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Greening Products in a Supply Chain under Market Segmentation and Different Channel Power Structures

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Abstract

This paper investigates product line expansion in which a green version of an existing conventional brown product is launched. We use a game-theoretic approach to study a supply chain consisting of one retailer and one manufacturer, either of which can be the leader of the supply chain. Our model assumes a market segmented based on the consumers' willingness to pay for the green feature of the product and incorporates a fixed cost related to launching the green product. Through our analysis, we define four pricing and positioning strategies for brown and green products. We explicitly express the conditions under which it is more profitable to expand the conventional product line with a green product and determine the region where each pricing strategy applies in the centralized system as well as in the two decentralized systems with each member as the leader of the supply chain. Our results also show that a manufacturer-led supply chain is better prepared than a retailer-led supply chain to overcome the fixed cost, launch the green product, and grasp benefits from the growth of the green consumer segment at an early stage of its development. We design two coordination mechanisms that allow the decentralized supply chain to achieve its first-best performance.

Keywords: Supply chain; Green products; Brown products; Substitutable products; Pricing strategy; Coordination

1 Introduction

Green products have been gaining increasing popularity among consumers. Recent surveys show that 26% of Europeans regularly buy green products (European Commission, 2013), and 66% of consumers worldwide declare that they are willing to pay more for sustainable goods, up from 55% in 2014 (The Nielsen Company, 2015). To cope with and exploit this growing consumer interest in green products, companies are expanding their offer in the market by launching greener versions of their conventional brown* products. It is now common in all industry sectors to offer both conventional brown products and greener versions, which are similar in all aspects except the green characteristic, together in the market. In the automotive industry, for instance, hybrid versions of cars that are believed to be eco-friendly (such as Toyota Yaris, Mercedes 300, Peugeot 3008) are produced and promoted by the same automakers together with traditional cars that use diesel or gasoil. Furthermore, almost all brands of home appliances (such as Siemens, Whirlpool, AEG) and electric bubbles (such as Philips) produce greener products that are similar to the standard ones in all aspects but differ in their energy consumption. In the apparel industry, many of the large brands, such as H&M, C&A, Zara, Nike, complete their collections with green versions of garments that are similar to the regular garments in every aspect but made of 100% organic fibers. The same situation can be observed in the chemical industry, where shoppers often find environmentally friendly versions of products shelved next to traditional or standard ones. In the food industry also, a bio version of different kinds of food (fish, poultry, fruits and

* Throughout this paper, we will use the adjective "brown" for conventional products in order to highlight the difference between these products and green ones.

vegetables, processed food, etc.) is often present on the shelves of supermarkets like Carrefour and Wal-Mart. along with conventional products.

Our research is motivated by two business concerns associated with launching new green products. The first is that a new green product cannot be launched by ignoring the already existing brown ones because of the potential cannibalization between the two products. Therefore, it is critical for the firm to strategically position and price the two products to achieve the maximum net profit in consideration of the cannibalization between them. The second business concern is that creating new green products and managing the resulting product variety requires decisions that span the producing firm's borders and involve supply chain members (Ramdas, 2003; Villas-Boas, 1998). In practice, product greening can be initiated by the retailer, the manufacturer or even both together. Retailers are striving to satisfy their environmentally conscious consumers by launching their own green product brands or by influencing suppliers and pushing them to green their products (European Commission, 2009; RILA, 2012). For instance, Carrefour sells green products under two store brands, Carrefour Bio, and Eco Planète, which comprise a wide range of product categories (Evans & Denney, 2009). For another example, the two large fashion retailers H&M and Zara offer wide ranges of green products made of sustainable raw material through their collections, respectively, Conscious Exclusive (https://www2.hm.com) and Join Life (https://www.zara.com). It is also a common practice among retailers to pressure suppliers and push them to green their products and to adopt more sustainable production processes. For instance, Walmart mandates its suppliers participate in carbon disclosure projects (Plambeck, 2011); H&M forbids the use by its suppliers of any material among a list of 250 chemicals selected from the most restrictive criteria in the legislations of the countries where H&M sells garments (European Commission, 2009); and

IKEA requires suppliers to meet the social and environmental requirements in the IKEA supplier code of conduct IWAY as a prerequisite for considering classifying their products as being "more sustainable" (IKEA, 2014). In addition, producers of all types of products are launching green products through their own initiative and selling them to customers through retailers. In this situation, the retailers do not take part in the product greening decision, and the manufacturer itself owns the pricing decision. As product greening and pricing could be the result of either the retailer's or the manufacturer's initiative, this raises the question of the best pricing strategy to adopt when the decision maker is the retailer versus the manufacturer.

Our paper investigates the product positioning and pricing problem when a green version of an already existing brown product is launched by either the retailer or the manufacturer. Specifically, we use a game theoretic approach (Cachon, 2003) to study a supply chain composed of one retailer and one manufacturer: while the manufacturer produces the products, the retailer decides the prices. To maximize the generated insights, we study two cases that are commonly observed in the real world. The first case corresponds to the situation in which the manufacturer owns the brand and acts as the supply chain leader by moving first to make decide whether to launch the green product. In the second case, the retailer is the brand owner and acts as the supply chain leader by moving first. In our study, we assume that the market is composed of two consumer segments: the green segment, which consists of consumers who are willing to pay a price premium for the green product, and the brown segment, which comprises those consumers who do not prefer one of the products over the other.

Through our analysis, we aim to address the following research questions: (1) Under what conditions is it more profitable to expand the product line with a green product? (2) If the green product is to be launched, what is the optimal pricing strategy for the product portfolio

(green and brown products)? (3) How do the variable unit production cost, the fixed cost related to introducing the green product, and the size of the green consumer segment influence the pricing strategy? (4) What are the effects of the different pricing strategies, if adopted, on the company's market coverage and profit? (5) How can the decentralized supply chain that offers the green and the brown products be coordinated?

Our study makes the following unique contributions:

- Determining the conditions under which launching the green product improves the supply chain profit in both the centralized system and decentralized systems when either the retailer or the manufacturer is the leader of the supply chain.
- Finding the optimal pricing strategies and analyzing the demand for the green and for the brown products in both the centralized and decentralized systems when either the retailer or the manufacturer is the leader of the supply chain.
- Analyzing the effects of a fixed cost associated with launching the green product and of the size of the green consumer segment on the product line expansion strategy.
- Designing coordination mechanisms for the decentralized supply chain with both the green and the brown products.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature related to our study. Section 3 states the assumptions and establishes the model framework. The optimal pricing strategies and profits in the centralized system and the decentralized systems are discussed in section 4. Finally, section 5 summarizes the key findings and the managerial implications from our research.

2 Literature Review

Our research studies green product offerings in a supply chain that are developed by extending the already existing offer of conventional brown products. There are three streams of research relevant to our study. The first one is related to product line design and pricing strategy for a single company, the second deals with coordinating product variety in a supply chain, and the third specifically discusses the question of coordinating supply chains that offer green products. We review the literature contributing to these three research streams and discuss the relationship of our work with each of them.

