciation of product A since A is not up to the environmental standard. Here we assume

TABLE 3. Net consumer utilities in different segments with $\alpha > 0$, $0 < \beta < 1$, $k > 0$ and $h > l > 0$.

Cases	Consumer utilities	
	Replacement consumers	Primary consumers
NU	$\theta - p_A + p_T - h\theta$ (A) $(1+\alpha)\theta - p_B + p_T - h\theta + ke$ (B)	$\theta - p_A$ (A) $(1+\alpha)\theta - p_B + ke$ (B)
EU	$(1-\beta)\theta - p_A + p_T - l\theta$ (A) $(1+\alpha)\theta - p_B + p_T - l\theta + ke$ (B)	$(1-\beta)\theta - p_A$ (A) $(1+\alpha)\theta - p_B + ke$ (B)

$h > l > 0$ to further depict the depreciation of the used product in hand when the new product B is introduced and "EU" is implemented. The utility functions are summarized in Table 3. We then derive the demands in the presence of prices as follows:

$$D_A^{R-\mathrm{EU}} = \int_{\frac{p_A - p_T}{1-\beta-l}}^{\frac{p_B - p_A - ke}{\alpha+\beta}} \mathrm{d}\theta = \frac{p_B - p_A - ke}{\alpha+\beta} - \frac{p_A - p_T}{1-\beta-l},\quad D_B^{R-\mathrm{EU}} = \int_{\frac{p_B - p_A - ke}{\alpha+\beta}}^{1} \mathrm{d}\theta = 1 - \frac{p_B - p_A - ke}{\alpha+\beta}$$

$$D_A^{P-\mathrm{EU}} = \int_{\frac{p_A}{1-\beta}}^{\frac{p_B - p_A - ke}{\alpha+\beta}} \mathrm{d}\theta = \frac{p_B - p_A - ke}{\alpha+\beta} - \frac{p_A}{1-\beta},\quad D_B^{P-\mathrm{EU}} = \int_{\frac{p_B - p_A - ke}{\alpha+\beta}}^{1} \mathrm{d}\theta = 1 - \frac{p_B - p_A - ke}{\alpha+\beta}\cdot$$

Before describing the analytical model, we discuss the key assumptions specific to the cost and consumer behavior across the two products:

(1) To make our analysis feasible, we assume that all the demands are non-negative. For example, in the benchmark scenario NU, $\max\left\{\frac{c_A(y(h-\alpha-1)+k^2)+k^2(h-s-1)+\alpha sy}{(h-1)y}, \frac{c_A(y+\alpha y-k^2)+k^2}{y}\right\} < c_B < \alpha + c_A$ is assumed to ensure the negativity of demands. Similar assumptions have been made in Liu *et al.* [23] and Yu *et al.* [49];
(2) A quadratic cost function is adopted to measure the convex cost of the green improvement on new product B. The quadratic cost structure (*i.e.*, $c = \frac{e^2 y}{2}$) is widely used to capture the green R&D cost [7];
(3) The marginal production cost of the new product B is exogenous and not a function of the functional coefficient α. Similar assumption has been found in Hong *et al.* [12].

4. Equilibrium results

In this section, we respectively derive the optimal decisions of the manufacturer under the scenario with and without environmental standard upgrading. In each scenario, the manufacturer has to maximize the profit functions consist of revenues from the two market segments and the costs from producing and innovating of the two kinds of products. The decision variables are prices (p_A and p_B) and the rebate (p_T) of products A and B, and the green level (e) of the new product B. We respectively use the superscript "NU" and "EU" to denote the scenario with and without environmental standard upgrading. All the proofs of propositions are provided in the appendix.

4.1. Without environmental standard upgrading

Without environmental standard upgrading, consumers do not depreciate their preferences of product A. The profit function of the manufacturer is given as follows:

$$\begin{aligned}\max \Pi^{\mathrm{NU}} = {} & (p_A - c_A)\left(D_A^{R-\mathrm{NU}} + D_A^{P-\mathrm{NU}}\right) + \left(D_A^{R-\mathrm{NU}} + D_B^{R-\mathrm{NU}}\right)(s - p_T)\\ & + (p_B - c_B)\left(D_B^{R-\mathrm{NU}} + D_B^{P-\mathrm{NU}}\right) - \frac{e^2 y}{2}\cdot \end{aligned} \tag{1}$$

In equation (1), the first and the third term respectively denotes the net revenue form selling products A and B. The second term is the net revenue from trade-ins. The last term describes the cost of green R&D. The equilibrium results are given as follows:

Lemma 1. *When* $\frac{k^2}{\alpha} - y < 0$*, the optimal decisions are:* $p_A^{\mathrm{NU}^*} = \frac{1}{2}(c_A + 1)$*,* $p_T^{\mathrm{NU}^*} = \frac{h+s}{2}$*,* $p_B^{\mathrm{NU}^*} = \frac{1}{2}\left(\alpha + c_B + e^{\mathrm{NU}^*}k + 1\right)$ *and* $e^{\mathrm{NU}^*} = -\frac{k(\alpha + c_A - c_B)}{k^2 - \alpha y}$*; The demands are given as:*

$$D_A^{R-\mathrm{NU}^*} = \frac{c_A\left(y(h-\alpha-1)+k^2\right)+c_B(y-hy)+k^2(h-s-1)+\alpha s y}{2(h-1)(k^2-\alpha y)}$$

$$D_B^{R-\mathrm{NU}^*} = \frac{y(\alpha+c_A-c_B)}{2(\alpha y-k^2)}$$

and

$$D_A^{P-\mathrm{NU}^*} = \frac{c_A\left(y+\alpha y-k^2\right)-yc_B+k^2}{2(k^2-\alpha y)}$$

$$D_B^{P-\mathrm{NU}^*} = \frac{y(\alpha+c_A-c_B)}{2(\alpha y-k^2)}\cdot$$

The closed form of the manufacturer's profit could be found the Appendix A.

In Lemma 1, optimal prices and demands are derived with closed forms. It can be found that there exists a upper bound of product B's unit cost ($c_B < \alpha + c_A$) that captures the no-negativity of $D_B^{P-\mathrm{NU}^*}$ and $D_B^{R-\mathrm{NU}^*}$. For the no-negativity of $D_A^{P-\mathrm{NU}^*}$ and $D_A^{R-\mathrm{NU}^*}$, there also exists a lower bound ($c_B > \max\left\{\frac{c_A(y(h-\alpha-1)+k^2)+k^2(h-s-1)+\alpha s y}{(h-1)y}, \frac{c_A(\alpha y+y-k^2)+k^2}{y}\right\}$). From the optimal equilibriums, it interesting to find that the price of product A and the trade-in rebate are not affected by the manufacturer's green decision, and the price of product B is increasing of with the green decision of product B. The sensitivity analysis on demands will be given in Section 5. Next, we will investigate how the manufacturer make the decisions when there exists an environmental standard.

4.2. Upgrading of environmental standard

With the upgrading of environmental standard, consumers depreciate their preference on product A. The profit function to maximize of the manufacturer is given as:

$$\max \Pi^{\mathrm{EU}} = (p_A - c_A)\left(D_A^{R-\mathrm{EU}} + D_A^{P-\mathrm{EU}}\right) + \left(D_A^{R-\mathrm{EU}} + D_B^{R-\mathrm{EU}}\right)(s - p_T) + (p_B - c_B)\left(D_B^{R-\mathrm{EU}} + D_B^{P-\mathrm{EU}}\right) - \frac{e^2 y}{2}\cdot \tag{2}$$

In equation (2), the component of the manufacturer's profit function is similar to the profit function when there is no implementation of environmental standard upgrading. The equilibrium results are given as follows:

Lemma 2. *When* $\frac{k^2}{\alpha+\beta} - y < 0$*, the optimal decisions are:* $p_A^{\mathrm{EU}^*} = \frac{1}{2}(c_A - \beta + 1)$*,* $p_T^{\mathrm{EU}^*} = \frac{l+s}{2}$*,* $p_B^{\mathrm{EU}^*} = \frac{1}{2}(\alpha + c_B + e^{\mathrm{EU}^*}k + 1)$ *and* $e^{\mathrm{EU}^*} = -\frac{k(\alpha+c_A+\beta-c_B)}{k^2-y(\alpha+\beta)}$*; The demands are given as:*

$$D_A^{R-\mathrm{EU}^*} = \frac{c_A\left(y(\alpha-l+1)-k^2\right)+yc_B(\beta+l-1)-k^2(\beta+l-s-1)-sy(\alpha+\beta)}{2(\beta+l-1)(y(\alpha+\beta)-k^2)}$$

$$D_B^{R-\mathrm{EU}^*} = \frac{y(\alpha+c_A+\beta-c_B)}{2(y(\alpha+\beta)-k^2)}$$

and

$$
D_A^{P-\mathrm{EU}^*} = \frac{c_A\big(y+\alpha y-k^2\big)-(\beta-1)\big(k^2-yc_B\big)}{2(\beta-1)(y(\alpha+\beta)-k^2)}
$$
$$
D_B^{P-\mathrm{NU}^*} = \frac{y(\alpha+c_A+\beta-c_B)}{2(y(\alpha+\beta)-k^2)}.
$$

The closed form of the manufacturer's profit could be found the Appendix B.

In Lemma 2, it could be found the the optimal prices of both products A and B varies as compared to the results demonstrated in Lemma 1. The consumers' depreciation (β) negatively affect the optimal price of product A (*i.e.*, $p_A^{\mathrm{EU}^*}-p_A^{\mathrm{NU}^*}<0$) and positively affects the optimal price of product B (*i.e.*, $p_B^{\mathrm{EU}^*}-p_B^{\mathrm{NU}^*}>0$). It also could be found that there exists a upper bound of product B's unit cost ($c_B<\alpha+c_A+\beta$) that captures the no-negativity of $D_B^{P-\mathrm{NU}^*}$ and $D_B^{R-\mathrm{NU}^*}$. For the no-negativity of $D_A^{P-\mathrm{NU}^*}$ and $D_A^{R-\mathrm{NU}^*}$, there also exists a lower bound ($c_B>\max\big\{\frac{c_A(k^2-(\alpha+1)y)+\beta_1k^2}{\beta_1 y},\frac{c_A(k^2+\alpha_1 y)+k^2(\beta_2-s)+sy(\alpha+\beta)}{y\beta_2}\big\}$). All the detail analysis on demands and profits are given in Section 5. In this section, we focus on the perfect scenarios that both the two kinds of products are produced. In Section 6, we will extend to study the cases when the manufacturer selectively give up specific market segments. In the next section, we detailedly investigating on model comparison and sensitivity analysis of key parameter.

5. Discussion

In this section, we will first compare models "NU" and "EU" to find the impacts of the implication of a upgrading environmental standard on specific product demands and firm profits.

5.1. Comparison

We first derive the implications on demands between the two models, *i.e.*, "NU" and model "EU". The following proposition gives the demands comparison:

Proposition 1. *The impacts of upgrading environmental standard on product demands are:*

(1) *For product A, we have* $D_A^{P-\mathrm{EU}^*}>D_A^{P-\mathrm{NU}^*}$ *if* $c_B<\frac{c_A(k^2-(\alpha+1)y)(k^2-y(\alpha+\beta_1))+\beta_1k^2y}{\beta_1y^2}$, *and* $D_A^{R-\mathrm{EU}^*}>D_A^{R-\mathrm{NU}^*}$ *if* $c_B<\frac{c_A((h-l)(k^2-\alpha y)^2-\beta(y(h-\alpha-1)+k^2)(k^2-y(\alpha+l-1))+\beta^2y(y(h-\alpha-1)+k^2))+x}{\beta(h-1)y^2(\beta+l-1)}$.

(2) *For product B, we have* $D_B^{P-\mathrm{EU}^*}>D_B^{P-\mathrm{NU}^*}$ *and* $D_B^{R-\mathrm{EU}^*}>D_B^{R-\mathrm{NU}^*}$ *if* $c_B>\frac{yc_A+k^2}{y}$.

Here, $x=h(s(2\alpha+\beta)-k^4s+k^2y\beta\beta_2-\alpha sy^2(\alpha+\beta))+k^4s(\beta+l)-k^2y((\beta+l)(\beta+s(2\alpha+\beta))-\beta)+\alpha sy^2(\alpha+\beta)(\beta+l)$, $\beta_1=\beta-1$ *and* $\beta_2=\beta+l-1$.

In Proposition 1, we provide the comparison of the two models to the impacts of "EU" on demands. Results show that the demand for product A under both scenarios ("EU" and "NU") is affected by the unit cost of product B. When the unit cost of product B is below a certain threshold, the primary segment and replacement segment demands for product A under the "EU" scenario are larger than those under the "NU" scenario. However, the result is opposite for product B, that is, when the unit cost of product B is above a certain threshold, the primary segment and replacement segment demands for product B under the "EU" scenario are larger than those under the "NU" scenario. These findings could be explained that the demand of product B (A) is decreasing (increasing) in c_B. That is, higher cost input can actually increase the demand for product B under an environmental standard upgrade. Further, by comparing the optimal profits between scenarios "NU" and "EU", we show how will the upgrade of environmental standard affect the manufacturer's profits:

Proposition 2. *For the impacts of upgrading environmental standard on firm profits, we have:*

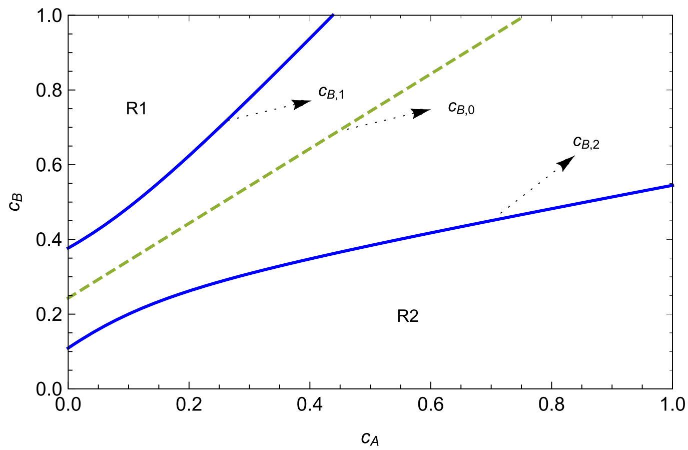

FIGURE 1. The effect of environmental standard upgrading on manufacturer's profit.

(1) *The implication of "EU" decreases the manufacturer's profit (i.e.,* $\Pi^{\mathrm{EU}^*} < \Pi^{\mathrm{NU}^*}$*) if and only if* $c_B > c_{B,1}$*, or* $c_B < c_{B,2}$*; and increases the manufacturer's profit (i.e.,* $\Pi^{\mathrm{EU}^*} \geq \Pi^{\mathrm{NU}^*}$*) if and only if* $c_{B,1} \leq c_B \leq c_{B,2}$*;*

(2) *When* $c_B < c_{B,0}$*, we have* $\frac{\partial(\Pi^{\mathrm{EU}^*}-\Pi^{\mathrm{NU}^*})}{\partial c_B} > 0$*, i.e., the difference of profit is increasing with new product cost.*

Here, $c_{B,12} = \frac{y(2\beta y c_A \pm \sqrt{2\Upsilon}(k^2(2\alpha+\beta)-\alpha y(\alpha+\beta)))-\sqrt{2\Upsilon}k^4+2\beta k^2 y}{2\beta y^2}$, $c_{B,0} = c_A + \frac{k^2}{y}$, $\beta_1 = \beta - 1$, *and* $\Upsilon = \frac{\beta y^2 c_A^2 (l-(\beta^2(h-2)+\beta((h-2)l+2)-h)-2\beta_1 s c_A(\beta-h+l)+\beta_1(h^2(\beta_1+l)-h(\beta+l(\beta+l)+s^2-1)+(\beta+l)(l+s^2)-l))}{\beta_1(h-1)(\beta_1+l)(k^2-\alpha y)(k^2-y(\alpha+\beta))}$.

In Proposition 2, it could be found that there exist two thresholds on c_B, *i.e.*, $c_{B,1}$ and $c_{B,2}$, which determine the comparison results of the manufacturer's profits under models "NU" and "EU". We find that the difference $\Pi^{\mathrm{EU}^*} - \Pi^{\mathrm{NU}^*}$ is a quadric concave function on c_B. In other words, the increase in profit brought by the environmental standard upgrade to the manufacturer is not always increasing with the increase in unit cost of product B. Results indicates that there exists a threshold $c_{B,0} = c_A + \frac{k^2}{y}$, below which $\Pi^{\mathrm{EU}^*} - \Pi^{\mathrm{NU}^*}$ is increasing with product B's unit production cost c_B, and above which $\Pi^{\mathrm{EU}^*} - \Pi^{\mathrm{NU}^*}$ is decreasing with product B's unit production cost c_B.

A numerical example (with $\alpha = 0.7$, $\beta = 0.3$, $h = 0.06$, $k = 0.27$, $l = 0.03$, $s = 0.05$, and $y = 0.3$) is provided for better illustrating this proposition. In Figure 1, regions $R1$ and $R2$ denote the zone that the implication of "EU" dominates "NU" in the manufacture's profit, and in the blank area, the manufacturer's profit is decreased by the implementation of "EU". In addition, the area above the dashed line (*i.e.*, $c_B = c_{B,0}$) represents the zone where the profit difference ($\Pi^{\mathrm{EU}^*} - \Pi^{\mathrm{NU}^*}$) is increasing with the decrease of new product cost c_B.

In the above analysis, we focus on the comparison of the two models under the implementation and non implementation of environmental protection standard upgrading. Next, we will analyze and compare the impact of environmental protection standard upgrading on the demand of consumers in different markets within a single scenario.

Another comparison is investigate how "EU" affects the firm's optimal green R&D.

Proposition 3. *With a threshold* $c_{B,0} = c_A + \frac{k^2}{y}$*, if* $c_B < c_{B,0}$ *is satisfied, then we have* $e^{\mathrm{EU}^*} > e^{\mathrm{NU}^*}$*; and* $e^{\mathrm{EU}^*} \leq e^{\mathrm{NU}^*}$ *if* $c_B \geq c_{B,0}$ *is satisfied.*

In this proposition, we provide under what circumstances the implementation of environmental standard upgrading will lead to a higher manufacturer's green R&D decision. Interestingly, the implementation of environmental upgrading does not necessarily lead to higher product green R&D, and only when the functional production cost of new products is low enough (*i.e.*, $c_B < c_{B,0}$), the implementation of environmental upgrading can bring higher product green investment. The viewpoint that cost has a negative impact on the production and sales of new products here is consistent with relevant literature [14, 24, 33], but these three articles do not consider the factor of environmental standard upgrades. Furthermore, by deriving the first order conditions of the optimal green decision e^{EU^*} and e^{NU^*} on c_B, we have $\frac{\partial e^{\mathrm{NU}^*}}{\partial c_B} = \frac{k}{k^2-y\alpha} < \frac{\partial e^{\mathrm{EU}^*}}{\partial c_B} = \frac{k}{k^2-y(\alpha+\beta)} < 0$. This implies that increasing the unit cost of producing product B has a negative impact on improving the manufacturer's green decision on product B, and the negative impact is stronger in scenario "NU".

In the above analysis, we focus on comparing the equilibriums between the two scenarios. The following two propositions describe the comparison between the two separated segments (*i.e.*, the replacement segment (R) and the primary segment (P)).

Within model "NU", we have the following findings:

Proposition 4. (1) *If $s > hc_A$, we have $D_A^{R-\mathrm{NU}^*} > D_A^{P-\mathrm{NU}^*}$; otherwise, $D_A^{R-\mathrm{NU}^*} \le D_A^{P-\mathrm{NU}^*}$;*

(2) *If $c_B > \frac{c_A\left(y(2h-\alpha-2)+k^2\right)+k^2(h-s-1)+\alpha y(h+s-1)}{2(h-1)y}$, we have $D_A^{R-\mathrm{NU}^*} > D_B^{R-\mathrm{NU}^*}$; otherwise, $D_A^{R-\mathrm{NU}^*} \le D_B^{R-\mathrm{NU}^*}$;*

(3) *If $c_B > \frac{\alpha y c_A k^2 - c_A + 2yc_A + k^2 + \alpha y}{2y}$, we have $D_A^{P-\mathrm{NU}^*} > D_B^{P-\mathrm{NU}^*}$; otherwise, $D_A^{P-\mathrm{NU}^*} \le D_B^{P-\mathrm{NU}^*}$.*

From Proposition 4, we can conclude that when the environmental standard is not upgraded ("NU") and the residual value of product A (s) is larger than a certain threshold (which is a linear function of the unit production cost of product A), the demand for product A in the replacement segment is larger than the demand for product A in the primary segment. This indicates that higher residual values make consumers more inclined to replace product A. When the unit production cost of product B is higher than a certain threshold, the demand for product A in the replacement segment will be larger than the demand for product B. Similarly, the demand for product A in the primary segment will also be larger than the demand for product B. Next, Within model "EU", we have the following findings:

Proposition 5. (1) *If $s > \frac{lc_A}{1-\beta}$, we have $D_A^{R-\mathrm{EU}^*} > D_A^{P-\mathrm{EU}^*}$; otherwise, $D_A^{R-\mathrm{EU}^*} \le D_A^{P-\mathrm{EU}^*}$;*

(2) *If $c_B > \frac{c_A\left(k^2+y(\beta-\alpha+2l-2)\right)+k^2(\beta+l-s-1)+y(\alpha+\beta)(\beta+l+s-1)}{2y(\beta+l-1)}$, we have $D_A^{R-\mathrm{EU}^*} > D_B^{R-\mathrm{EU}^*}$; otherwise, $D_A^{R-\mathrm{EU}^*} \le D_B^{R-\mathrm{EU}^*}$;*

(3) *If $c_B > \frac{c_A\left(k^2+y(\beta-\alpha-2)\right)+(\beta-1)\left(k^2+y(\alpha+\beta)\right)}{2(\beta-1)y}$, we have $D_A^{P-\mathrm{EU}^*} > D_B^{P-\mathrm{EU}^*}$; otherwise, $D_A^{P-\mathrm{EU}^*} \le D_B^{P-\mathrm{EU}^*}$.*

The conclusion of Proposition 5 is consistent with that of Proposition 4, but the relevant thresholds are different. In order to further compare the demand relationship under the two models ("NU" and "EU"), we compare the relevant thresholds in the two propositions and obtain the following observation:

Observation 1.
- For the thresholds of comparing D_A^R and D_A^{P*}, we find that if $h > \frac{l}{1-\beta}$ or $l < h(1+\beta)$ we have $hc_A - \frac{lc_A}{1-\beta} > 0$. This finding implies that the implementation of "EU" enlarges the possibility of $D_A^R > D_A^{P*}$ when h is large enough or l is low enough;
- $\frac{c_A\left(y(2h-\alpha-2)+k^2\right)+k^2(h-s-1)+\alpha y(h+s-1)}{2(h-1)y} > \frac{c_A\left(k^2+y(\beta-\alpha+2l-2)\right)+k^2(\beta+l-s-1)+y(\alpha+\beta)(\beta+l+s-1)}{2y(\beta+l-1)}$ if h is large enough, that is $h > \frac{c_A\left(y(\beta+\alpha(\beta+l))-k^2(\beta+l)\right)+k^2 s(\beta+l)-y\left(\beta^2+\beta(l+\alpha s+s-1)+\alpha ls\right)}{c_A(y(\alpha+\beta)-k^2)+k^2 s-y(\beta(\beta+l-1)+s(\alpha+\beta))}$ or l is small enough, that is $l < \frac{c_A\left(h\left(y(\alpha+\beta)-k^2\right)+\beta\left(k^2-(\alpha+1)y\right)\right)+h\left(k^2 s-y(\beta_1\beta+s(\alpha+\beta))\right)+\beta\left(y(\beta+\alpha s+s-1)-k^2 s\right)}{c_A(\alpha y-k^2)+\beta(h-1)y+s(k^2-\alpha y)}$. This implies that the implementation of "EU" enlarges the possibility of $D_A^R > D_B^R$ when h is large enough or l is low enough;
- $\frac{c_A\left(k^2+y(\beta-2-\alpha)\right)+(\beta-1)\left(k^2+y(\alpha+\beta)\right)}{2(\beta-1)y} > \frac{\alpha y c_A k^2-c_A+2yc_A+k^2+\alpha y}{2y}$ exits all the time, this implies that the threshold of $D_A^{P*} > D_B^{P*}$ is raised by improving environmental protection standards. On the other hand, it also indicates that improving environmental protection standard reduces the threshold of $D_B^{P*} > D_A^{P*}$ for green product cost c_B.

5.2. Sensitivity analysis of consumer preference variance

In this section, we will first analyze the sensitivity of product demand to key parameters in the segmented market, and then analyze the sensitivity of manufacturer's profit.

Proposition 6. *With $c_{B,0} = c_A + \frac{k^2}{y}$, $\alpha_1 = l - \alpha - 1$, $\beta_1 = \beta - 1$*

(1) *If $c_B < c_{B,0}$, we have $\frac{\partial D_B^{R-\mathrm{NU}^*}}{\partial \alpha} > 0$, $\frac{\partial D_B^{P-\mathrm{NU}^*}}{\partial \alpha} > 0$, $\frac{\partial D_B^{R-\mathrm{EU}^*}}{\partial \alpha} > 0$, and $\frac{\partial D_B^{P-\mathrm{EU}^*}}{\partial \alpha} > 0$; $\frac{\partial D_A^{R-\mathrm{NU}^*}}{\partial \alpha} < 0$, $\frac{\partial D_A^{P-\mathrm{NU}^*}}{\partial \alpha} < 0$, $\frac{\partial D_A^{R-\mathrm{EU}^*}}{\partial \alpha} < 0$, and $\frac{\partial D_A^{P-\mathrm{EU}^*}}{\partial \alpha} < 0$;*

(2) *If $c_B > \frac{k^4 s - c_A(k^2+y\alpha_1)(k^2-y(\alpha+2\beta+l-1)) + k^2 y(\beta_1^2+l^2+2\beta_1 l - 2s(\alpha+\beta)) + sy^2(\alpha+\beta)^2}{y^2(\beta+l-1)^2}$, we have $\frac{\partial D_A^{R-\mathrm{EU}^*}}{\partial \beta} > 0$; If $c_B > \frac{\beta_1^2 k^2 y - c_A(k^2-(\alpha+1)y)(k^2-y(\alpha+2\beta-1))}{\beta_1^2 y^2}$, we have $\frac{\partial D_A^{P-\mathrm{EU}^*}}{\partial \beta} > 0$; If $c_B < c_{B,0}$, we have $\frac{\partial D_B^{R-\mathrm{NU}^*}}{\partial \beta} > 0$, $\frac{\partial D_B^{P-\mathrm{NU}^*}}{\partial \beta} > 0$;*

(3) *$\frac{\partial D_B^{R-\mathrm{NU}^*}}{\partial h} = \frac{\partial D_B^{P-\mathrm{NU}^*}}{\partial h} = \frac{\partial D_A^{P-\mathrm{NU}^*}}{\partial h} = 0$ and $\frac{\partial D_A^{R-\mathrm{NU}^*}}{\partial h} < 0$; $\frac{\partial D_B^{R-\mathrm{EU}^*}}{\partial l} = \frac{\partial D_B^{P-\mathrm{EU}^*}}{\partial l} = \frac{\partial D_A^{P-\mathrm{EU}^*}}{\partial l} = 0$ and $\frac{\partial D_A^{R-\mathrm{EU}^*}}{\partial l} < 0$.*

In Proposition 6, we analyze the influence of consumer's preference on product demands. Generally speaking, consumer preferences (such as green preference, quality preference, etc.) are often positively correlated with product demand [10,47,53]. However, unlike these literature, we find that there exists an inconsistency between consumer's functional quality preference and the actual demand of the product. That is, the increase of consumer preferences on product functional quality does not necessarily lead to the corresponding positive growth of product demand. It can be explained that the utility function of consumers' purchases of products is influenced not only by the product's functional utility, but also by the green utility of products. Note that in the same scenario setting of c_B, the demands of products A and B will change in the opposite direction. It is also interesting to find that both the parameters h and l merely affect the demands of product A in the replacement segment, and does not affect the demand of product B in each segment.

As we have assumed in Section 3, the consumers' preference of the green product hold the same $(1+\alpha)\theta$ no matter the government/regulator implements "EU" or not. However, the preference for the primary products varies. In the following proposition, we show how the change of parameters α and β jointly affect the manufacturer's profit.

Proposition 7. *With $c_{B,0} = c_A + \frac{k^2}{y}$,*

(1) *For the profit of model* NU*;*
(a) *When $c_B < c_{B,0}$, $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} > 0$ if $\alpha < c_B - c_A$ or $\alpha > c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} \le 0$ if $c_B - c_A \le \alpha \le c_A - c_B + \frac{2k^2}{y}$;* (b) *When $c_B \ge c_{B,0}$, $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} > 0$ if $\alpha > c_B - c_A$ or $\alpha < c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} \le 0$ if $c_A - c_B + \frac{2k^2}{y} \le \alpha \le c_B - c_A$;*

(2) *For the profit of model* EU*;*
(c) *When $c_B < c_{B,0}$, $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} > 0$ if $\alpha < c_B - c_A - \beta$ or $\alpha > c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} \le 0$ if $c_B - c_A - \beta \le \alpha \le c_A - c_B + \frac{2k^2}{y}$;* (d) *When $c_B \ge c_{B,0}$, $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} > 0$ if $\alpha > c_B - c_A - \beta$ or $\alpha < c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} \le 0$ if $c_A - c_B + \frac{2k^2}{y} \le \alpha \le c_B - c_A - \beta$.*

In this proposition, we show how manufacturer's profit change when consumer preference index α increases. We find that the relationship between manufacturer's profit and consumer preference is not simply positive or negative in both scenarios (scenarios "NU" and "EU"), but is influenced by the unit cost of product A and product B. This finding is similar to that of Zhang and Zheng [50]. Note that the key finding is that with the increase of product B's functional quality, the manufacturer's profit is not necessarily increase (While Xu *et al.* [43] argue that quality improvement can increase manufacturer's profit). Therefore, manufacturers do not need

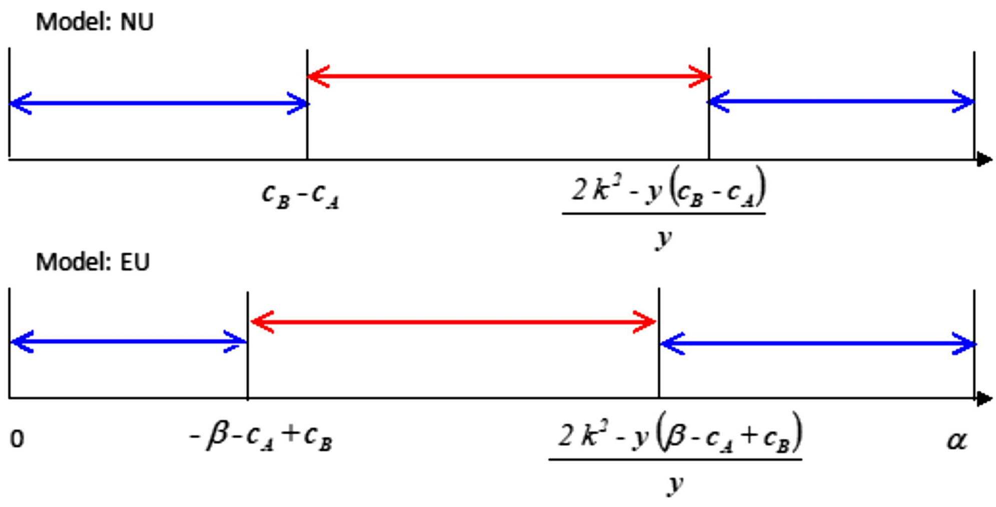

FIGURE 2. The impacts of product functional improvement on manufacturer's profit in the case of $c_B < c_{B,0}$ (where "$\leftrightarrow$" denotes $\frac{\partial \Pi^{NU^*}}{\partial \alpha} < 0$ and "$\leftrightarrow$" denotes $\frac{\partial \Pi^{NU^*}}{\partial \alpha} > 0$).