2.1 Product Line Design and Pricing Strategy

Managerial decision making on product line design is an important research topic, and work in this area has been reviewed by Yano & Dobson (1998), Ramdas (2003) and Kök et al. (2008). Mussa & Rosen (1978) are credited as the first study to suggest a model for determining the number of optimal attribute-price offerings for a product to maximize profit. The model proposed by Mussa & Rosen (1978) takes into account customers' heterogeneity with regard to their willingness to pay for a given increment of the product attribute (quality, for example) and the cannibalization effect within the product line. Moorthy (1984) generalized this model to nonlinear customer preferences by introducing discrete market segmentation. Subsequent research has developed in multiple directions by incorporating the effect of different technological and economic factors, such as production costs, economies/diseconomies of scale and limitations in production capacity. Dobson & Kalish (1988) formulated and solved a model for product line design and pricing that incorporates both the fixed and the variable costs related

to the production and marketing of each product. Raman & Chhajed (1995) studied simultaneous product line design and process selection decisions while considering the fixed costs related to the processes and the variable costs related to the level of the product attributes. Ramdas & Sawhney (2001) developed a model that incorporates cost interactions, demand expansion, and cannibalization effects in the case of product line extensions using shared components. Heese & Swaminathan (2006) studied product differentiation for products using common components while explicitly integrating interdependencies between cost-reduction efforts and quality decisions. Krishnan & Zhu (2006) derived the conditions under which product line profitability exceeds the single product profits in the case of a development-intensive product with two coupled quality dimensions offered in a market composed of two customer segments. In a similarly segmented market, Netessine & Taylor (2007) characterized the impact of production technology on the optimal product line design by considering the effect of cannibalization between the products, the setup costs and the inventory holding costs. Tang & Yin (2010) studied the strategy of a manufacturer who can offer two substitutable products differentiated by their quality levels in a homogenous market. They characterized the situations in which it is optimal for the manufacturer to offer a single product and those in which offering both products is optimal. Chen et al. (2013) studied the effect of the production cost on product line design by a manufacturer operating a vertical co-product technology and showed that the number of products can increase the marginal production cost. Ozinci et al. (2017) considered the pricing decisions of retailers offering organic and nonorganic conventional versions of a perishable agricultural product. The two product versions were assumed to be different from each other in terms of their shelf lives and their utility to customers. The conventional product is associated with a longer shelf life compared with its organic counterpart. The authors examined different pricing

strategies and the resulting profit in the case where a single retailer sells the two products and in the case of two competing retailers, each of which sells one of the two products.

Our work is similar to the literature mentioned above in that it analyzes the problem of product line design under self-selection, taking into account fixed and variable production costs. However, our model of consumer utility is different because the products under consideration are not differentiated vertically. The products in our model are differentiated horizontally by the green characteristic, which offers more utility for only a portion of the consumers in the market. Differentiated valuation of the product's green quality by different consumer segments was used by Chen (2001) and Krishnan and Lecourbe (2011), who considered the question of designing green products with two competing green and traditional qualities. A similar valuation scheme of green and brown products by consumers pertaining to two market segments is used by Yenipazarli & Vakharia (2015), who studied the strategic choice of a firm with regard to offering and pricing a green version of an already existing brown product. Their model considers the cannibalization between the two products and assumes a fixed cost associated with the introduction of the new green product. The product differentiation and the market structure in our model are similar to those used in the latter three studies. However, all the above studies consider a single company interacting directly with the market, while in our work, we consider a supply chain composed of a manufacturer and a retailer.

2.2 Coordinating Product Variety in a Supply Chain

Studies on product line design or assortment planning that incorporate supply chain issues are scarce (Kök et al., 2008). One of the first research works on this topic is Villas-Boas (1998), who analyzed the targeting strategies of a manufacturer and a retailer by considering the optimal

number of differentiated products and their prices. This study shows that depending on the pricing scheme applied by the manufacture, the retailer will only target the high-end segment of consumers with a single product or both segments with two different products. Aydın & Hausman (2009) investigated the assortment decision and coordination issues in a single-retailer, single-manufacturer supply chain and found that double marginalization results in a discrepancy between the retailer's optimal assortment and the optimal assortment for the centralized supply chain. de Matta et al. (2015) investigated vertically differentiated product line design in a supply chain composed of a manufacturer and a retailer under both a centralized system and a decentralized system. Yang et al. (2015) investigated which channel structure a manufacturer would choose for two products that are asymmetric in substitutability and brand equity. Seifbarghy et al. (2015) studied contract design for coordinating a supply chain composed of a manufacturer and a retailer facing price-dependent and quality-dependent demand in a market composed of a quality-oriented customer segment and a price-oriented customer segment.

Similar to this literature, we discuss assortment decisions in a supply chain. However, our model is different from all the abovementioned models because it considers a segmented market in conjunction with horizontally differentiated products.

2.3 Coordinating the Green Product Offering in the Supply Chain

Coordinating to offer of green products on the market constitutes an important aspect of green supply chain management (Beamon, 1999; Paksoy et al., 2019; Sarkis & Müller, 2003; Seuring, 2008; Srivastava, 2007). Among the studies on this topic, Barari et al. (2012) investigated the coordination between a manufacturer investing in greening the product and a retailer investing marketing expenditures to sell it. Similarly, Swami & Shah (2013) investigated the coordination

between a manufacturer and a retailer who both invest effort in greening their respective operations. Ghosh & Shah (2012) analyzed greening investment and pricing decisions in a supply chain composed of one manufacturer and one retailer. Later, Ghosh & Shah (2015) proposed two types of cost-sharing contracts to coordinate the product greening efforts of the manufacturer and the retailer. Zhang et al. (2014) studied pricing strategies in a supply chain composed of one manufacturer and one supplier, assuming a utility-based demand model and a nonsegmented market in which all consumers have a higher valuation for the green product than for the non-green one. Zhang et al. (2015) examined the ordering and pricing policies in a supply chain composed of a manufacturer and a retailer offering two products with two different levels of environmental quality and facing linear demand. Using a similar demand model and considering the coexistence of two green and non-green substitutable products, Basiri & Heydari (2017) studied the coordination between a manufacturer who invests in product greening and a retailer who exerts sales efforts.

None of the abovementioned studies on offering green products in the supply chain considered the case of two substitutable products, green and brown, offered in a segmented market.

Our literature review shows that no study in the extent literature investigated the case of a two-level supply chain operating in a segmented market and aiming at expanding the product line by launching a green version of an existing brown product.

3 Model Framework

In this section, we describe the model setup, set assumptions, formulate the different possible pricing strategies for the green and brown products, and present the demand and profit functions under each pricing strategy.