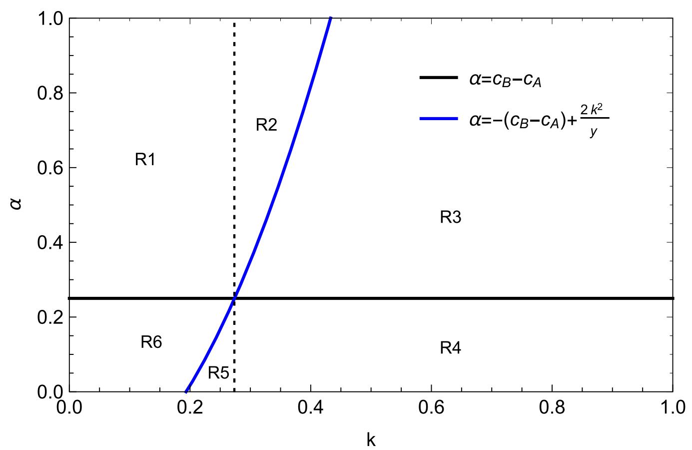

FIGURE 3. The impact of α on manufacturer's profit (Model NU).

to excessively pursue the improvement of functional quality when designing product B. In each scenario, there both exist two cases. Further, in each case, there also exist two thresholds that affect the trends. We use Figure 2 to capture the impact of implementing "EU" on the two thresholds. It could be observed that the implication of "EU" decrease both the two thresholds.

To better understand the impacts of α on profits, numerical examples (with $\beta = 0.7$, $y = 0.3$, $c_A = 0.2$ and $c_B = 0.45$) are given in the Figures 3 and 4. By observing the two figures, it could be found that there exists a dashed line in each figure. On the left side of the dashed line, we have $c_B - c_A > c_A - c_B + \frac{2k^2}{y}$ and $c_B - c_A - \beta > c_A - c_B + \frac{2k^2}{y}$; On the right side of of the dashed line, we have $c_B - c_A \leq c_A - c_B + \frac{2k^2}{y}$ and $c_B - c_A - \beta \leq c_A - c_B + \frac{2k^2}{y}$. Therefore, we have the following observation.

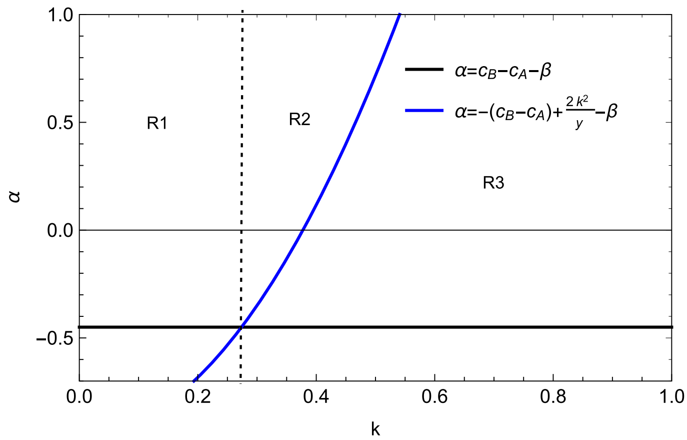

FIGURE 4. The impact of α on manufacturer's profit (Model EU).

Observation 2. – In Figure 3, regions $R1$, $R2$, $R4$ and $R5$ denote the scenario that Π^{NU^*} is increasing with α; and regions $R3$ and $R6$ denotes the scenario that Π^{NU^*} is decreasing with α; In Figure 4, regions $R1$ and $R2$ denote the scenario that Π^{EU^*} is increasing with α; and regions $R3$ denotes the scenario that Π^{EU^*} is decreasing with α. Note that regions $R4$, $R5$ and $R6$ in Figure 4 are meaningless (because $\alpha > 0$), so we do not label them.

– Compared with Figure 3, it can be found that regions $R1$ and $R3$ in Figure 4 decrease while $R2$ increases with the implication of "EU", *i.e.*, both the two thresholds are decreased by the depreciation (β) on product A under "EU".

6. Extensions

In this section, we first analyze the impact of changes in costs and consumer preferences on the manufacturer's product line strategies; then we analyze the relationship between manufacturers' actual green decisions and product environmental standards.

6.1. The manufacturer's product line strategy in each segment

In Lemmas 1 and 2, we demonstrate the optimal pricing decisions of manufacturers for new and old products in two markets under the condition of full market coverage. In reality, because of the possible high cost or high net revenue, the manufacturer may give up a certain part of the market, *e.g.*, when the production cost of the product is too high, the decision-maker may give up the production of the product because of the low profit. Next, we will derive the cost thresholds that identify the manufacturer's strategic choices to explore how costs and key parameters affect the equilibriums.

First, we analyze the manufacturer's production and pricing decisions without environmental protection policies. The optimal solution is as follows:

Proposition 8. *In scenario NU, the manufacturer's optimal policies on product A are characterized by linear relations between c_A and c_B, specifically we have 3 cases:*

Case I. *If* $\frac{c_A(y(2\alpha-h+2)-2k^2)+2k^2+sy}{2y} < c_B < \min\left\{\frac{2\alpha+c_A-h+s+1}{2}, \frac{c_A(y(h-\alpha-1)+k^2)+k^2(h-s-1)+\alpha sy}{(h-1)y}\right\}$, *the manufacturer will give up selling product A in the replacement market* $D_A^{R-\mathrm{NU}^*}=0$, *and* $D_B^{R-\mathrm{NU}^*}=D_B^{P-\mathrm{NU}^*}=\frac{y(-2\alpha-c_A+2c_B+h-s-1)}{2y(h-2\alpha-1)+4k^2}$, $D_A^{P-\mathrm{NU}^*}=\frac{c_A(y(2\alpha-h+2)-2k^2)-2yc_B+2k^2+sy}{2y(-2\alpha+h-1)+4k^2}$.

Case II. *If* $\frac{c_A\left(y(h-2\alpha-2)+2k^2\right)+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)y} < c_B < \frac{c_A(\alpha y+y-k^2)+k^2}{y}$, *the manufacturer will give up selling product A in the primary market* $D_A^{P-\mathrm{NU}^*} = 0$, *and and* $D_B^{R-\mathrm{NU}^*} = D_B^{P-\mathrm{NU}^*} = \frac{y(2c_B+h-2\alpha-c_A-s-1)}{2y(h-2\alpha-1)+4k^2}$, $D_A^{R-\mathrm{NU}^*} = \frac{c_A(y(-2\alpha+h-2)+2k^2)-2(h-1)yc_B+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)(2k^2-(2\alpha+1)y)}$.

Case III. *If* $c_B < \min\left\{\frac{c_A(y(-2\alpha+h-2)+2k^2)+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)y}, \frac{c_A(y(2\alpha-h+2)-2k^2)+2k^2+sy}{2y}\right\}$, *the manufacturer will give up selling the older generation product in the primary and the replacement market* $D_A^{R-\mathrm{NU}^*} = D_A^{P-\mathrm{NU}^*} = 0$, *and* $D_B^{R-\mathrm{NU}^*} = D_B^{P-\mathrm{NU}^*} = \frac{y(2c_B-2\alpha+h-s-2)}{2y(h-2(\alpha+1))+4k^2}$.

In the above proposition, we focus on how the manufacturer changes the market strategy for product A when the unit production cost of the new product (c_B) changes. We give the circumstances under which the manufacturer will give up or partially give up the production and sale of the old generation product (product A). There are five thresholds for c_B that determine whether the manufacturer will continue to produce product A. We show that when the unit cost of c_B is lower enough ($c_B < \min\left\{\frac{c_A(y(-2\alpha+h-2)+2k^2)+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)y}, \frac{c_A(y(2\alpha-h+2)-2k^2)+2k^2+sy}{2y}\right\}$), the manufacturer will totally give up producing product A and focusing on producing product B. There also exists a upper bound threshold, and the manufacturer will produce and sell product A in both the replacement and the primary segment if c_B is larger enough, *i.e.*, $c_B > \max\left\{\frac{c_A(\alpha y+y-k^2)+k^2}{y}, \frac{c_A(y(h-\alpha-1)+k^2)+k^2(h-s-1)+\alpha sy}{(h-1)y}\right\}$. The optimal prices in each case of this proposition are presented in Table 4.

Note that we are focusing on the conditions of the manufacturer of whether or not to produce product A in Proposition 8, and also exist the scenarios when the manufacturer give up to produce product B. The following thresholds determine the manufacturer's strategic choice on product B.

– If $c_B > \frac{2\alpha+c_A-h+s+1}{2}$, $D_A^{P-\mathrm{NU}^*} = \frac{1-c_A}{2}$; $D_B^{R-\mathrm{NU}^*} = D_A^{R-\mathrm{NU}^*} = D_B^{P-\mathrm{NU}^*} = 0$.
– If $c_B > \alpha + c_A$, $D_A^{P-\mathrm{NU}^*} = \frac{1-c_A}{2}$, $D_A^{R-\mathrm{NU}^*} = \frac{c_A+h-s-1}{2(h-1)}$, $D_B^{R-\mathrm{NU}^*} = D_B^{P-\mathrm{NU}^*} = 0$.

It is straightforward to find that the manufacturer will totally abandon product B if $c_B > \max\{\frac{1}{2}(2\alpha + c_A - h + s + 1), \alpha + c_A\}$. We use Figure 5 ($\alpha = 0.4$, $h = 0.8$, $k = 0.3$, $s = 0.2$ and $y = 0.4$) to describe the manufacturer's optimal strategies that are characterized by linear relations between c_A and c_B. In Figure 5, we demonstrate four regions which correspond to the cases in Proposition 8 (In Case IV, all the demands are positive for each product in each segment).

In the above analysis, all the conclusions are analyzed without the implementation of environmental upgrading. Next, we will analyze how the implementation of environmental upgrading affects the manufacturer's product category strategy.

Proposition 9. *In scenario EU, the manufacturer's optimal policies on product A are characterized by linear relations between* c_A *and* c_B, *specifically we have 3 cases:*

Case I. *If* $\frac{c_A(2k^2+y(1-2\alpha-2))+\beta_1(2k^2+sy)}{2\beta_1 y} < c_B < \min\left\{\frac{c_A(k^2+\alpha_1 y)+k^2(\beta_2-s)+sy(\alpha+\beta)}{y\beta_2}, \frac{2\alpha+c_A+\beta_2+s}{2}\right\}$, *the manufacturer will give up selling product A in the replacement market* $D_A^{R-\mathrm{EU}^*} = 0$, *and* $D_B^{R-\mathrm{EU}^*} = D_B^{P-\mathrm{EU}^*} = \frac{y(2c_B-2\alpha-c_A-\beta+l-s-1)}{4k^2+2y(-2\alpha-\beta+l-1)}$, $D_A^{P-\mathrm{EU}^*} = \frac{c_A(y(2\alpha-l+2)-2k^2)-\beta_1(2k^2-2yc_B+sy)}{2\beta_1(y(2\alpha+\beta_2)-2k^2)}$.

Case II. *If* $\frac{c_A(2k^2+y(-2\alpha+l-2))+2k^2(\beta_2-s)+sy(2\alpha+\beta+1)}{2\beta_2 y} < c_B < \frac{c_A(k^2-(\alpha+1)y)+\beta_1 k^2}{\beta_1 y}$, *the manufacturer will give up selling product A in the primary market* $D_A^{P-\mathrm{NU}^*} = 0$, *and and* $D_B^{R-\mathrm{NU}^*} = D_B^{P-\mathrm{NU}^*} = -\frac{y(2\alpha+c_A+\beta-2c_B+1)}{4k^2-2y(2\alpha+\beta+1)}$, $D_A^{R-\mathrm{NU}^*} = \frac{c_A(y(2\alpha-l+2)-2k^2)+2\beta_2 yc_B-2k^2(\beta_2-s)-sy(2\alpha+\beta+1)}{2(\beta+l-1)(y(2\alpha+\beta+1)-2k^2)}$.

Case III. *If* $c_B < \min\left\{\frac{c_A\left(y(-2\alpha+h-2)+2k^2\right)+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)y}, \frac{c_A(y(2\alpha-h+2)-2k^2)+2k^2+sy}{2y}\right\}$, *the manufacturer will give up selling the older generation product in the primary and the replacement market* $D_A^{R-\mathrm{NU}^*} = D_A^{P-\mathrm{NU}^*} = 0$, *and* $D_B^{R-\mathrm{NU}^*} = D_B^{P-\mathrm{NU}^*} = \frac{y(-2\alpha+2c_B+l-s-2)}{4k^2+2y(l-2(\alpha+1))}$.

Table 4. Optimal prices in Proposition 8.

Cases	Optimal prices
Cases I: $\left(D_A^{R-\mathrm{NU}^*}=0, D_B^{R-\mathrm{NU}^*}>0, D_A^{P-\mathrm{NU}^*}>0, D_B^{P-\mathrm{NU}^*}>0\right)$	$e^{\mathrm{NU}^*}=\dfrac{k(-2\alpha-c_A+2c_B+h-s-1)}{y(-2\alpha+h-1)+2k^2}$, $p_A^{\mathrm{NU}^*}=\dfrac{c_A+1}{2}$, $p_T^{\mathrm{NU}^*}=\dfrac{2c_A(h-\alpha-1)-2(h-1)c_B+(h-1)(2e^{\mathrm{NU}^*}k+h+s)-2\alpha h}{2(-2\alpha+h-1)}$, $p_B^{\mathrm{NU}^*}=\dfrac{c_A(h-\alpha-1)-2\alpha^2-2\alpha c_B+\alpha(h-2e^{\mathrm{NU}^*}k+s-3)+(h-1)(2e^{\mathrm{NU}^*}k+1)}{2(-2\alpha+h-1)}$
Cases II: $\left(D_A^{R-\mathrm{NU}^*}>0, D_B^{R-\mathrm{NU}^*}>0, D_A^{P-\mathrm{NU}^*}=0, D_B^{P-\mathrm{NU}^*}>0\right)$	$e^{\mathrm{NU}^*}=\dfrac{k(2\alpha+c_A-2c_B+1)}{-2k^2+2\alpha y+y}$, $p_A^{\mathrm{NU}^*}=\dfrac{2\alpha-c_A+2c_B-2e^{\mathrm{NU}^*}k+1}{4\alpha+2}$, $p_T^{\mathrm{NU}^*}=\dfrac{-2(\alpha+1)c_A+2c_B-2e^{\mathrm{NU}^*}k+2\alpha(h+s)+h+s}{4\alpha+2}$, $p_B^{\mathrm{NU}^*}=\dfrac{-(\alpha+1)c_A+2(\alpha+1)c_B+\alpha(2\alpha+2e^{\mathrm{NU}^*}k+3)+1}{4\alpha+2}$
Cases III: $\left(D_A^{R-\mathrm{NU}^*}=0, D_B^{R-\mathrm{NU}^*}>0, D_A^{P-\mathrm{NU}^*}=0, D_B^{P-\mathrm{NU}^*}>0\right)$	$e^{\mathrm{NU}^*}=\dfrac{k(2c_B-2\alpha+h-s-2)}{y(h-2(\alpha+1))+2k^2}$, $p_A^{\mathrm{NU}^*}=\dfrac{2e^{\mathrm{NU}^*}k+h+s-2\alpha-2c_B-2}{2(h-2(\alpha+1))}$, $p_T^{\mathrm{NU}^*}=\dfrac{h\left(2e^{\mathrm{NU}^*}k-2\alpha-2c_B+h+s-2\right)}{2(h-2(\alpha+1))}$, $p_B^{\mathrm{NU}^*}=\dfrac{h(\alpha+2e^{\mathrm{NU}^*}k-2(\alpha+1)c_B+1)-(\alpha+1)(2\alpha+2e^{\mathrm{NU}^*}k-s+2)}{2(h-2(\alpha+1))}$

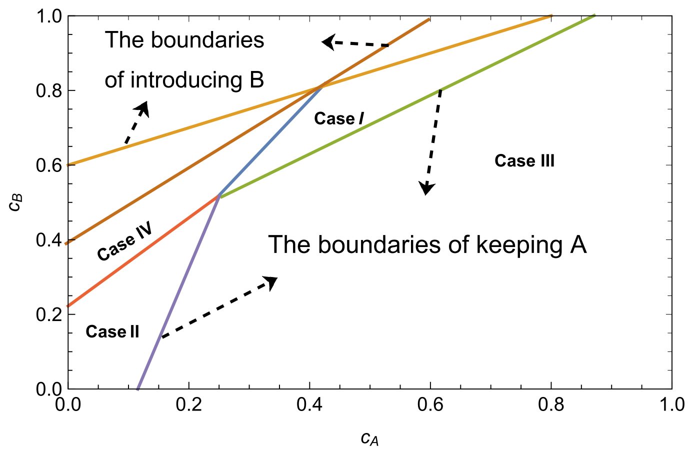

Figure 5. Market coverage without environmental standard upgrading.

TABLE 5. Optimal prices in Proposition 9.

Cases	Optimal prices
Cases I $\left(D_A^{R-\mathrm{EU}^*}=0, D_B^{R-\mathrm{EU}^*}>0,\ D_A^{P-\mathrm{EU}^*}>0, D_B^{P-\mathrm{EU}^*}>0\right)$	$e^{\mathrm{EU}^*}=\frac{k(-2\alpha-c_A-\beta+2c_B+l-s-1)}{2k^2+y(-2\alpha-\beta+l-1)}$, $p_A^{\mathrm{EU}^*}=\frac{1}{2}(c_A-\beta+1)$, $p_T^{\mathrm{EU}^*}=\frac{2c_A\alpha_1-2c_B\beta_1+2e^{\mathrm{EU}^*}k\beta_1+l(-2\alpha+l+s-1)+\beta(s-l)-s}{2(-2\alpha-\beta+l-1)}$, $p_B^{\mathrm{EU}^*}=\frac{c_A\alpha_1-3\alpha-\beta-2(\alpha+\beta)c_B+2e^{\mathrm{EU}^*}k\alpha_1+\alpha(-2\alpha+l+s)+l+\beta(s-\alpha)-1}{2(-2\alpha-\beta+l-1)}$
Cases II: $\left(D_A^{R-\mathrm{EU}^*}>0, D_B^{R-\mathrm{EU}^*}>0,\ D_A^{P-\mathrm{EU}^*}=0, D_B^{P-\mathrm{EU}^*}>0\right)$	$e^{\mathrm{EU}^*}=\frac{k(2\alpha+c_A+\beta-2c_B+1)}{y(2\alpha+\beta+1)-2k^2}$, $p_A^{\mathrm{EU}^*}=-\frac{(\beta-1)\left(2\alpha-c_A+\beta+2c_B-2e^{\mathrm{EU}^*}k+1\right)}{2(2\alpha+\beta+1)}$, $p_T^{\mathrm{EU}^*}=\frac{2(\beta-1)e^{\mathrm{EU}^*}k-2(\alpha+1)c_A-2(\beta-1)c_B+(2\alpha+\beta+1)(l+s)}{2(2\alpha+\beta+1)}$, $p_B^{\mathrm{EU}^*}=\frac{\beta-(\alpha+1)c_A+2(\alpha+1)c_B+\beta(\alpha+2e^{\mathrm{EU}^*}k)+\alpha(2\alpha+2e^{\mathrm{EU}^*}k+3)+1}{2(2\alpha+\beta+1)}$
Cases III: $\left(D_A^{R-\mathrm{EU}^*}=0, D_B^{R-\mathrm{EU}^*}>0,\ D_A^{P-\mathrm{EU}^*}=0, D_B^{P-\mathrm{EU}^*}>0\right)$	$e^{\mathrm{EU}^*}=\frac{k(-2\alpha+2c_B+l-s-2)}{2k^2+y(l-2(\alpha+1))}$, $p_A^{\mathrm{EU}^*}=-\frac{\beta_1\left(S-2\alpha-2c_B+2e^{\mathrm{EU}^*}k+l-2\right)}{2(l-2(\alpha+1))}$, $p_T^{\mathrm{EU}^*}=\frac{l\left(-2\alpha-2c_B+2e^{\mathrm{EU}^*}k+l+s-2\right)}{2(l-2(\alpha+1))}$, $p_B^{\mathrm{EU}^*}=\frac{-2(\alpha+1)c_B+2e^{\mathrm{EU}^*}k\alpha_1+(\alpha+1)(l-2\alpha+s-2)}{2(l-2(\alpha+1))}$

In Proposition 9, we give the conditions under which the manufacturer will give up or partially give up the production and sale of the old generation product (product A) when environmental standard upgrades. Similar to Proposition 8, there are five thresholds for c_B that determine whether the manufacturer will continue to produce product A. It can be found that when producing product B is cost efficiency, or equivalently when the unit cost of c_B is lower enough ($c_B<\min\left\{\frac{c_A(y(-2\alpha+h-2)+2k^2)+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)y}, \frac{c_A(y(2\alpha-h+2)-2k^2)+2k^2+sy}{2y}\right\}$), the manufacturer will totally give up producing product A and focusing on producing product B. The optimal prices in each case of this proposition are presented in Table 5.

There also exists a upper bound threshold, and the manufacturer will produce and sell product A in both the replacement and the primary segment if the unit cost of producing product B is larger enough, *i.e.*, $c_B>\max\left\{\frac{c_A(k^2-(\alpha+1)y)+\beta_1k^2}{\beta_1 y}, \frac{c_A(k^2+\alpha_1 y)+k^2(\beta_2-s)+sy(\alpha+\beta)}{y\beta_2}\right\}$. The following thresholds determine the manufacturer's strategic choice on product B.

- If $c_B>\frac{2\alpha+c_A+\beta-l+s+1}{2}$, $D_A^{P-\mathrm{EU}^*}=\frac{c_A+\beta-1}{2(\beta-1)}$; $D_B^{R-\mathrm{EU}^*}=D_A^{R-\mathrm{EU}^*}=D_B^{P-\mathrm{EU}^*}=0$.
- If $c_B>\alpha+c_A+\beta$, $D_A^{P-\mathrm{EU}^*}=\frac{c_A+\beta-1}{2(\beta-1)}$, $D_A^{R-\mathrm{EU}^*}=\frac{c_A+\beta+l-s-1}{2(\beta+l-1)}$, $D_B^{R-\mathrm{EU}^*}=D_B^{P-\mathrm{EU}^*}=0$.

It is straightforward to find that the manufacturer will totally abandon product B if $c_B>\max\{\frac{2\alpha+c_A+\beta-l+s+1}{2}, \alpha+c_A+\beta\}$. It could be calculated that both the two lower bounds ($\frac{2\alpha+c_A+\beta-l+s+1}{2}$ and $\alpha+c_A+\beta$) is larger than the lower bounds ($\frac{1}{2}(2\alpha+c_A-h+s+1)$ and $\alpha+c_A$) in scenario "NU". We

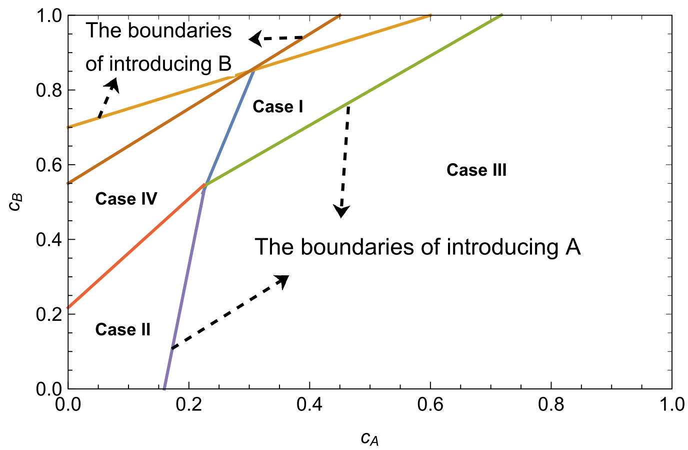

FIGURE 6. Market coverage with environmental standard upgrading.

use Figure 6 ($\alpha = 0.4$, $\beta = 0.15$, $k = 0.3$, $l = 0.75$, $s = 0.2$ and $y = 0.4$) to graphically illustrate the impact of implementing EU on the manufacturer's strategic choices on product A. By comparing Figures 5 and 6, it can be observed that, in the case of environmental upgrading, it is more likely that the manufacturer will give up product A at the same time in the initial market and the old for new market, and it could be found that the total coverage of Cases I–IV is increased with the implication of EU. In addition, it is obvious to find that with the introduction of "EU", the two boundary lines of product B move up and the zone of not feasible to introduce product B has shrunk.

6.2. The manufacturer's actual green decision *vs.* the specified product environmental standard

In many countries, environmental policy makers will set a specific indicator when planning the environmental requirements of certain products. Below this target will be considered non-compliance. To maximize the profit, one of the decision problem of the manufacturer is to set the optimal green level of the upgraded product. In this section, we extend to investigate the manufacturer's strategic decision described in Section 4.2 under specific environmental standard: When the "green" decision is lower than the environmental standard $\bar{E}$, the consumer also values the upgraded product lower even if the manufacturer lunched a green product B. We use parameter γ denotes the depreciation on the upgraded product when $e < \bar{E}$. Then, we have:

$$\left(D_A^{R-\mathrm{EU}^*}, \hat{D}_B^{R-\mathrm{EU}^*}\right) = \begin{cases} \left(\frac{p_B-p_A-ek}{\alpha(1-\gamma)+\beta} - \frac{p_A-p_T}{1-\beta-l}, 1 - \frac{p_B-p_A-ek}{\alpha(1-\gamma)+\beta}\right), & \text{when } e < \bar{E}; \\ \left(\frac{p_B-p_A-ek}{\alpha+\beta} - \frac{p_A-p_{2T}}{1-\beta-l}, 1 - \frac{p_B-p_A-ek}{\alpha+\beta}\right), & \text{when } e \geq \bar{E}; \end{cases} \tag{3}$$

$$\left(D_A^{P-\mathrm{EU}^*}, \hat{D}_B^{P-\mathrm{EU}^*}\right) = \begin{cases} \left(\frac{p_B-p_A-ek}{\alpha(1-\gamma)+\beta} - \frac{p_A}{1-\beta}, 1 - \frac{p_B-p_A-ek}{\alpha(1-\gamma)+\beta}\right), & \text{when } e < \bar{E}; \\ \left(\frac{p_B-p_A-ek}{\alpha+\beta} - \frac{p_A}{1-\beta}, 1 - \frac{p_B-p_A-ek}{\alpha+\beta}\right), & \text{when } e \geq \bar{E}. \end{cases} \tag{4}$$

In this case, as the decision maker, the manufacturer needs to make a strategic choice: whether to manufacture a green product that meets the environmental protection standard. The manufacturer needs to make a trade-off between meeting and not meeting standards. Failure to meet the standard will lead to lower consumer evaluation. However, meeting the standard can obtain higher consumer evaluation, it also means that the manufacturer has to pay more environmental costs. Because we have assumed that the manufacturer is pure profit maximizer, and therefore, we optimize the manufacturer's profit under two cases:

(1) When $e < \bar{E}$, the profit function the manufacturer has to optimize is:

$$\begin{aligned} \max \Pi^{\mathrm{EU}}\left(e < \bar{E}\right) = & \left(2\left(\frac{p_B - p_A - ek}{\alpha(1-\gamma)+\beta}\right) - \frac{p_A - p_T}{1-\beta-l} - \frac{p_A}{1-\beta}\right)(p_A - c_A) \\ & + \left(1 - \frac{p_A - p_T}{1-\beta-l}\right)(s - p_T) + 2\left(1 - \frac{p_B - p_A - ek}{\alpha(1-\gamma)+\beta}\right)(p_B - c_B) - \frac{e^2 y}{2}. \end{aligned} \tag{5}$$

(2) When $e \geq \bar{E}$, the profit function the manufacturer can be wrote as:

$$\begin{aligned} \max \Pi^{\mathrm{EU}}\left(e \geq \bar{E}\right) = & \left(2\left(\frac{p_B - p_A - ek}{\alpha+\beta}\right) - \frac{p_A - p_T}{1-\beta-l} - \frac{p_A}{1-\beta}\right)(p_A - c_A) \\ & + \left(1 - \frac{p_A - p_T}{1-\beta-l}\right)(s - p_T) + 2\left(1 - \frac{p_B - p_A - ek}{\alpha+\beta}\right)(p_B - c_B) - \frac{e^2 y}{2}. \end{aligned} \tag{6}$$

In order to find the optimal choice of the manufacturer, we first give the optimal pricing, the optimal green decision and the profit of the manufacturer when the environmental protection is not up to the standard. Let $\hat{D}$ denotes the demands when the "green" performance of the new product does not meet the environmental standards $\bar{E}$. We derive the optimal decisions of the manufacturer when the product is not up to the standard in the following proposition.