3.1 The Supply Chain Structure, Products and Production Costs

We consider a two-level supply chain composed of a manufacturer (M) and a retailer (R) offering a single product. This product can be manufactured and sold in two versions: the brown version and the green version. We use w_b (w_g) and p_b (p_g) to denote the wholesale prices and the retail prices of the brown (green) products, respectively. We denote the unit production cost of the brown (green) product by c_b (c_g). Note that the materials used to produce green products are generally more expensive than those used to produce brown products (Carus et al., 2014; Peuckert & Quitzow, 2017). Therefore, in line with most of the previous research in this area (Yenipazarli & Vakharia, 2015; Zhang et al., 2014, 2015; Zhu & He, 2017), we can reasonably assume that $c_g > c_b$ and consider it as the scenario case in our study. However, to obtain the most general results and insights from all potential scenarios, we also consider the uncommon scenario where $c_g \leq c_b$, i.e., the production cost of the green product may be lower than that of the brown product, in section subsection 4.4. Finally, we assume that launching the green product requires additional fixed capital (F) invested by the manufacturer in production-related activities, such as upgrading the production processes and training employees (Chen, 2001; Ghosh & Shah, 2012, 2015; Krishnan & Lacourbe, 2011; Yenipazarli & Vakharia, 2015).

In the next section, we describe the market segments and derive the resulting demand and profit functions associated with different production and marketing strategies.

3.2 Market Segments and Consumers' Characteristics

We consider a market composed of two segments: the green segment and the brown segment. The green segment comprises consumers who value the green product more highly than the brown one. The proportion of this segment in the overall product market is $\rho \in [0, 1]$. The brown segment, which is $(1 - \rho)$ of the total market, includes the consumers who do not have a preference for the green characteristic of the product and hence value the green and the brown products equally. We assume that consumers from both segments obtain the same value from the brown product. Our model of the market segments is aligned with the empirical investigations in the previous literature in marketing as well as in operations management (Chen, 2001; Ginsberg & Bloom, 2004; Kassarjian, 1971; Laroche et al., 2001; Roberts, 1996; Rowlands et al., 2003; Yenipazarli & Vakharia, 2015; Zhang et al., 2014).

Let θ denote the value of the brown product derived by consumers in both segments, and assume that θ is uniformly distributed in the interval [0, 1]. The green product is valued at θ by consumers in the brown market segment and at $\omega\theta$ by consumers in the green market segment, where $\omega > 1$ and is a constant that represents the preference of green consumers for the green product. We use U_b^B (U_g^B) and U_b^G (U_g^G) to denote the utilities of the consumers in the brown market segment and the green segment, respectively, when they buy the brown (green) product. According to the above model framework, we have $U_b^B = U_b^G = \theta - p_b$; $U_g^B = \theta - p_g$ and $U_g^G = \omega\theta - p_g$.

3.3 Pricing and Product Line Strategies

Consider a supply chain that offers the brown version of a product. This supply chain has three choices regarding the product line design: continually offering the brown product only in the

market, offering both the brown and green products, or removing the brown product and offering the green product only.

When the brown product is the only product offered by the supply chain, consumers from both brown and green market segments will buy this product if the utility they derive from it is positive (i.e. $\theta - p_b > 0$). Similarly, when the green product is the only product offered by the supply chain, consumers from both brown and green market segments will buy this product if the utility they derive from it is positive (i.e., $\theta - p_g > 0$ and $\omega\theta - p_g > 0$). For the case where both brown and green products are offered, consumers will choose the product version that gives them a higher positive utility. Specifically, consumers from the brown market segment will prefer the green product if the utility they derive from it is positive and dominates the utility from the brown product ($i.e.,\ \theta - p_g > 0\ and\ \theta - p_g > \theta - p_b$). Therefore, when the above two conditions are satisfied, or in other words, when $\theta > p_g$ and $p_g < p_b$, consumers in the brown segment will exclusively purchase the green product. Similarly, consumers from the green market segment will purchase the brown product if the utility they derive from it is positive and dominates the utility they obtain from the green product (i.e.,$\theta - p_b > 0$ and $\omega\theta - p_g < \theta - p_b$). Note that the two conditions hold simultaneously if $p_g > \omega p_b$[†].

Based on the above reasoning, we distinguish four possible pricing and product line strategies for the supply chain: (1) the pure brown (PB) strategy consists of only offering the brown production the market, (2) the pure green (PG) strategy consists of only offering the green

[†] Subtracting ωp_b from both sides of $p_g > \omega\theta - \theta + p_b$, we get $p_g - \omega p_b > \omega\theta - \theta + p_b$-$\omega p_b$. Thus, $p_g - \omega p_b > (\omega - 1)(\theta - p_b)$. If $\theta > p_b$, since $\omega - 1 > 0$, we can write $p_g - \omega p_b > 0$. Thus, $p_g > \omega p_b$.

product, (3) the wide green market coverage mix-product (WGC Mix-Product) strategy consists of offering brown and green products and setting a relatively low price for the green product (i.e., $p_g < \omega p_b$), and (4) the reduced green market coverage mix-product (RGC Mix-Product) strategy consists of offering the green and brown products while setting a relatively high price for the green product (i.e., $\omega p_b \leq p_g$).

We denote the demand for the brown product by the green segment as d_b^G, the demand for the brown product by the brown segment as d_b^B, and the total demand for the brown product by the two segments as $d_b = d_b^G + d_b^B$. The other notations of the demands are defined similarly, and hence, we omit the details. We use π_M and π_R to denote the manufacturer's profit and the retailer's profit, respectively. Then, assuming that the market size is normalized to 1 and that each consumer buys at most one single unit of the product, the four strategies identified above yield the following demand and profit functions.

- PB strategy. Under this strategy, only the brown product is present in the market. Demand for this product is generated by consumers in both the brown and green market segments, i.e., $d_b = 1 - p_b$.

The manufacturer's profit and the retailer's profit respectively are:

$\pi_M = (w_b - c_b)(1 - p_b)$ and $\pi_R = (p_b - w_b)(1 - p_b)$.

- PG strategy. Under this strategy, only the green product is present in the market. Demand is generated by consumers in both the brown and green market segments, i.e., $d_g = (1 - \rho)(1 - p_g) + \rho(1 - \frac{p_g}{\omega})$.

The manufacturer's profit and the retailer's profit are:

$\pi_M = (w_g - c_g)\left((1 - \rho)(1 - p_g) + \rho\left(1 - \frac{p_g}{\omega}\right)\right) - F$ and

$\pi_R = (p_g - w_g)((1-\rho)\left(1-p_g\right) + \rho(1-\frac{p_g}{\omega}))$.

- WGC Mix-Product strategy. Under this strategy, green and brown products are both present on the market. Demand for the brown product is exclusively generated by consumers in the brown market segment, while consumers in the green segment will only buy the green product. Thus,

$d_b = d_b^B = (1-\rho)(1-p_b)$ and $d_g = d_g^G = \rho(1-\frac{p_g}{\omega})$.

Furthermore, $\pi_M = (w_b - c_b)(1-\rho)(1-p_b) + \rho\left(w_g - c_g\right)\left(1-\frac{p_g}{\omega}\right) - F$ and

$\pi_R = (p_b - w_b)(1-\rho)(1-p_b) + \rho(p_g - w_g)(1-\frac{p_g}{\omega})$.