Proposition 10. *When* $\frac{k^2}{\alpha(1-\gamma)+\beta} - y < 0$*, the optimal decisions are:* $\hat{p}_A^{\mathrm{EU}^*} = \frac{1}{2}(c_A - \beta + 1)$*,* $\hat{p}_T^{\mathrm{EU}^*} = \frac{l+s}{2}$*,* $\hat{p}_B^{\mathrm{EU}^*} = \frac{1}{2}\left(\alpha(1-\gamma) + c_B + \hat{e}^{\mathrm{EU}^*}k + 1\right)$ *and* $\hat{e}^{\mathrm{EU}^*} = -\frac{k(\alpha(1-\gamma)+c_A+\beta-c_B)}{k^2 - y(\alpha+\beta)+\alpha\gamma y}$*; The demands are given as:*

$$\hat{D}_A^{R-\mathrm{EU}^*} = \frac{c_A\left(k^2 + y\alpha_2\right) - yc_B\beta_2 + k^2(\beta_2 - s) + sy(\alpha(1-\gamma)+\beta)}{-2\beta_2(y(\alpha(1-\gamma)+\beta) - k^2)}$$
$$\hat{D}_B^{R-\mathrm{EU}^*} = -\frac{y(\alpha + c_A - c_B)}{2(k^2 - \alpha y)}$$

and

$$\hat{D}_A^{P-\mathrm{EU}^*} = \frac{c_A\left(\alpha y + y - k^2\right) - yc_B + k^2}{2(k^2 - \alpha y)}$$
$$\hat{D}_B^{P-\mathrm{EU}^*} = -\frac{y(\alpha + c_A - c_B)}{2(k^2 - \alpha y)}$$

where $\alpha_2 = \alpha(\gamma - 1) + l - 1$ *and* $\beta_2 = \beta + l - 1$*.*

The above proposition gives the optimal results of the optimization problem described in equation (5). As compared to the equilibrium results given in Lemma 2, it can be found the optimal prices of product A ($\hat{p}_A^{\mathrm{EU}^*}$) and the rebate price ($\hat{p}_T^{\mathrm{EU}^*}$) hold the same when the environmental performance of product B does not reach the standard $\bar{E}$. Further, we find that the optimal price of product B decreases when the environmental performance of product B does not reach the standard $\bar{E}$, *i.e.*, $\hat{p}_B^{\mathrm{EU}^*} < p_B^{\mathrm{EU}^*}$. Note that we are working on the optimization problem when the manufacturer's "green decision" (e) is always less than $\bar{E}$. Next, we will investigate how environmental standard $\bar{E}$ affect the manufacturer's strategic pricing and "green decision" decisions.

Assuming that product environmental scoring is composed of many subdivision levels and the unit interval is $\delta, \delta > 0$. Define E_L as the green level which is closest to and less than the environmental standard $\bar{E}$, *i.e.*, $E_L = \bar{E} - \delta < \bar{E}$. Then, we give the manufacturer's optimal decisions with specific environmental standard $\bar{E}$ as follows.

Proposition 11. *The manufacturer's optimal "green decision" can be described as:*

Case I. *When* $\hat{e}^{\mathrm{EU}^*} < \bar{E} < e^{\mathrm{EU}^*}$*, we have:*

$$e^* = \begin{cases} \hat{e}^{\mathrm{EU}^*} = \frac{k(\alpha(1-\gamma)+c_A+\beta-c_B)}{y(\alpha+\beta)-k^2-\alpha\gamma y}, & \text{if } c_B > c_{B,3},\ \textit{or}\ c_B < c_{B,4}; \\ e^{\mathrm{EU}^*} = \frac{k(\alpha+c_A+\beta-c_B)}{y(\alpha+\beta)-k^2}, & \text{if } c_{B,4} < c_B < c_{B,3}; \end{cases}$$

where $c_{B,3} = \frac{k^2}{y} + c_A + \frac{(k^2-y(\alpha+\beta))(k^2-y(\alpha+\beta)+\alpha\gamma y)\sqrt{\frac{\alpha^2(\beta-1)^2\gamma^2y^2(\beta+l-1)^2}{(k^2-y(\alpha+\beta))(k^2-y(\alpha+\beta)+\alpha\gamma y)}}}{\alpha(\beta-1)\gamma y^2(\beta+l-1)}$*, and* $c_{B,4} = \frac{k^2}{y} + c_A - \frac{(k^2-y(\alpha+\beta))(k^2-y(\alpha+\beta)+\alpha\gamma y)\sqrt{\frac{\alpha^2(\beta-1)^2\gamma^2y^2(\beta+l-1)^2}{(k^2-y(\alpha+\beta))(k^2-y(\alpha+\beta)+\alpha\gamma y)}}}{\alpha(\beta-1)\gamma y^2(\beta+l-1)}$.

Case II. *When* $\bar{E} \le \min\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\}$*, we have:*

$$e^* = \begin{cases} E_L, & \text{if } c_B > c_{B,5},\ \textit{or}\ c_B < c_{B,6}; \\ e^{\mathrm{EU}^*} = \frac{k(\alpha+c_A+\beta-c_B)}{y(\alpha+\beta)-k^2}, & \text{if } c_{B,6} < c_B < c_{B,5}; \end{cases}$$

where $c_{B,5} = \frac{(\alpha(1-\gamma)+\beta)\left(y(\alpha+\beta)\sqrt{\frac{\alpha\gamma y(\alpha\gamma+E_L^2y-2E_Lk)}{(\alpha(\gamma-1)-\beta)(k^2-y(\alpha+\beta))}}-k^2\left(\sqrt{\frac{\alpha\gamma y(\alpha\gamma+E_L^2y-2E_Lk)}{(\alpha(\gamma-1)-\beta)(k^2-y(\alpha+\beta))}}-1\right)\right)+E_Lk(k^2-y(\alpha+\beta))}{k^2-\alpha\gamma y}$*, and* $c_{B,6} = \frac{E_Lk(k^2-y(\alpha+\beta))-(\alpha(1-\gamma)+\beta)\left(y(\alpha+\beta)\sqrt{\frac{\alpha\gamma y(\alpha\gamma+E_L^2y-2E_Lk)}{(\alpha(\gamma-1)-\beta)(k^2-y(\alpha+\beta))}}-k^2\left(\sqrt{\frac{\alpha\gamma y(\alpha\gamma+E_L^2y-2E_Lk)}{(\alpha(\gamma-1)-\beta)(k^2-y(\alpha+\beta))}}+1\right)\right)}{k^2-\alpha\gamma y}$.

Case III. *When* $\max\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\} \le \bar{E}$*, we have:*

$$e^* = \begin{cases} \hat{e}^{\mathrm{EU}^*} = \frac{k(\alpha(1-\gamma)+c_A+\beta-c_B)}{y(\alpha+\beta)-k^2-\alpha\gamma y}, & \text{if } c_B > c_{B,7},\ \textit{or}\ c_B < c_{B,8}; \\ \bar{E}, & \text{if } c_{B,8} < c_B < c_{B,7}; \end{cases}$$

where $c_{B,7} = c_A + \frac{(\alpha+\beta)\left(k^2\left(\sqrt{\frac{\alpha\gamma y(\bar{E}^2y-2\bar{E}k-\alpha\gamma)}{(\alpha+\beta)(k^2-y(\alpha+\beta)+\alpha\gamma y)}}+1\right)-y(\alpha(1-\gamma)+\beta)\sqrt{\frac{\alpha\gamma y(\bar{E}^2y-2\bar{E}k-\alpha\gamma)}{(\alpha+\beta)(k^2-y(\alpha+\beta)+\alpha\gamma y)}}\right)+E_1}{k^2+\alpha\gamma y}$, $c_{B,8} = c_A + \frac{(\alpha+\beta)\left(k^2\left(1-\sqrt{\frac{\alpha\gamma y(\bar{E}^2y-2\bar{E}k-\alpha\gamma)}{(\alpha+\beta)(k^2-y(\alpha+\beta)+\alpha\gamma y)}}\right)+y(\alpha(1-\gamma)+\beta)\sqrt{\frac{\alpha\gamma y(\bar{E}^2y-2\bar{E}k-\alpha\gamma)}{(\alpha+\beta)(k^2-y(\alpha+\beta)+\alpha\gamma y)}}\right)+E_1}{k^2+\alpha\gamma y}$*, and* $E_1 = \bar{E}k(k^2-y(\alpha+\beta)+\alpha\gamma y)$.

Case IV. *When* $e^{\mathrm{EU}^*} < \bar{E} < \hat{e}^{\mathrm{EU}^*}$*, we have:*

$$e^* = \begin{cases} E_L, & \text{if } c_B > c_{B,9},\ \textit{or}\ c_B < c_{B,10}; \\ \bar{E}, & \text{if } c_{B,10} < c_B < c_{B,9}; \end{cases}$$

where, $c_{B,9} = c_A + \frac{\sqrt{(\alpha+\beta)(\beta-\alpha(\gamma-1))\left(\alpha^2\gamma^2+\bar{E}^2k^2+E_L\left(e_1(k^2-\alpha\gamma y)+2k(\alpha\gamma-\bar{E}k)\right)+\alpha\gamma\bar{E}(\bar{E}y-2k)\right)}+\delta k(\alpha+\beta)}{\alpha\gamma} + E_L$, $c_{B,10} = c_A + \frac{\delta k(\alpha+\beta)-\sqrt{(\alpha+\beta)(\beta-\alpha(\gamma-1))\left(\alpha^2\gamma^2+e^2k^2+E_L\left(E_L(k^2-\alpha\gamma y)+2k(\alpha\gamma-\bar{E}k)\right)+\alpha\gamma\bar{E}(\bar{E}y-2k)\right)}}{\alpha\gamma} + E_L$ *and* $\delta = \bar{E} - E_L$.

In the first case (Case I), the manufacturer can optimize the profit under two different demand and profit functions described respectively in equations (5) and (6). There are two threshold points (*i.e.*, $c_{B,3}$ and $c_{B,4}$ with $c_{B,4} < c_{B,3}$), that is, between these two thresholds, the manufacturer will choose a green level which is greater than the predetermined standard $\bar{E}$ for the product design of product B.

In Case II when $\bar{E} < \min\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\}$, the optimization of profit function $\hat{\Pi}^{\mathrm{EU}^*}$ (Eq. (5)) will be ended at the point that $e = E_L < \bar{E} < \hat{e}^{\mathrm{EU}^*}$, while the manufacturer could choose the optimal e^{EU^*} to maximize profit function Π^{EU^*} (Eq. (6)). Two threshold points (*i.e.*, $c_{B,5}$ and $c_{B,6}$ with $c_{B,6} < c_{B,5}$) capture the manufacturer's strategic "green decision". That is, the manufacturer will choose a green level greater than or equals the predetermined standard $\bar{E}$ for the design of product B between these two thresholds, and outside these

Table 6. Optimal prices and demands in Proposition 11.

Cases	Optimal prices	Demands
Cases II (If $c_B > c_{B,5}$, or $c_B < c_{B,6}$)	$\hat{p}_A^{\mathrm{EU}^*} = \frac{1}{2}(c_A - \beta + 1), \hat{p}_T^{\mathrm{EU}^*} = \frac{l+s}{2}$, $\hat{p}_B^{\mathrm{EU}^*} = \frac{1}{2}(\alpha(1-\gamma) + c_B + E_L k + 1)$	$\hat{D}_A^{R-\mathrm{EU}^*} = \frac{c_A\alpha_l + (c_B - E_L)\beta_2 - s(\alpha+\beta) + \alpha\gamma s}{2\beta_2(\alpha(1-\gamma)+\beta)}$, $\hat{D}_B^{R-\mathrm{EU}^*} = \hat{D}_B^{P-\mathrm{NU}^*} = \frac{\alpha(1-\gamma) + c_A + \beta - c_B + E_L k}{2(\alpha(1-\gamma)+\beta)}$, and $\hat{D}_A^{P-\mathrm{EU}^*} = \frac{(\alpha(1-\gamma)+1)c_A - (\beta-1)(E_L k - c_B)}{2\beta_1(\alpha(1-\gamma)+\beta)}$
Cases III (If $c_{B,8} < c_B < c_{B,7}$)	$p_A^{\mathrm{EU}^*} = \frac{1}{2}(c_A - \beta + 1), p_T^{\mathrm{EU}^*} = \frac{l+s}{2}$, $p_B^{\mathrm{EU}^*} = \frac{1}{2}\left(\alpha + c_B + \bar{E}k + 1\right)$	$D_A^{R-\mathrm{EU}^*} = \frac{-c_A\alpha_l + (c_B - Ek)\beta_2 - s(\alpha+\beta)}{2(\alpha+\beta)\beta_2}$, $D_B^{R-\mathrm{EU}^*} = D_B^{P-\mathrm{NU}^*} = \frac{\alpha + c_A + \beta - c_B + \bar{E}k}{2(\alpha+\beta)}$, and $D_A^{P-\mathrm{EU}^*} = \frac{(\alpha+1)c_A - (\beta-1)\left(\bar{E}k - c_B\right)}{2\beta_1(\alpha+\beta)}$
Cases IV (If $c_B > c_{B,9}$, or $c_B < c_{B,10}$)	$p_A^{\mathrm{EU}^*} = \frac{1}{2}(c_A - \beta + 1), p_T^{\mathrm{EU}^*} = \frac{l+s}{2}$, $p_B^{\mathrm{EU}^*} = \frac{1}{2}(\alpha + c_B + E_L k + 1)$	$D_A^{R-\mathrm{EU}^*} = \frac{-c_A\alpha_l + (c_B - E_L k)\beta_2 - s(\alpha+\beta)}{2(\alpha+\beta)\beta_2}$, $D_B^{R-\mathrm{EU}^*} = D_B^{P-\mathrm{NU}^*} = \frac{\alpha + c_A + \beta - c_B + E_L k}{2(\alpha+\beta)}$, and $D_A^{P-\mathrm{EU}^*} = \frac{(\alpha+1)c_A - (\beta-1)(E_L k - c_B)}{2\beta_1(\alpha+\beta)}$

two thresholds, the manufacturer will choose the green level equals E_L which is lower than the predetermined standard $\bar{E}$. In Case III when $\max\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\} < \bar{E}$, the procedure of the optimization of profit functions is reversely symmetric with Case II, and the manufacturer will choose the green level less than or equals the predetermined standard $\bar{E}$ outside these two thresholds (*i.e.*, $c_{B,7}$ and $c_{B,8}$ with $c_{B,8} < c_{B,7}$).

In Case IV when $e^{\mathrm{EU}^*} < \bar{E} < \hat{e}^{\mathrm{EU}^*}$, the manufacturer is unable to obtain the maximum profit at the extreme points ($\hat{e}^{\mathrm{EU}^*}$ and e^{EU^*}). When the green decision is less than $\bar{E}$, the manufacturer's profit ($\hat{\Pi}^{\mathrm{EU}^*}$) increases with the increase of e; when the green decision is greater than $\bar{E}$, the manufacturer's profit (Π^{EU^*}) decreases with the increase of e. Because the manufacturer has different profit functions on both sides of $\bar{E}$, we get the optimal decision of the manufacturer by comparing $\hat{\Pi}^{\mathrm{EU}^*}(E_L)$ and $\Pi^{\mathrm{EU}^*}(\bar{E})$. That is to say, when green decision e is within the interval between two thresholds ($c_{B,9}$ and $c_{B,10}$), the manufacturer will follow the environmental protection standard $\bar{E}$, while when it is outside the threshold range, the manufacturer can only make decisions according to E_L. Proposition 11 also tells us that in many cases, the actual green decision-making of the manufacturer can not meet the environmental standard $\bar{E}$. According to the above conclusion, if the policy planners blindly improve the environmental protection standards, it will not necessarily lead to the improvement of the manufacturer's green decision e^*.