- RGC Mix-Product strategy. Similar to WGC Mix-Product, green and brown products are both present in the market. However, under this strategy, a portion of the consumers in the green market segment buy the brown product. Specifically, consumers in the green market segment purchase the brown products when $0 < U_b^G$ and $U_g^G < U_b^G$ (i.e., $p_b < \theta < \frac{p_g - p_b}{\omega - 1}$) and purchase the green products when $0 < U_g^G$ and $U_b^G < U_g^G$ (i.e., $\frac{p_g - p_b}{\omega - 1} < \theta < 1$). Hence, the demand for each product and the two supply chain members' profits are given as follows:

$d_b = (1-\rho)(1-p_b) + \frac{\rho}{\omega-1}(p_g - \omega p_b)$, $d_g = \rho(1-\frac{p_g - p_b}{\omega-1})$,

$\pi_M = (w_b - c_b)((1-\rho)(1-p_b) + \frac{\rho}{\omega-1}(p_g - \omega p_b)) + \rho(w_g - c_g)(1-\frac{p_g - p_b}{\omega-1}) - F$,

and $\pi_R = (p_b - w_b)((1-\rho)(1-p_b) + \frac{\rho}{\omega-1}(p_g - \omega p_b)) + (p_g - w_g)\rho(1-\frac{p_g - p_b}{\omega-1})$.

4 Analysis and Results

In this section, we first consider the main scenario in which the production cost of the green product is higher than that of the brown product ($c_g > c_b$). We study different supply chain systems, namely, the centralized system, the decentralized system with the manufacturer as the leader, and the decentralized system with the retailer as the leader. For each system, we derive the optimal product line and pricing strategies as well as the demand and profit obtained by each supply chain member and by the whole system. Then, we compare the product line and pricing strategies in the three supply chain systems, analyze the effects of the fixed cost and the size of the green market segment and provide the corresponding managerial insights. Finally, we design a coordination mechanism for the decentralized supply chain systems. As mentioned in section 3, to obtain full insights from our study, we also examine the case in which the cost of producing the green product is lower than that of producing the brown product ($c_g \leq c_b$) and provide the corresponding insights.

Lemma 1. When $c_g > c_b$, in either the centralized system or the decentralized system, if both green and brown products exist in the market, the retail prices must satisfy $p_g \geq p_b$.

Lemma 1 indicates that in the case where the production cost of green products is higher than that of brown products (the commonly observed case in real life), it is always optimal for the retailer to set a higher retail price for the green product than the brown product. This is intuitive because a higher retail price for the green product is better for the retailer to compensate for the higher product cost. In addition, because the retail price of the green product is never lower than the price of the brown product, the customers in the brown segment will always choose to buy brown products (even in the special case of tied prices, the consumers still have a 50% probability of buying brown products). Therefore, in the case where $c_g > c_b$, the PG strategy will never be applied.

4.1 Optimal Strategies for the Supply Chain

In this section, we find the optimal product line and pricing strategies in the three different supply chain systems under the assumption that the cost of producing the green product is lower than that of producing the brown product ($i.e., c_g > c_b$).

4.1.1 The Centralized System

In a centralized supply chain system, the manufacturer and the retailer make their decisions aiming to maximize the total supply chain profit.

As the analysis in section 3 shows, there are three potential product lines and pricing strategies: PB, WGC Mix-Product or RGC Mix-Product. The system profit, Π, under each of these strategies could be written as follows:

Under PB strategy: $\Pi = (p_b - c_b)(1 - p_b)$.

Under the RGC Mix-Product strategy (i.e., $p_g > \omega p_b$):

$$\Pi = (p_b - c_b)((1-\rho)(1-p_b) + \frac{\rho(p_g - \omega p_b)}{\omega - 1}) + (p_g - c_g)\rho(1 - \frac{p_g - p_b}{\omega - 1}) - F.$$

Under the WGC Mix-Product strategy (i.e., $p_g \leq \omega p_b$):

$$\Pi = (p_b - c_b)(1-\rho)(1-p_b) + (p_g - c_g)\rho(1 - \frac{p_g}{\omega}) - F.$$

We denote the first-best solution as $\{p_g^c, p_b^c\}$, under which the system profit is maximized. We denote the maximal system profit under $\{p_g^c, p_b^c\}$ as the first-best system profit, Π^c. In addition, we denote the demand for the brown and the green products under $\{p_g^c, p_b^c\}$ as D_b^c and D_g^c.

Theorem 1. In the centralized supply chain system, the first-best pricing and product line strategy is

- PB strategy in any of the following cases:
  - $c_g > c_b + \omega - 1$
  - $\omega c_b < c_g \leq c_b + \omega - 1$ and $F > \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2$
  - $c_g \leq \omega c_b$ and $F > \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1 - c_b)^2)$

  Under this strategy, $p_b^c = \frac{1}{2} + \frac{c_b}{2}$, $D_b^c = \frac{1}{2} - \frac{c_b}{2}$, and $\Pi^c = \frac{(1-c_b)^2}{4}$.

- RGC Mix-Product strategy when $\omega c_b < c_g \leq c_b + \omega - 1$ and $F \leq \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2$.

  Under this strategy, $p_b^c = \frac{1}{2} + \frac{c_b}{2}$, $p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$, $D_b^c = \frac{1-\rho}{2} - \frac{c_b}{2} + \frac{\rho(c_g - c_b)}{2(\omega-1)}$, $D_g^c = \frac{\rho}{2} - \frac{\rho(c_g - c_b)}{2(\omega-1)}$, and $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2 - F$.

- WGC Mix-Product strategy when $c_g \leq \omega c_b$ and $F \leq \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1 - c_b)^2)$.

  Under this strategy, $p_b^c = \frac{1}{2} + \frac{c_b}{2}$; $p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$, $D_b^c = \frac{(1-\rho)(1-c_b)}{2}$, $D_g^c = \frac{\rho(\omega - c_g)}{2\omega}$, and $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4\omega}\left((\omega - c_g)^2 - \omega(1 - c_b)^2\right) - F$.

All proofs are in the Appendix

As shown in Lemma 1, in the centralized system, all pricing strategies can potentially be applied except the PG strategy. In addition, Theorem 1 indicates that the price of the brown product only depends on its unit production cost, regardless of whether only the brown product or both the brown and the green products are offered. When the green product is launched, its price is a set function of the unit production cost and the green consumers' preference for the

green product and does not depend on which mix-product strategy is applied. Theorem 1 also shows how the decision to launch the green product depends on the cost structure, the consumers' preference for the green product and the proportion of green consumers in the market. It is not surprising that our results in Theorem 1 exhibit the same structure as the results reported in Yenipazarli & Vakharia (2015) for the case of a single company, as the centralized system considers the two parties as a single decision maker.

4.1.2 Manufacturer-Lead Decentralized System

In the decentralized system when the manufacturer is the leader, the two supply chain members play a two-stage Stackelberg game. The sequence of events is as follows:

1. At the first stage, the manufacturer decides the wholesale prices of the two products, $\{w_g, w_b\}$.
2. In the second stage, the retailer decides the retail prices of the two products, $\{p_g, p_b\}$.

We denote the manufacturer's (retailer's) pricing strategy at equilibrium as $\{w_b^{1*}, w_g^{1*}\}$ ($\{p_b^{1*}, p_g^{1*}\}$); the demand for the brown (green) product at the equilibrium solution as D_b^{1*} (D_g^{1*}); and the profits of the manufacturer, the retailer and the system at equilibrium as π_M^{1*}, π_R^{1*}, and Π^{1*}, respectively.

Theorem 2. In the manufacturer-led decentralized system, the pricing and product line strategy at equilibrium is

- PB strategy in any of the following cases.
  - $c_g > c_b + \omega - 1$

- $\omega c_b < c_g \leq c_b + \omega - 1$ and $F > \frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}$
- $c_g \leq \omega c_b$ and $F > \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$

Under this strategy, we have $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2}$, $p_b^{1*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{1*} = \frac{1}{4} - \frac{c_b}{4}$, $\pi_M^{1*} = \frac{(1-c_b)^2}{8}$, $\pi_R^{1*} = \frac{(1-c_b)^2}{16}$, and $\Pi^{1*} = \frac{3(1-c_b)^2}{16}$.

- RGC Mix-Product strategy when $\omega c_b < c_g \leq c_b + \omega - 1$ and $F \leq \frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}$.

Under this strategy, we have $w_g^{1*} = \frac{\omega}{2} + \frac{c_g}{2}$, $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2}$, $p_g^{1*} = \frac{3\omega}{4} + \frac{c_g}{4}$, $p_b^{1*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{1*} = \frac{1-\rho}{4} - \frac{c_b}{4} + \frac{\rho(c_g-c_b)}{4(\omega-1)}$, $D_g^{1*} = \frac{\rho}{4} - \frac{\rho(c_g-c_b)}{4(\omega-1)}$, $\pi_M^{1*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)} - F$, $\pi_R^{1*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)}$, and $\Pi^{1*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)} - F$.

- WGC Mix-Product strategy when $c_g \leq \omega c_b$ and $F \leq \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$.

Under this strategy, we have $w_g^{1*} = \frac{\omega}{2} + \frac{c_g}{2}$, $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2}$, $p_g^{1*} = \frac{3\omega}{4} + \frac{c_g}{4}$, $p_b^{1*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{1*} = \frac{(1-\rho)(1-c_b)}{4}$, $D_g^{1*} = \frac{\rho(\omega-c_g)}{4\omega}$, $\pi_M^{1*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega} - F$, $\pi_R^{1*} = \frac{(1-c_b)^2}{16} + \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega}$ and $\Pi^{1*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega} - F$.

Theorem 2 shows the prices of the two products under the manufacturer-led decentralized system. Similar to the centralized system, we note that a PG strategy is never applied. We also observe that the price of the brown product only depends on its unit production cost and is always the same under all product line strategies. The price of the green product depends on its unit production cost and the green customers' preference for green products and is the same under any mix-product strategy.

4.1.3 Retailer-Led Decentralized System

This is a two-stage Stackelberg game, and the sequence of events is as follows:

1. In the first stage, the retailer decides the marginal profits of the two products, $\{m_g, m_b\}$.
2. In the second stage, the manufacturer decides the wholesale prices of the two products, $\{w_g, w_b\}$.

Unlike the manufacturer-lead decentralized system where the retailer directly decides the retail prices $\{p_g, p_b\}$, in the retailer-led decentralized system, the retailer decides the marginal profits $\{m_g, m_b\}$. Hence, under this system, the two products' prices are $\{p_g = m_g + w_g, p_b = m_b + w_b\}$.

We denote the manufacturer's (retailer's) pricing strategy at equilibrium as $\{w_b^{2*}, w_g^{2*}\}$ ($\{m_b^{2*}, m_g^{2*}\}$); the demand for the brown (green) product at the equilibrium solution as D_b^{1*} (D_g^{1*}); and the profits of the manufacturer, the retailer and the system at equilibrium as π_M^{2*}, π_R^{2*}, and Π^{2*}, respectively.

Theorem 3. In the retailer-led decentralized system, the pricing and product line strategy at equilibrium is

- PB strategy in any of the following cases.
  - $c_g > c_b + \omega - 1$
  - $\omega c_b < c_g \leq c_b + \omega - 1$ and $F > \frac{\rho(\omega - 1 + c_b - c_g)^2}{16(\omega - 1)}$
  - $c_g \leq \omega c_b$ and $F > \frac{\rho((\omega - c_g)^2 - \omega(1 - c_b)^2)}{16\omega}$

Under this strategy, $w_b^{2*} = \frac{1}{4} + \frac{3c_b}{4}$, $m_b^{2*} = \frac{1}{2} - \frac{c_b}{2}$ and hence $p_b^{2*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{2*} = \frac{1}{4} - \frac{c_b}{4}$, $\pi_R^{2*} = \frac{(1-c_b)^2}{8}$, $\pi_M^{2*} = \frac{(1-c_b)^2}{16}$, and $\Pi^{2*} = \frac{3(1-c_b)^2}{16}$.

- PGC Mix-Product strategy when $\omega c_b < c_g \leq c_b + \omega - 1$ and $F \leq \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)}$.

Under this strategy, $w_g^{2*} = \frac{\omega}{4} + \frac{3c_g}{4}$; $w_b^{2*} = \frac{1}{4} + \frac{3c_b}{4}$, $m_g^{2*} = \frac{\omega}{2} - \frac{c_g}{2}$, and $m_b^{2*} = \frac{1}{2} - \frac{c_b}{2}$ and hence $p_g^{2*} = \frac{3\omega}{4} + \frac{c_g}{4}$ and $p_b^{2*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{2*} = \frac{1-\rho}{4} - \frac{c_b}{4} + \frac{\rho(c_g-c_b)}{4(\omega-1)}$, $D_g^{2*} = \frac{\rho}{4} - \frac{\rho(c_g-c_b)}{4(\omega-1)}$, $\pi_M^{2*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)} - F$, $\pi_R^{2*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}$, and $\Pi^{2*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)} - F$.

- WGC Mix-Product strategy when $c_g \leq \omega c_b$ and $F \leq \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega}$.

Under this strategy, $w_g^{2*} = \frac{\omega}{4} + \frac{3c_g}{4}$, $w_b^{2*} = \frac{1}{4} + \frac{3c_b}{4}$, $m_g^{2*} = \frac{\omega}{2} - \frac{c_g}{2}$, and $m_b^{2*} = \frac{1}{2} - \frac{c_b}{2}$ and hence $p_g^{2*} = \frac{3\omega}{4} + \frac{c_g}{4}$ and $p_b^{2*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{2*} = \frac{(1-\rho)(1-c_b)}{4}$, $D_g^{2*} = \frac{\rho(\omega-c_g)}{4\omega}$, $\pi_M^{2*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega} - F$, $\pi_R^{2*} = \frac{(1-c_b)^2}{8} + \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$, and $\Pi^{2*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega} - F$.