When $e^* = e^{\mathrm{EU}^*}$ or $e^* = \hat{e}^{\mathrm{EU}^*}$, the optimal prices and demands are given in Lemma 2 and Proposition 9 respectively. The optimal prices and the realized demands of the other cases in Proposition 11 are summarized and given as below:

In Table 6, it could be found that the optimal p_T and p_A hold the same and only the optimal p_B changes, and there respectively lies a largest and lowest p_B in Cases III and II. Therefore, the introduction of product B is most attractive in Case II. Next, we will study the relationship between manufacturers' actual green R&D decisions and environmental protection standard $\bar{E}$. Take the Case I in Proposition 11 for example, we derive the following findings:

Proposition 12. *With two thresholds* $c_{B,11} = c_A + \frac{\bar{E}(k^2 - y(\alpha+\beta) + \alpha\gamma y) + k(\alpha(1-\gamma)+\beta)}{k}$ *and* $c_{B,12} = c_A + \frac{\bar{E}(k^2 - y(\alpha+\beta)) + k(\alpha+\beta)}{k}$. *The relationship of the manufacturer's strategic green decision with the predetermined environmental standard* $\bar{E}$ *can be summarized in Table 7.*

Table 7. The relationship of $\bar{E}$ and the manufacturer's actual green decision.

Cases	Conditions	
	$\bar{E} < \frac{k}{y}$	$\bar{E} \geq \frac{k}{y}$
$\bar{E} < e^*$	Case I: $\{c_B \mid (c_B < c_{B,4}) \cup (c_B > c_{B,3})\} \cap \{c_B \mid (c_{B,11} < c_B < c_{B,12})\}$ Case II: $\{c_B \mid (c_B < c_{B,6}) \cup (c_B > c_{B,5})\} \cap \{c_B \mid (c_{B,11} < c_B < c_{B,12})\}$ Case III: $\{c_B \mid (c_B < c_{B,8}) \cup (c_B > c_{B,7})\} \cap \{c_B \mid (c_{B,11} < c_B < c_{B,12})\}$ Case IV: N/A	Case I: N/A Case II: $\{c_B \mid (c_B < c_{B,6}) \cup (c_B > c_{B,5})\} \cap \{c_B \mid (c_{B,12} < c_B < c_{B,11})\}$ Case II: $\{c_B \mid (c_B < c_{B,8}) \cup (c_B > c_{B,7})\} \cap \{c_B \mid (c_{B,12} < c_B < c_{B,11})\}$ Case IV: $\{c_B \mid (c_B < c_{B,10}) \cup (c_B > c_{B,9})\} \cap \{c_B \mid (c_{B,12} < c_B < c_{B,11})\}$
$\bar{E} \geq e^*$	Case I: $\{c_B \mid (c_{B,4} < c_B < c_{B,3})\} \cap \{c_B \mid (c_{B,11} < c_B < c_{B,12})\}$ Case II: $\{c_B \mid (c_{B,6} < c_B < c_{B,5})\} \cap \{c_B \mid (c_{B,11} < c_B < c_{B,12})\}$ Case III: $\{c_B \mid (c_{B,8} < c_B < c_{B,7})\} \cap \{c_B \mid (c_{B,11} < c_B < c_{B,12})\}$ Case IV: N/A	Case I: N/A Case II: $\{c_B \mid (c_{B,6} < c_B < c_{B,5})\} \cap \{c_B \mid (c_{B,12} < c_B < c_{B,11})\}$ Case III: $\{c_B \mid (c_{B,8} < c_B < c_{B,7})\} \cap \{c_B \mid (c_{B,12} < c_B < c_{B,11})\}$ Case IV: $\{c_B \mid (c_{B,10} < c_B < c_{B,9})\} \cap \{c_B \mid (c_{B,12} < c_B < c_{B,11})\}$

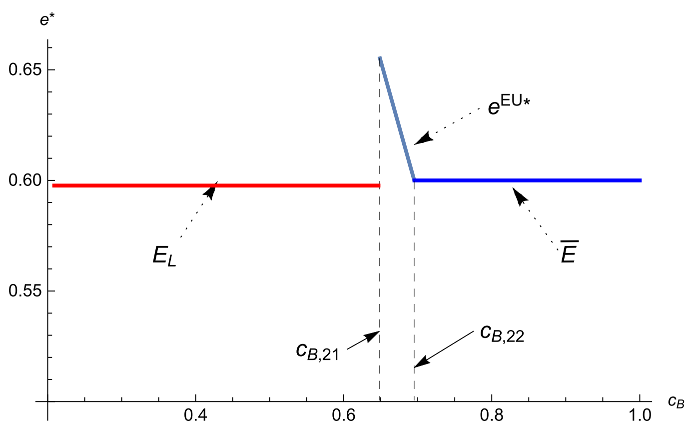

Figure 7. The impact of c_B on manufacturer's green decision ($\gamma = 0.2$).

With a numerical example ($\alpha = 0.7$, $\beta = 0.3$, $\bar{E} = 0.6$, $E_L = 0.58$, $h = 0.06$, $k = 0.27$, $l = 0.03$, $s = 0.05$, $y = 0.3$ and $c_A = 0.2$), we use Figures 7 and 8 to illustrate the manufacturer's strategic green decision when unit production cost c_B varies. In Figure 7 ($\gamma = 0.2$), we show that the manufacturer's green decision is a piecewise function of c_B. The two thresholds ($c_{B,11}$ and $c_{B,12}$) captures the optimums. When the functional cost of product B (c_B) is too large ($c_B > c_{B,12}$) the optimal decision is smaller than the environmental standard ($\bar{E}$); and when c_B is small enough ($c_B < c_{B,11}$), the manufacturer's green decision will be consistent with the environmental standard ($\bar{E}$). In Figure 8 ($\gamma = 0.25$), we show different results. That is, when $c_B > c_{B,12}$, the optimal green decision of product B is always lower than the case when $c_B < c_{B,11}$, and is decreasing with the increase of c_B (see the green line in Fig. 8).

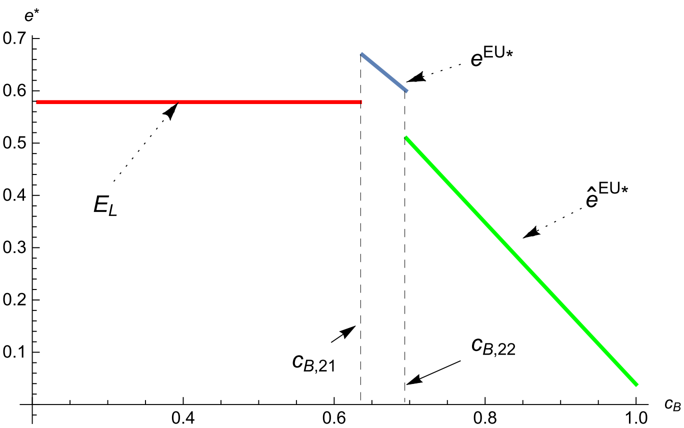

FIGURE 8. The impact of c_B on manufacturer's green decision ($\gamma = 0.25$).

7. Conclusion

This paper investigates the influence of specific product environmental standards on product development and pricing strategies. We analyze how the introduction of product environmental standards affects the manufacturer's pricing strategy, product line strategy and profitability. Our findings indicate that upgrading environmental standards does not have an impact on the price of older generation products, but it can have a series of effects on the replacement and primary segment markets. When the unit production cost of a new product is within a certain range, the manufacturer's profit will increase, while it will decrease otherwise. Moreover, we find that increasing consumer preference for functional improvements in new products does not necessarily lead to increased profits. Additionally, we present product strategies for manufacturers in different market segments defined by different cost thresholds, *i.e.*, when the production of older generation products should be discontinued. Finally, we examine the relationship between the manufacturer's actual green level decision for new products and the specified environmental standard, and identify the decision areas where the manufacturer's actual green decision is higher (or lower) than or equal to the specified green standard. These studies and findings are innovative and can provide manufacturers with valuable guidance to optimize their product pricing and product line design strategies in practical production when faced with environmental standard upgrades. Furthermore, they offer a theoretical foundation for policy-making departments to establish more reasonable environmental protection standards.

7.1. Managerial insight

When confronted with upgraded environmental standards, manufacturers are more likely to adopt a strategy of withdrawing older generation products from both the primary and replacement segments, and transitioning towards the new product market. Besides, when creating new products, manufacturers should avoid excessively pursuing quality improvements. Over-design not only leads to increased costs and resource wastage, but also does not necessarily guarantee better environmental performance. Furthermore, upgrading environmental standards does not necessarily result in higher levels of green product development. Only when the production cost of new products is sufficiently low can implementing environmental upgrades lead to greater investment in green products. Most importantly, in many instances, manufacturers' actual green decisions do not align with environmental standards. Therefore, if policymakers blindly increase environmental standards, it may not necessarily enhance manufacturers' green decision-making.

7.2. Limitations and future research

This paper focuses on a single-period decision problem. However, in reality, manufacturers often prioritize long-term operational management to optimize multi-period total profits. Therefore, further research can explore a multi-period decision model to analyze how manufacturers respond to the upcoming environmental standard upgrade. Additionally, it would be an intriguing topic to investigate how consumers' expectation behavior will impact manufacturers' multi-period product line strategies and product pricing strategies. We propose these issues for future study.

Appendix A. Solution procedure

Proof of Lemma 1. By submitting the demand function given in Section 3.2 in to equation (1), we can derive the first order conditions of the profit on prices as follows:

$$\begin{aligned}
\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial p_A} &= \frac{2(p_{2B}-p_{2A}-ek)}{\alpha} + \left(-\frac{1}{\alpha}-\frac{1}{1-h}\right)(p_{2A}-p_{2T}-c_A+s) - p_{2A} \\
&\quad + \left(-\frac{1}{\alpha}-1\right)(p_{2A}-c_A) - \frac{p_{2A}-p_{2T}}{1-h} + \frac{p_{2B}-c_B}{\alpha} + \frac{p_{2B}-p_{2T}-c_B+s}{\alpha} \\
\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial p_A} &= \frac{p_{2A}-c_A}{\alpha} - \frac{2(p_{2B}-p_{2A}-ek)}{\alpha} + \frac{p_{2A}-p_{2T}-c_A+s}{\alpha} - \frac{p_{2B}-c_B}{\alpha} - \frac{p_{2B}-p_{2T}-c_B+s}{\alpha} + 2 \\
\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial p_A} &= \frac{-c_A+p_{2A}-p_{2T}+s}{1-h} + \frac{p_{2A}-p_{2T}}{1-h} - 1.
\end{aligned}$$

By solving the systems of equations $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial p_A}=0$, $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial p_B}=0$ and $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial p_T}=0$, we have the optimal prices of the second stage in the presence of e as: $p_A(e)=\frac{1}{2}(c_A+1)$, $p_T(e)=\frac{h+s}{2}$ and $p_B(e)=\frac{1}{2}(\alpha+c_B+ek+1)$. Then, with these, we have the optimal profit as

$$\Pi^{\mathrm{NU}^*}(e) = \frac{\begin{array}{c}4(1-h)c_B(\alpha+c_A+ek)+c_A(c_A((\alpha+2)h-2(\alpha+1))+4e(h-1)k+2\alpha s)+2(h-1)c_B^2 \\ +2e^2(h-1)\left(k^2-\alpha y\right)+4\alpha e(h-1)k-\alpha\left(h^2-h(2\alpha+2s+3)+s^2+2(\alpha+s+1)\right)\end{array}}{4\alpha(h-1)}.$$

We solve the first and second order conditions of $\Pi^{\mathrm{NU}^*}(e)$ on e as:

$$\begin{aligned}
\frac{\partial \Pi^{\mathrm{NU}^*}(e)}{\partial e} &= \frac{kc_A-kc_B+ek^2-\alpha ey+\alpha k}{\alpha} \\
\frac{\partial^2 \Pi^{\mathrm{NU}^*}(e)}{\partial e^2} &= \frac{k^2}{\alpha}-y.
\end{aligned}$$

Then, for $\frac{k^2}{\alpha}-y<0$, $\Pi^{\mathrm{NU}^*}(e)$ is concave on e, *i.e.*, the profit function of the manufacturer has a maximum value and we have $e^{\mathrm{NU}^*}=-\frac{k(\alpha+c_A-c_B)}{k^2-\alpha y}$ by solving $\frac{\partial \Pi^{\mathrm{NU}^*}(e)}{\partial e}=0$. Thus, the closed form of the optimal profit is given as:

$$\Pi^{\mathrm{NU}^*} = \frac{\begin{array}{c}c_A\left(c_A\left((h-2)k^2+y(2(\alpha+1)-(\alpha+2)h)\right)+2k^2(-2h+s+2)-2\alpha sy\right) \\ +4(h-1)yc_B(\alpha+c_A)-2(h-1)yc_B^2-k^2\left(h^2-h(2s+3)+s(s+2)+2\right) \\ +\alpha y\left(h^2-h(2\alpha+2s+3)+s^2+2(\alpha+s+1)\right)\end{array}}{4(h-1)(k^2-\alpha y)}.$$

The optimal prices and green decisions in Lemma 2 and Proposition 10 could be solved similarly and thus we omit to show them. ☐

Appendix B. Proofs of model comparison

Proof of Proposition 1. By deriving the differences, we have:

$$
\begin{aligned}
D_A^{P-\mathrm{EU}^*} - D_A^{P-\mathrm{NU}^*} &= \frac{c_A\left(-k^2+\alpha y+y\right)-(\beta-1)\left(k^2-yc_B\right)}{2(\beta-1)(y(\alpha+\beta)-k^2)} - \frac{c_A\left(-k^2+\alpha y+y\right)-yc_B+k^2}{2(k^2-\alpha y)} \\
&= \frac{\beta\left(c_A\left(k^2-(\alpha+1)y\right)\left(k^2-y(\alpha+\beta-1)\right)+(\beta-1)y\left(k^2-yc_B\right)\right)}{2(\beta-1)(k^2-\alpha y)(k^2-y(\alpha+\beta))}.
\end{aligned}
$$

It is direct to have $\frac{\partial(D_A^{P-\mathrm{EU}^*}-D_A^{P-\mathrm{NU}^*})}{\partial c_B} = -\frac{\beta y^2}{2(k^2-\alpha y)(k^2-y(\alpha+\beta))} < 0$, therefore, $D_A^{P-\mathrm{EU}^*} - D_A^{P-\mathrm{NU}^*} > 0$ if $c_B < \frac{c_A\left(k^2-(\alpha+1)y\right)\left(k^2-y(\alpha+\beta_1)\right)+\beta_1 k^2 y}{\beta_1 y^2}$ is satisfied. Similarly, we have $D_A^{R-\mathrm{EU}^*} > D_A^{R-\mathrm{NU}^*}$ if $c_B < \frac{c_A\left((h-l)\left(k^2-\alpha y\right)^2-\beta\left(y(h-\alpha-1)+k^2\right)\left(k^2-y(\alpha+l-1)\right)+\beta^2 y\left(y(-\alpha+h-1)+k^2\right)\right)+x}{\beta(h-1)y^2(\beta+l-1)}$, and we have $D_B^{P-\mathrm{EU}^*} > D_B^{P-\mathrm{NU}^*}$ and $D_B^{R-\mathrm{EU}^*} > D_B^{R-\mathrm{NU}^*}$ if $c_B > \frac{yc_A+k^2}{y}$. The proof of Propositions 3–5 could be obtained similarly, and we choose to omit the details. □