The results obtained in Theorem 3 for the retailer-led decentralized system show the same structure for product prices as in the centralized system and the manufacturer-led decentralized system. The results also show that a PG strategy is never applied in the retailer-led decentralized system.

Surprisingly, we find that possession of the first mover right significantly impacts the optimal pricing strategy. Specifically, when the first mover right switches from the manufacturer

to the retailer, the final prices of the green/brown products will not change, but it becomes more difficult to launch the green product in the market. This result is not intuitive and provides managerial insights to practitioners.

4.2 Analysis of the Optimal Strategies

In this section, we use the results presented in section 4.1 to analyze the key elements that characterize the optimal product line strategies at equilibrium for the centralized system and the two decentralized systems. Then, we compare the performance of these three different supply chain systems. Finally, we discuss the related managerial insights.

4.2.1 Analysis of the Prices and Profits

Comparing the prices and profits at equilibrium for the three supply chain systems, we find the following.

Corollary 1.

- Under each pricing and product line strategy, $p_b^{1*} = p_b^{2*} > p_b^c$, $p_g^{1*} = p_g^{2*} > p_g^c$, and $\Pi^c > \Pi^{1*} = \Pi^{2*}$.
- Under each pricing and product line strategy, $w_b^{1*} > w_b^{2*}$, $w_g^{1*} > w_g^{2*}$, and $\pi_M^{1*} > \pi_M^{2*}$, and $\pi_R^{1*} < \pi_R^{2*}$.

The first part of Corollary 1 confirms the well-established observation that the centralized system is more efficient than the decentralized systems due to double marginalization. This inefficiency linked with decentralization leads to higher product prices and a lower system profit. Interestingly, we also notice that in the decentralized systems, the identity of the leader has no influence on the retail prices of the two products regardless of the strategy (i.e., PB, RGC Mix-

Product, or WGC Mix-Product). The system profit in the two decentralized systems is also the same. The second part of Corollary 1 shows that the manufacturer can charge a higher wholesale price to the retailer when it has the first mover right. Thus, the manufacturer can obtain a higher profit by moving first. This result indicates that in this green supply chain, the first mover right always benefits the leader.

4.2.2 Analysis of the Demand for the Two Products

Corollary 2.

- Under each pricing and product line strategy, $D_b^{2*} = D_b^{1*} = \frac{1}{2} D_b^c$ and $D_g^{2*} = D_g^{1*} = \frac{1}{2} D_g^c$.
- In each of the three systems:
  - The demand for the brown product is higher under the PB strategy than under the RGC Mix-Product strategy as well as the WGC Mix-Product strategy.
  - Demand for the two products under the RGC Mix-Product strategy is equal to the demand for the brown product under the PB strategy.
  - Demand for the two products under the WGC Mix-Product strategy is higher than the demand for the brown product under the PB strategy.

The first part of Corollary 2 confirms the inefficiency of the decentralized systems compared to the centralized system in terms of lower demand for the products. The second part of Corollary 2 provides important insights into the cannibalization between green and brown products. This indicates that the green product will always cannibalize the sales of the brown product regardless of the strategy adopted. However, despite the cannibalization, launching the

green product never leads to lower overall market coverage regardless of the supply chain system or the pricing strategy. Specifically, introducing a green product will keep market coverage unchanged if the RGC Mix-Product strategy is applied and will even increase market coverage under the WGC Mix-Product strategy.

4.2.3 Analysis of the Effect of the Fixed Cost (F) *Related to Launching the Green Product*

Theorems 1, 2 and 3 show how the fixed cost (F) related to launching the green product and the variable costs (c_b, c_g) affect the choice of strategy to adopt. To analyze this effect, we first consider the case of a centralized system. Figs. 1 and 2 show the optimal strategies according to the results established in Theorem 1 for the centralized system under the assumption of no fixed cost associated with launching the green product ($F = 0$) and a positive fixed cost ($F > 0$), respectively. Assuming $F = 0$ and replacing this in the conditions of application of the RGC Mix-Product strategy in Theorem 1, we find that this strategy is optimal in the area situated between line $c_g = \omega c_b$ (upper frontier) and line (lower frontier) $c_g = c_b + \omega - 1$ (See Fig. 1).

Fig. 1. Product line and pricing strategies in the case where $F = 0$

Fig. 2. Product line and pricing strategies in the case where $F > 0$

For the case where the fixed cost is not zero ($F > 0$), Theorem 1 shows that the area of application of the RGC Mix-Product strategy is between line $c_g = \omega c_b$ (upper frontier) and line

(lower frontier) $c_g = c_b + \omega - 1 - \sqrt{4F\frac{\omega-1}{\rho}}$. Thus, the fixed cost causes the area of application of the RGC Mix-Product strategy to shrink proportionally to the square root of this fixed cost (see Fig. 2). For a fixed cost higher than a certain level, this area will completely disappear. Similarly, from the conditions of application of the WGC Mix-Product strategy established in Theorem 1, we can see that if $F = 0$, the WGC Mix-Product strategy will be applied in the area situated under line $c_g = c_b\sqrt{\omega} + \omega - \sqrt{\omega}$. Fig. 1 shows that this area comprises the entire region under line $c_g = \omega c_b$, as $\omega c_b \leq c_b\sqrt{\omega} + \omega - \sqrt{\omega}$. However, if a fixed cost $(F > 0)$ is engaged when introducing the green product, this area will shrink, and the WGC Mix-Product strategy becomes optimal only under the curve $c_g = \omega - \sqrt{4F\frac{\omega}{\rho} + \omega(1 - c_b)^2}$.

The shrinkage of the areas where the two products coexist benefits the area of application of the PB strategy (Fig. 2). Based on this analysis, we conclude that a fixed cost associated with offering the green product reduces the chances that the supply chain will launch this product. Moreover, the higher the fixed cost is, the narrower the region where launching the green product would be the best strategy for the supply chain.

Corollary 3.

- If launching the green product does not require any additional fixed cost ($F = 0$), the area where each strategy would be applied is the same in the three systems.
- If launching the green product requires an additional fixed cost ($F > 0$), the area where a Mixed-Product strategy would be applied is smaller in the decentralized system than in the centralized case, and it is smaller in the retailer-led decentralized system than in the manufacturer-led one.

The first part of Corollary 3 can be derived directly from the conditions of application of the RGC Mix-Product and WGC Mix-Product strategies in Theorems 1, 2 and 3. When $F = 0$, the RGC Mix-Product strategy should be applied on the same area between the line $c_g = \omega c_b$ (upper frontier) and the line $c_g = c_b + \omega - 1$ (lower frontier) for each of the three systems. Similarly, the WGC Mix-Product strategy should be applied in the same area under the line $c_g = c_b\sqrt{\omega} + \omega - \sqrt{\omega}$ for each of the three systems. This means that in the case in which there is no fixed cost related to the introduction of the green product, the system structure (centralized vs decentralized) does not affect the decision to launch the green product and the pricing strategy to be adopted for this product.