Proof of Proposition 2. Firstly, we have:

$$
\Pi^{\mathrm{EU}^*} = \frac{\begin{array}{l} 2(\beta-1)c_A(-2yc_B(\beta+l-1)+k^2(2\beta+2l-s-2)+sy(\alpha+\beta))+c_A^2(k^2(2\beta+l-2) \\ \quad +y(l(-\alpha+\beta-2)-2(\alpha+1)(\beta-1)))+(\beta-1)(2yc_B(\beta+l-1)(c_B-2(\alpha+\beta)) \\ \quad +k^2(2(\beta-1)^2+l^2+l(3\beta-2s-3)+s^2-2(\beta-1)s)+y(\alpha+\beta)(2(\alpha+1)(\beta-1) \\ \quad -l^2+l(2\alpha-\beta+2s+3)-s^2+2(\beta-1)s))\end{array}}{4(\beta-1)(\beta+l-1)(y(\alpha+\beta)-k^2)}.
$$

Let $Z^{\mathrm{EU-NU}} = \Pi^{\mathrm{EU}^*} - \Pi^{\mathrm{NU}^*}$, we have:

$$
\frac{\partial Z^{\mathrm{EU-NU}}}{\partial c_B} = \frac{y(\alpha+c_A+\beta-c_B)}{k^2-y(\alpha+\beta)} - \frac{4(h-1)y(\alpha+c_A)-4(h-1)yc_B}{4(h-1)(k^2-\alpha y)} = \frac{\beta y\left(yc_A-yc_B+k^2\right)}{(k^2-\alpha y)(k^2-y(\alpha+\beta))}
$$

and

$$
\frac{\partial^2 Z^{\mathrm{EU-NU}}}{\partial c_B^2} = y\left(\frac{1}{y(\alpha+\beta)-k^2}+\frac{1}{k^2-\alpha y}\right).
$$

Because $k^2-\alpha y<0$ and $\beta>0$, then we have $y(\alpha+\beta)-k^2 > y\alpha-k^2>0$ which leads to

$$
\left|\frac{1}{y(\alpha+\beta)-k^2}\right| < \left|\frac{1}{k^2-\alpha y}\right|.
$$

Then we have $\frac{\partial^2 Z^{\mathrm{EU-NU}}}{\partial c_B^2}<0$. This indicates that $Z^{\mathrm{EU-NU}}$ is concave on c_B. By solving $Z^{\mathrm{EU-NU}}=0$, we have two roots:

$$
\begin{aligned}
c_{B,1} &= \frac{y\left(2\beta yc_A+\sqrt{2X}\left(k^2(2\alpha+\beta)-\alpha y(\alpha+\beta)\right)\right)-k^4\sqrt{2X}+2\beta k^2 y}{2\beta y^2} \\
c_{B,2} &= \frac{y\left(2\beta yc_A+\sqrt{2X}\left(\alpha y(\alpha+\beta)-k^2(2\alpha+\beta)\right)\right)+k^4\sqrt{2X}+2\beta k^2 y}{2\beta y^2}.
\end{aligned}
$$

Then, $Z^{\mathrm{EU-NU}}$ could be expressed as:

$$
Z^{\mathrm{EU-NU}} = y\left(\frac{1}{y(\alpha+\beta)-k^2}+\frac{1}{k^2-\alpha y}\right)(c_B-c_{B,1})(c_B-c_{B,2}).
$$

Here, $X = \frac{\beta y^2\left(\beta_1\left(h^2(\beta_1+l)-h\left(\beta+l(\beta+l)+s^2-1\right)+(\beta+l)\left(l+s^2\right)-l\right)-c_A^2\left(\beta^2(h-2)+\beta((h-2)l+2)-h+l\right)-2\beta_1 s c_A(\beta-h+l)\right)}{\beta_1(h-1)(\beta_1+l)(k^2-\alpha y)(k^2-y(\alpha+\beta))}$ and $\beta_1 = \beta-1$. Therefore, $\Pi^{\mathrm{EU}^*} < \Pi^{\mathrm{NU}^*}$ if and only if $c_B > c_{B,1}$, or $c_B < c_{B,2}$; and $\Pi^{\mathrm{EU}^*} \geq \Pi^{\mathrm{NU}^*}$ if and only if $c_{B,1} \leq c_B \leq c_{B,2}$. By solving $\frac{\partial Z^{\mathrm{EU-NU}}}{\partial c_B} = 0$, we have $c_B = c_{B,0} = c_A + \frac{k^2}{y}$. It also could be found that when $c_B < c_{B,0}$, $Z^{\mathrm{EU-NU}}$ is increasing and otherwise, $Z^{\mathrm{EU-NU}}$ is decreasing with c_B. □

Appendix C. Proofs of sensitivity analysis

The proof of Proposition 6 is straightforward and similar to that of Proposition 1, we omit it and choose to give the proof of Proposition 7 as follows.

Proof of Proposition 7. By deriving the first order condition of Π^{NU^*} on α, we have:

$$\begin{aligned}\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} &= \frac{y(\alpha+c_A-c_B)\left(-yc_A+yc_B-2k^2+\alpha y\right)}{2(k^2-\alpha y)^2}\\ &= \frac{y^2}{2(k^2-\alpha y)^2}(\alpha-(c_B-c_A))\left(\alpha-\frac{yc_A-yc_B+2k^2}{y}\right).\end{aligned}$$

There exit two roots, *i.e.*, $c_B - c_A$ and $\frac{yc_A-yc_B+2k^2}{y}$. Because $\frac{y^2}{2(k^2-\alpha y)^2} > 0$, therefore, we have two cases to consider: (1) When $c_B < c_{B,0} = c_A + \frac{k^2}{y}$, we have $c_A - c_B + \frac{2k^2}{y} > c_B - c_A$. Then, $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} > 0$ if $\alpha < c_B - c_A$ or $\alpha > c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} \leq 0$ if $c_B - c_A \leq \alpha \leq c_A - c_B + \frac{2k^2}{y}$; (2) When $c_B \geq c_{B,0} = c_A + \frac{k^2}{y}$, we have $c_A - c_B + \frac{2k^2}{y} \leq c_B - c_A$. Then, $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} > 0$ if $\alpha > c_B - c_A$ or $\alpha < c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{NU}^*}}{\partial \alpha} \leq 0$ if $c_A - c_B + \frac{2k^2}{y} \leq \alpha \leq c_B - c_A$; On model "EU", we have:

$$\begin{aligned}\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} &= \frac{y(\alpha+c_A+\beta-c_B)\left(-yc_A+yc_B-2k^2+y(\alpha+\beta)\right)}{2(k^2-y(\alpha+\beta))^2}\\ &= \frac{y^2}{2(k^2-y(\alpha+\beta))^2}(\alpha-(c_B-c_A-\beta))\left(\alpha-\frac{yc_A-yc_B+2k^2-\beta y}{y}\right).\end{aligned}$$

In this scenario, there also exit two cases divided by the threshold $c_{B,0} = c_A + \frac{k^2}{y}$. (1) When $c_B < c_{B,0}$, we have $\frac{yc_A-yc_B+2k^2-\beta y}{y} > c_B - c_A - \beta$. Then, $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} > 0$ if $\alpha < c_B - c_A - \beta$ or $\alpha > c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} \leq 0$ if $c_B - c_A - \beta \leq \alpha \leq c_A - c_B + \frac{2k^2}{y}$; (2) When $c_B \geq c_{B,0}$, we have $\frac{yc_A-yc_B+2k^2-\beta y}{y} \leq c_B - c_A - \beta$. Then, $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} > 0$ if $\alpha > c_B - c_A - \beta$ or $\alpha < c_A - c_B + \frac{2k^2}{y}$; and $\frac{\partial \Pi^{\mathrm{EU}^*}}{\partial \alpha} \leq 0$ if $c_A - c_B + \frac{2k^2}{y} \leq \alpha \leq c_B - c_A - \beta$. □

Appendix D. Proofs of extension

Proof of Proposition 8. To investigate the manufacturer's trade-off on the older and the new generation products, we derive the following lagrangian function:

$$\begin{aligned}\max L^{\mathrm{NU}} = {} & (p_A - c_A)\left(D_A^{R-\mathrm{NU}} + D_A^{P-\mathrm{NU}}\right) + \left(D_A^{R-\mathrm{NU}} + D_B^{R-\mathrm{NU}}\right)(s-p_T) + (p_B - c_B)\left(D_B^{R-\mathrm{NU}} + D_B^{P-\mathrm{NU}}\right)\\ & - \frac{e^2 y}{2} + \mu_1 D_A^{R-\mathrm{NU}} + \mu_2 D_B^{R-\mathrm{NU}} + \mu_3 D_A^{P-\mathrm{NU}} + \mu_4 D_B^{R-\mathrm{NU}}\end{aligned}$$

with the constraints:

$$\mu_1 D_A^{R-\mathrm{NU}} \geq 0; \mu_2 D_B^{R-\mathrm{NU}} \geq 0; \mu_3 D_A^{P-\mathrm{NU}} \geq 0; \mu_4 D_B^{P-\mathrm{NU}} \geq 0.$$

The KKT conditions for optimal results could be expressed as $\frac{\partial L^{\mathrm{NU}}}{\partial p_A} = \frac{\partial L^{\mathrm{NU}}}{\partial p_T} = \frac{\partial L^{\mathrm{NU}}}{\partial p_B} = 0$, and $\mu_1 \geq 0$, $\mu_2 \geq 0$, $\mu_3 \geq 0$ and $\mu_4 \geq 0$. Generally, we have $2^4 = 16$ cases to consider since each multiplier could either be 0 or positive. Because $D_B^{R-\mathrm{NU}} = D_B^{P-\mathrm{NU}}$, thus, the cases $\mu_2 > 0; \mu_4 = 0$ and $\mu_2 = 0; \mu_4 > 0$ can be excluded, then 8 cases left. We first focus on the cases when product A is not sold on specific segments.

Case 1. $\mu_1 = \mu_2 = \mu_4 = 0$ and $\mu_3 \geq 0$. $\mu_3 \geq 0$ indicates that $D_A^{P-\mathrm{NU}} = 0$. By solving the KKT conditions, we have: $p_A^{\mathrm{NU}^*} = \frac{2\alpha - c_A + 2c_B - 2e^{\mathrm{NU}^*}k + 1}{4\alpha+2}$, $p_B^{\mathrm{NU}^*} = \frac{2(\alpha+1)c_B - (\alpha+1)c_A + \alpha(2\alpha+2e^{\mathrm{NU}^*}k+3)+1}{4\alpha+2}$, $p_T^{\mathrm{NU}^*} = \frac{2c_B - 2(\alpha+1)c_A - 2e^{\mathrm{NU}^*}k + 2\alpha(h+s)+h+s}{4\alpha+2}$, $e^{\mathrm{NU}^*} = \frac{k(2\alpha+c_A-2c_B+1)}{-2k^2+2\alpha y+y}$ and $\mu_3 = \frac{2((\alpha+1)c_A - c_B + e^{\mathrm{NU}^*}k)}{2\alpha+1}$. $\frac{c_A(y(2\alpha-h+2)-2k^2)+2k^2+sy}{2y} < c_B < \min\left\{\frac{2\alpha+c_A-h+s+1}{2}, \frac{c_A(y(h-\alpha-1)+k^2)+k^2(h-s-1)+\alpha sy}{(h-1)y}\right\}$ is required for the non-negativity constraints.

Case 2. $\mu_1 > 0$ and $\mu_2 = \mu_3 = \mu_4 = 0$. $\mu_1 > 0$ indicates that $D_A^{R-\mathrm{NU}} = 0$. By solving the KKT conditions, we have: $p_B^{\mathrm{NU}^*} = \frac{-2\alpha^2 + c_A(-\alpha+h-1) - 2\alpha c_B + \alpha(-2e^{\mathrm{NU}^*}k+h+s-3)+(h-1)(2ek+1)}{2(h-2\alpha-1)}$, $p_T^{\mathrm{NU}^*} = \frac{2c_A(h-\alpha-1) - 2(h-1)c_B + (h-1)(2e^{\mathrm{NU}^*}k+h+s) - 2\alpha h}{2(-2\alpha+h-1)}$, $e^{\mathrm{NU}^*} = \frac{k(-2\alpha-c_A+2c_B+h-s-1)}{y(-2\alpha+h-1)+2k^2}$, $p_A^{\mathrm{NU}^*} = \frac{1}{2}(c_A+1)$ and $\mu_1 = \frac{2(c_A(h-\alpha-1)-(h-1)c_B+e^{\mathrm{NU}^*}(h-1)k+\alpha s)}{-2\alpha+h-1}$. The non-negativity constraints of demands and μ_1 require $\frac{c_A(y(-2\alpha+h-2)+2k^2)+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)y} < c_B < \frac{c_A(-k^2+\alpha y+y)+k^2}{y}$.

Case 3. $\mu_1 > 0$, $\mu_2 = \mu_4 = 0$ and $\mu_3 > 0$. $\mu_1 > 0$ and $\mu_3 > 0$ indicate that $D_A^{R-\mathrm{NU}} = D_A^{P-\mathrm{NU}} = 0$. The KKT conditions give that: $p_B^{\mathrm{NU}^*} = \frac{-2(\alpha+1)c_B + h(\alpha+2ek+1) - (\alpha+1)(2\alpha+2ek-s+2)}{2(h-2(\alpha+1))}$, $p_T^{\mathrm{NU}^*} = \frac{h(-2\alpha-2c_B+2ek+h+s-2)}{2(h-2(\alpha+1))}$, $e^{\mathrm{NU}^*} = \frac{k(-2\alpha-c_A+2c_B+h-s-1)}{y(-2\alpha+h-1)+2k^2}$, $p_A^{\mathrm{NU}^*} = \frac{-2\alpha-2c_B+2ek+h+s-2}{2(h-2(\alpha+1))}$ and $\mu_1 = \frac{c_A(h-2(\alpha+1))-2(h-1)c_B+2e(h-1)k+2\alpha s+s}{h-2(\alpha+1)}$, $\mu_3 = \frac{c_A(h-2(\alpha+1))+2c_B-2ek-s}{h-2(\alpha+1)}$. The non-negativity constraints require $c_B < \min\left\{\frac{c_A(y(-2\alpha+h-2)+2k^2)+2k^2(h-s-1)+(2\alpha+1)sy}{2(h-1)y}, \frac{c_A(y(2\alpha-h+2)-2k^2)+2k^2+sy}{2y}\right\}$.

Next, we will show the cases when product B is not sold on the markets.

Case 4. $\mu_1 = 0$, $\mu_2 > 0$, $\mu_3 > 0$ and $\mu_4 > 0$. In this case, we have $D_A^{R-\mathrm{NU}} > 0$; $D_B^{R-\mathrm{NU}} = D_A^{P-\mathrm{NU}} = D_B^{P-\mathrm{NU}} = 0$. With the KKT conditions, we have: $p_A^{\mathrm{NU}^*} = 1$, $p_B^{\mathrm{NU}^*} = \alpha + e^{\mathrm{NU}^*}k + 1$, $p_T^{\mathrm{NU}^*} = \frac{1}{2}(-c_A+h+s+1)$, $e^{\mathrm{NU}^*} = 0$ and $\mu_2 = -\alpha - \frac{c_A}{2} + c_B - e^{\mathrm{NU}^*}k - \frac{1}{2}$, $\mu_3 = c_A - 1$, $\mu_4 = -\alpha - \frac{c_A}{2} + c_B - e^{\mathrm{NU}^*}k - \frac{1}{2}$. Note that we have defined that $\mu_3 > 0$, and this is contradict to the result $\mu_3 = c_A - 1 < 0$. Thus, Case 4 is excluded.