The second part of Corollary 3 is also directly derived from the conditions of application of the RGC Mix-Product and WGC Mix-Product strategies in Theorems 1, 2 and 3. When $F > 0$, the RGC Mix-Product strategy should be applied to the area between the line $c_g = \omega c_b$ (lower frontier) and the line $c_g = c_b + \omega - 1 - \sqrt{4F\frac{\omega-1}{\rho}}$ (lower frontier) in the case of a centralized system. For the case of a decentralized system, this strategy is applied in the region limited by the same lower-frontier line $c_g = \omega c_b$ and the upper-frontier line $c_g = c_b + \omega - 1 - \sqrt{8F\frac{\omega-1}{\rho}}$ in the case in which the manufacturer is the leader or by the upper-frontier line $c_g = c_b + \omega - 1 - \sqrt{16F\frac{\omega-1}{\rho}}$ in the case in which the retailer is the leader. Thus, while $c_g = \omega c_b$ constitutes a lower limit for the region of application of the RGC Mix-Product strategy in the three systems, the upper limit of this region is closer to the lower limit in the two decentralized systems than it is to that in the centralized system. Similarly, we observe that the upper limit of the region where the RGC Mix-Product strategy should be applied is closer to the

lower limit in the decentralized system with the retailer as the leader than when the manufacturer is the leader. In conclusion, we can say that the area of application of the RGC Mix-Product strategy is smaller in the two cases of the decentralized system compared to the case of a centralized system, and it is smaller in the case in which the retailer is leading the supply chain compared to the case in which the manufacturer is the leader. When $F > 0$, the WGC Mix-Product strategy should be applied in the area situated under the line $c_g = \omega - \sqrt{4F\frac{\omega}{\rho} + \omega(1-c_b)^2}$, under the line $c_g = \omega - \sqrt{8F\frac{\omega}{\rho} + \omega(1-c_b)^2}$ in the case of a decentralized system with the manufacturer as the leader and under the line $c_g = \omega - \sqrt{16F\frac{\omega}{\rho} + \omega(1-c_b)^2}$ in the case of a decentralized system with the retailer as the leader. Note that $c_b\sqrt{\omega} + \omega - \sqrt{\omega} > \omega - \sqrt{4F\frac{\omega}{\rho} + \omega(1-c_b)^2} > \omega - \sqrt{8F\frac{\omega}{\rho} + \omega(1-c_b)^2\omega - \sqrt{16F\frac{\omega}{\rho} + \omega(1-c_b)^2}}$. Thus, compared to the case where no fixed cost is required to introduce the green product, the upper frontier of the area where the WGC Mix-Product strategy should be applied is lower when there is a positive fixed cost, and the area where this strategy is optimal is smaller. Similarly, if we compare the results of the three systems in the case when a fixed cost is engaged, we find that the frontier of the area of application of the WGC Mix-Product strategy is lower and the area where this strategy should be applied is smaller in the two cases of the decentralized system compared to the case of a centralized system. We conclude that decentralization negatively affects the opportunity to offer a green product when there is a fixed cost associated with introducing this product because it reduces the area where mix-product strategies are optimal. This finding points out a type of inefficiency in the decentralized system for expanding the supply chain offering to include a green product when a

fixed cost is required. We also observe that the case where the retailer is leader exhibits a smaller area of application of the WGC Mix-Product strategy compared to the case where the manufacturer is leader. Fig. 3 shows the area of application of the three different strategies for the three supply chain systems.

Fig. 3. Product line and pricing strategies for the three systems in the case where $F > 0$

4.2.4 Analysis of the Effect of the Green Market Segment Size (ρ)

From the results presented in Theorems 1, 2 and 3, we observe that for any given value of the unit production cost and the fixed cost, there is a threshold for the green segment in the market (ρ) under which a mix-product strategy is no longer optimal. This means that for a mix-product strategy to be optimal, the proportion of the green consumer segment should be above a given rate. In the centralized system, this rate is equal to $\frac{4F(\omega-1)}{(\omega-1+c_b-c_g)^2}$ when the variable cost of the green product compared to that of the brown one is relatively high ($i.e. c_g > \omega c_b$) and equal to $\frac{4F\omega}{(\omega-c_g)^2-\omega(1-c_b)^2}$ when the variable cost of the green product is relatively low ($i.e. c_g \leq \omega c_b$). These values of the threshold for ρ are twice as large in the decentralized system, with the manufacturer being the leader and 4 times larger when the retailer is leader.

Fig. 4 shows the threshold for ρ above which a WGC Mix-Product strategy is optimal in the three supply systems: centralized, decentralized with the manufacturer being the leader and decentralized with the retailer being the leader. Based on the above analysis and on Fig. 4, all else being equal, a supply chain with centralized decision making will be able to take advantage

of a growing tendency in the market towards green consumption earlier than a decentralized supply chain. Further, comparing the two decentralized systems, we observe that a manufacturer-led supply chain would be able to benefit from the growth of the green market segment earlier than a retailer-led supply chain. Fig. 4 also shows that a trade-off exists between the proportion of the green market segment (ρ) and the willingness to pay for the green product (ω), which means that a higher willingness to pay for the green product could compensate for the low proportion of the green market segment and have a positive effect on the adoption of a mix-product strategy by the supply chain at an early stage in the development of the green market segment (when ρ is still relatively small).

Fig. 4. Threshold of ρ for the WGC mix-product strategy to be adopted

4.3 Coordination of the Decentralized Green Supply Chain

The above analysis and results demonstrate the superior performance of the centralized system compared to the two decentralized systems. The results also show the inherent differences between the two centralized systems in their ability to launch the green product and to grasp the benefit of the growing number of green consumers. Given these results, it is important to explore how the supply chain can be coordinated to avoid the inefficiencies of the decentralized systems. Therefore, in this section, we study how to design a contract to coordinate the decentralized green supply chain. Without loss of generality, we only consider a manufacturer-led supply chain because the design of the coordination contract in this case is very similar to that in the case when the retailer is leader.

Similar to Taylor (2002) and Cachon & Lariviere (2005), we define a "coordinating contract" as one that satisfies the following two conditions:

C1: Under a coordinating contract, the retailer's optimal decisions are the same between the decentralized system and the centralized system (i.e., $\{p_g^{1*}, p_b^{1*}\} = \{p_g^c, p_b^c\}$).

C2: Under a coordinating contract, each party obtains an arbitrary pre-negotiated portion of the total system profit, i.e., $\pi_R^{1*} = \chi \Pi^c$, for any $\chi \in [0,1]$.

While condition (C1) ensures that the decisions made in the decentralized system be aligned with the first-best decisions in the centralized system and hence that the total system profit can be maximized, condition (C2) ensures that the supply chain members can obtain a profit according to any possible allocation plan. Therefore, by satisfying both conditions, it guarantees that each supply chain member is better off.