Case 5. $\mu_1 > 0$, $\mu_2 > 0$, $\mu_3 = 0$ and $\mu_4 > 0$. In this case, the assumptions give that $D_A^{P-\mathrm{NU}} > 0$; $D_B^{R-\mathrm{NU}} = D_A^{R-\mathrm{NU}} = D_B^{P-\mathrm{NU}} = 0$. With the KKT conditions, we have: $p_A^{\mathrm{NU}^*} = \frac{1}{2}(c_A+1)$, $p_B^{\mathrm{NU}^*} = \alpha + \frac{c_A}{2} + e^{\mathrm{NU}^*}k + \frac{1}{2}$, $p_T^{\mathrm{NU}^*} = \frac{1}{2}(c_A + 2h - 1)$, $e^{\mathrm{NU}^*} = 0$ and $\mu_1 = c_A + h - s - 1$, $\mu_2 = \frac{1}{2}(h - 2\alpha - c_A - 2e^{\mathrm{NU}^*}k - s - 1) + c_B$, $\mu_4 = \frac{1}{2}(h - 2\alpha - c_A - 2e^{\mathrm{NU}^*}k - s - 1) + c_B$. The non-negativity constraints require $c_B > \frac{1}{2}(2\alpha + c_A - h + s + 1)$.

Case 6. $\mu_1 > 0$, $\mu_2 > 0$, $\mu_3 > 0$ and $\mu_4 > 0$. In this case, all the demands are 0, that is, $D_A^{P-\mathrm{NU}} = D_B^{R-\mathrm{NU}} = D_A^{R-\mathrm{NU}} = D_B^{P-\mathrm{NU}} = 0$. With the KKT conditions, we have: $p_A^{\mathrm{NU}^*} = 1$, $p_B^{\mathrm{NU}^*} = \alpha + e^{\mathrm{NU}^*}k + 1$, $p_T^{\mathrm{NU}^*} = h$, $e^{\mathrm{NU}^*} = 0$ and $\mu_1 = c_A + h - s - 1$, $\mu_2 = \mu_4 = c_B + \frac{1}{2}(-2\alpha - 2e^{\mathrm{NU}^*}k + h - s - 2)$, $\mu_3 = c_A - 1$. Note that we have defined that $\mu_3 > 0$, and this is contradict to the result $\mu_3 = c_A - 1 < 0$. Thus, Case 6 is excluded.

Case 7. $\mu_1 = \mu_3 = 0$, $\mu_2 > 0$ and $\mu_4 > 0$. In this case, the assumptions give that $D_A^{P-\mathrm{NU}} > 0$, $D_A^{R-\mathrm{NU}} > 0$, $D_B^{R-\mathrm{NU}} = D_B^{P-\mathrm{NU}} = 0$. With the KKT conditions, we have: $p_A^{\mathrm{NU}^*} = \frac{1}{2}(c_A+1)$, $p_B^{\mathrm{NU}^*} = \frac{1}{2}(2\alpha + c_A + 2e^{\mathrm{NU}^*}k + 1)$, $p_T^{\mathrm{NU}^*} = \frac{h+s}{2}$, $e^{\mathrm{NU}^*} = 0$ and $\mu_1 = c_A + h - s - 1$, $\mu_2 = \mu_4 = -\alpha - c_A + c_B - e^{\mathrm{NU}^*}k$. The non-negativity constraints require $c_B > \alpha + c_A$.

The last case (Case 8) is $\mu_1 = \mu_2 = \mu_3 = \mu_4 = 0$. In this case, all the demands are positive. This case equal to the case we presented in Lemma 1. The solution procedure of "EU" in Proposition 9 is similar and we omit it.

□

Proof of Proposition 11. To show how the manufacturer make optimal green decision and optimal prices, we need to compare the profits under different demand functions. Because the demand function in equation (5) occur before the demand function in equation (6) all the time, therefore, in this proof, there exist four cases to consider: (1) $\hat{e}^{\mathrm{EU}^*} < \bar{E} < e^{\mathrm{EU}^*}$; (2) $\bar{E} \leq \min\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\}$; (3) $\max\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\} \leq \bar{E}$; and (4) $e^{\mathrm{EU}^*} < \bar{E} < \hat{e}^{\mathrm{EU}^*}$. In Case 1 $\hat{e}^{\mathrm{EU}^*} < \bar{E} < e^{\mathrm{EU}^*}$. In this case, the optimal profits in equations (5) and (6) could both be obtained and maximized at the optimal green decision level $\hat{e}^{\mathrm{EU}^*}$ and $\hat{e}^{\mathrm{EU}^*}$. Thus, the optimal choice could be derived by directly compare the maximized profits:

$$\hat{\Pi}^{\mathrm{EU}^*} - \Pi^{\mathrm{EU}^*} = \frac{\alpha\gamma y\big((c_A - c_B)\big(yc_A - yc_B + 2k^2\big) + k^2(2(\alpha+\beta) - \alpha\gamma) + y(\alpha+\beta)(\alpha(\gamma-1) - \beta)\big)}{2(k^2 - y(\alpha+\beta))(k^2 - y(\alpha+\beta) + \alpha\gamma y)}$$

$$\frac{\partial^2\left(\hat{\Pi}^{\mathrm{EU}^*} - \Pi^{\mathrm{EU}^*}\right)}{\partial c_B^2} = \frac{\alpha\gamma y^2}{(k^2 - y(\alpha+\beta))(k^2 - y(\alpha+\beta) + \alpha\gamma y)}.$$

By solving $\hat{\Pi}^{\mathrm{EU}^*} - \Pi^{\mathrm{EU}^*} = 0$, we have two roots: $c_{B,3} = \frac{k^2}{y} + c_A + \frac{\left(k^2 - y(\alpha+\beta)\right)\left(k^2 - y(\alpha+\beta) + \alpha\gamma y\right)\sqrt{\frac{\alpha^2(\beta-1)^2\gamma^2 y^2(\beta+l-1)^2}{\left(k^2 - y(\alpha+\beta)\right)\left(k^2 - y(\alpha+\beta) + \alpha\gamma y\right)}}}{\alpha(\beta-1)\gamma y^2(\beta+l-1)}$, and $c_{B,4} = \frac{k^2}{y} + c_A - \frac{\left(k^2 - y(\alpha+\beta)\right)\left(k^2 - y(\alpha+\beta) + \alpha\gamma y\right)\sqrt{\frac{\alpha^2(\beta-1)^2\gamma^2 y^2(\beta+l-1)^2}{\left(k^2 - y(\alpha+\beta)\right)\left(k^2 - y(\alpha+\beta) + \alpha\gamma y\right)}}}{\alpha(\beta-1)\gamma y^2(\beta+l-1)}$. Because we are working under the assumption that all the profit functions are convex in e and thus the manufacturer's optimal strategy is to make the green level at $\hat{e}^{\mathrm{EU}^*}$ if $c_B > c_{B,3}$, or $c_B < c_{B,4}$; and if $c_{B,4} < c_B < c_{B,3}$, the manufacturer's optimal strategy is to make the green level at e^{EU^*}. In Case 2 $\bar{E} \leq \min\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\}$, when $e < \bar{E}$, the demands would be realized in equation (3) with profit function $\hat{\Pi}^{\mathrm{EU}}(e < \bar{E})$, and when $e \geq \bar{E}$, the demands would be realized in equation (4) with profit $\Pi^{\mathrm{EU}}(e \geq \bar{E})$. Because $\bar{E} < \hat{e}^{\mathrm{EU}^*}$, it could be observed that the manufacturer could not reach the maximum profit under profit function (5) at any green level product B, however $\Pi^{\mathrm{EU}}(e < \bar{E})$ is increasing in $(0, E_L]$. In addition, the manufacturer could not reach the maximum profit under profit function (6) at any green level product B at green level e^{EU^*}. The optimal strategy could be obtained by comparing $\hat{\Pi}^{\mathrm{EU}}(e = E_L)$ with Π^{EU^*}:

$$\begin{aligned}
&\hat{\Pi}^{\mathrm{EU}}(e = E_L) - \Pi^{\mathrm{EU}^*} \\
&= \frac{\begin{aligned}&(c_B - c_A)\big((c_A - c_B)\big(k^2 - \alpha\gamma y\big) + 2k\big(e\big(k^2 - y(\alpha+\beta)\big) + k(\alpha(-\gamma) + \alpha + \beta)\big)\big) \\ &\quad + e^2\big(-\big(k^2 - y(\alpha+\beta)\big)\big)\big(k^2 - y(\alpha+\beta) + \alpha\gamma y\big) + 2ek(\alpha(\gamma-1) - \beta)\big(k^2 - y(\alpha+\beta)\big) \\ &\quad + (\alpha(\gamma-1) - \beta)\big(k^2(\alpha(-\gamma) + \alpha + \beta) + \alpha\gamma y(\alpha+\beta)\big)\end{aligned}}{2(\alpha(\gamma-1) - \beta)(k^2 - y(\alpha+\beta))}.
\end{aligned}$$

Further, we have:

$$\frac{\partial^2\left(\hat{\Pi}^{\mathrm{EU}}(e = E_L) - \Pi^{\mathrm{EU}^*}\right)}{\partial c_B^2} = \frac{\alpha\gamma y^2(\alpha+\beta)}{(\alpha(-\gamma) + \alpha + \beta)(k^2 - y(\alpha+\beta))^2} > 0.$$

By solving $\hat{\Pi}^{\mathrm{EU}}(e = E_L) - \Pi^{\mathrm{EU}^*} = 0$, we have two roots: $c_{B,5} = \frac{(\alpha(1-\gamma)+\beta)\left(y(\alpha+\beta)\sqrt{\frac{\alpha\gamma y\left(\alpha\gamma + E_L^2 y - 2E_L k\right)}{(\alpha(\gamma-1)-\beta)\left(k^2 - y(\alpha+\beta)\right)}} - k^2\left(\sqrt{\frac{\alpha\gamma y\left(\alpha\gamma + E_L^2 y - 2E_L k\right)}{(\alpha(\gamma-1)-\beta)\left(k^2 - y(\alpha+\beta)\right)}} - 1\right)\right) + E_L k\left(k^2 - y(\alpha+\beta)\right)}{k^2 - \alpha\gamma y}$, and $c_{B,6} = \frac{E_L k\left(k^2 - y(\alpha+\beta)\right) - (\alpha(1-\gamma)+\beta)\left(y(\alpha+\beta)\sqrt{\frac{\alpha\gamma y\left(\alpha\gamma + E_L^2 y - 2E_L k\right)}{(\alpha(\gamma-1)-\beta)\left(k^2 - y(\alpha+\beta)\right)}} - k^2\left(\sqrt{\frac{\alpha\gamma y\left(\alpha\gamma + E_L^2 y - 2E_L k\right)}{(\alpha(\gamma-1)-\beta)\left(k^2 - y(\alpha+\beta)\right)}} + 1\right)\right)}{k^2 - \alpha\gamma y}$. Therefore, we have $e^* = E_L$, if $c_B > c_{B,5}$, or $c_B < c_{B,6}$; and $e^* = e^{\mathrm{EU}^*} = \frac{k(\alpha + c_A + \beta - c_B)}{y(\alpha+\beta) - k^2}$ if $c_{B,6} < c_B < c_{B,5}$. The proof of Case 3 $\max\{\hat{e}^{\mathrm{EU}^*}, e^{\mathrm{EU}^*}\} \leq \bar{E}$ is similar to Case 2, and we omit it. In Case 4 $e^{\mathrm{EU}^*} < \bar{E} < \hat{e}^{\mathrm{EU}^*}$. In this case, we could infer that the manufacturer's profit is increasing when $e \leq E_L$ with profit function $\hat{\Pi}^{\mathrm{EU}}(e = E_L)$ and decreasing when $e \geq \bar{E}$ with profit function $\Pi^{\mathrm{EU}}(e = \bar{E})$. Similarly, the manufacturer's strategic choice could be obtained by solving the difference:

$$
\begin{aligned}
&\Pi^{\mathrm{EU}}\big(e=\bar{E}\big)-\hat{\Pi}^{\mathrm{EU}}(e=E_L)\\
&=\frac{\begin{array}{l}-2E_Lk(\alpha(1-\gamma)+\beta)(\alpha+c_A+\beta-c_B)+(c_A-c_B)(\alpha\gamma(c_A-c_B)\\ \quad+2\bar{E}k(\alpha+\beta))+(\alpha+\beta)(\alpha\gamma(\alpha(\gamma-1)-\beta)+\bar{E}^2\big(k^2-y(\alpha+\beta)+\alpha\gamma y\big)\\ \quad+2\bar{E}k(\alpha(-\gamma)+\alpha+\beta))+E_L^2(\alpha(\gamma-1)-\beta)\big(k^2-y(\alpha+\beta)\big)\end{array}}{2\alpha\gamma(\alpha+\beta)-2(\alpha+\beta)^2}.
\end{aligned}
$$

Because $0<\alpha<1$, $0<\beta<1$ and $0<\gamma<1$, we further have:

$$\frac{\partial^2\Big(\Pi^{\mathrm{EU}}(e=\bar{E})-\hat{\Pi}^{\mathrm{EU}}(e=E_L)\Big)}{\partial c_B^2}=\frac{2\alpha\gamma}{2\alpha\gamma(\alpha+\beta)-2(\alpha+\beta)^2}<0.$$

By solving $\Pi^{\mathrm{EU}}(e=\bar{E})-\hat{\Pi}^{\mathrm{EU}}(e=E_L)=0$, we have two roots: $c_{B,9}=c_A+\frac{\sqrt{(\alpha+\beta)(\beta-\alpha(\gamma-1))\left(\alpha^2\gamma^2+\bar{E}^2k^2+E_L\left(e_1(k^2-\alpha\gamma y)+2k(\alpha\gamma-\bar{E}k)\right)+\alpha\gamma\bar{E}(\bar{E}y-2k)\right)}+\delta k(\alpha+\beta)}{\alpha\gamma}+E_L$, $c_{B,10}=c_A+\frac{\delta k(\alpha+\beta)-\sqrt{(\alpha+\beta)(\beta-\alpha(\gamma-1))\left(\alpha^2\gamma^2+e^2k^2+E_L\left(E_L(k^2-\alpha\gamma y)+2k(\alpha\gamma-\bar{E}k)\right)+\alpha\gamma\bar{E}(\bar{E}y-2k)\right)}}{\alpha\gamma}+E_L$ and $\delta=\bar{E}-E_L$. Because $\Pi^{\mathrm{EU}}(e=\bar{E})-\hat{\Pi}^{\mathrm{EU}}(e=E_L)=\frac{2\alpha\gamma}{2\alpha\gamma(\alpha+\beta)-2(\alpha+\beta)^2}(c_B-c_{B,9})(c_B-c_{B,10})$, therefore The manufacturer's optimal "green decision" is $\bar{E}$ if $c_{B,10}<c_B<c_{B,9}$; and if $c_B>c_{B,9}$, or $c_B<c_{B,10}$ the manufacturer will choose $e^*=E_L$. □

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