Theorem 4. Price-only contracts with $\{w_g, w_b\}$ cannot coordinate the manufacturer-led decentralized system.

Theorem 4 seems to be intuitive because of the coordination conditions: condition (C1) requires that the two retail prices $\{p_g^{1*}, p_b^{1*}\}$ are aligned with the first-best prices $\{p_g^c, p_b^c\}$. Therefore, two contract parameters should be used to satisfy this condition. In addition, condition (C2) requires that profit allocation plan χ be implemented under the contract. This condition requires another contract parameter in the contract. Thus, it seems that at least three contract parameters are needed to achieve coordination for such a green supply chain. This result is consistent with that of Yan & Zaric (2016), who found that to achieve coordination in such a supply chain where the two prices are decided, the coordinating contract should include at least three parameters.

Next, in addition to the two wholesale prices $\{w_g, w_b\}$, we consider whether coordination can be achieved by adding one more contract parameter. We first consider the simplest case: adding a constant payment to the contract, which we denote by Ω. This contract with $\{w_g, w_b, \Omega\}$ is called a two-part tariff contract. Note that in the decentralized supply chain considered in our study, there are two products, and therefore, there are two wholesale prices.

We denote the manufacturer's profit and the retailer's profits under two-part tariff contract as π_M^T and π_R^T, respectively. Recall that in the decentralized system considered in section 4, the two members' profits are denoted as π_M and π_R, respectively. Then, we have $\pi_M^T = \pi_M + \Omega$ and $\pi_R^T = \pi_R - \Omega$.

Theorem 5. The two-part tariff contract with $\{w_g, w_b, \Omega\}$ achieves coordination if and only if

- $w_g = c_g$ and $w_b = c_b$.
- When $c_g > c_b + \omega - 1$, $\omega c_b < c_g \leq c_b + \omega - 1$ and $F > \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2$, or $c_g \leq \omega c_b$ and $F > \frac{\rho}{4\omega}\left(\left(\omega - c_g\right)^2 - \omega(1 - c_b)^2\right)$, $\Omega = (1 - \chi)\Pi^c$. Otherwise, $\Omega = (1 - \chi)\Pi^c + F$.

Theorem 5 indicates that a two-part tariff contract does achieve coordination. However, under this contract, the two wholesale prices must be set to be the same as the two production costs. In this case, the manufacturer's profit can be rewritten as $\pi_M^T = \Omega - F$, which is equivalent to the manufacturer selling the business to the retailer and obtaining a fixed payment from it. This may make it difficult to implement a two-part tariff contract. Thus, we next consider other contract formats without a constant payment in the contract.

One contract with a nonconstant additional payment is a revenue sharing contract, which is also commonly used in business. Under this contract, the retailer will share a portion of the total revenue with the manufacturer. We denote this portion as γ, where $\gamma \in [0,1]$. We denote the manufacturer's profit and the retailer's profit under the revenue sharing contract as π_R^M and π_R^R, respectively.

For example, when the WGC Mix-Product strategy is used, π_M^R and π_R^R can be written as

$$\pi_M^R = (w_b - c_b + \gamma p_b)(1-\rho)(1-p_b) + \left(w_g - c_g + \gamma p_g\right)\rho\left(1 - \frac{p_g}{\omega}\right) - F$$

$$\pi_R^R = ((1-\gamma)p_b - w_b)(1-\rho)(1-p_b) + \ ((1-\gamma)p_g - w_g)\rho(1 - \tfrac{p_g}{\omega}).$$

Theorem 6. The revenue sharing contract with $\{w_g, w_b, \gamma\}$ achieves coordination if and only if

- $w_g = \chi c_g$ and $w_b = \chi c_b$.
- When $c_g > c_b + \omega - 1$, $\omega c_b < c_g \leq c_b + \omega - 1$ and $F > \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2$, or $c_g \leq \omega c_b$ and $F > \frac{\rho}{4\omega}\left(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2\right)$, $\gamma = 1 - \chi$. Otherwise, $\gamma = 1 - \frac{\chi \Pi^c}{\Pi^c + F}$.

Theorem 6 indicates that a revenue sharing contract can achieve coordination for the decentralized supply chain. Under this contract, the retailer is required to share a portion of its revenue with the manufacturer according to the prenegotiated profit allocation plan χ. As compensation to the retailer, the two wholesale prices are set to be as low as a portion of production costs, which are also based on the prenegotiated profit allocation plan χ.

Unlike a two-part tariff contract, under the revenue sharing contract, each supply chain member's profit is a portion of the system profit, and hence, the decisions are aligned with the

first-best ones. Thus, the contract can be implemented more easily in reality than the two-part tariff contract.

4.4 Optimal Strategies for the Supply Chain in the Case where $c_g \leq c_b$

As we indicated in section 3.1, most of the literature adopts the assumption of higher production costs for the green product in comparison with the brown conventional product. This is because the materials used to produce green products are generally more expensive than those used to produce brown products. However, to obtain the most general results and insights, we still consider the uncommon case where $c_g \leq c_b$. Thus, in this section, we extend our analysis to this case, where the production cost of the green product is lower than the cost of the brown traditional product. Our objective is, first, to find the optimal product line and pricing strategies in the three different supply chain systems under the assumption $c_g \leq c_b$ and to extract the corresponding managerial insights.

Second, we conduct the analysis of the optimal pricing strategies and profits for the centralized system and decentralized systems.

The first-best pricing strategy and system profit in the centralized system is given by Theorem 7.

Theorem 7. In the centralized supply chain system where $c_g \leq c_b$, the first-best pricing and product line strategy is

- PB strategy in any of the following cases:
  - $c_b - (\omega - 1) \leq c_g \leq c_b$ and $F > \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1 - c_b)^2)$
  - $c_g < c_b - (\omega - 1)$ and $F > \frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega + \rho)} - \frac{(1-c_b)^2}{4}$

Under this strategy, $p_b^c = \frac{1}{2} + \frac{c_b}{2}$, $D_b^c = \frac{1}{2} - \frac{c_b}{2}$, and $\Pi^c = \frac{(1-c_b)^2}{4}$.

- WGC Mix-Product strategy when $c_b - (\omega - 1) \leq c_g \leq c_b$ and $F \leq \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1 - c_b)^2)$.

Under this strategy, $p_b^c = \frac{1}{2} + \frac{c_b}{2}$; $p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$, $D_b^c = \frac{(1-\rho)(1-c_b)}{2}$, $D_g^c = \frac{\rho(\omega - c_g)}{2\omega}$, and $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4\omega}\left(\left(\omega - c_g\right)^2 - \omega(1 - c_b)^2\right) - F$.

- PG strategy when $c_g < c_b - (\omega - 1)$ and $F \leq \frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega + \rho)} - \frac{(1-c_b)^2}{4}$.

Under this strategy, $p_g^c = \frac{\omega(1 + c_g - \rho c_g) + \rho c_g}{2\omega((1-\rho)\omega + \rho)}$, $D_g^c = \frac{\omega(1 - c_g + \rho c_g) - \rho c_g}{2\omega}$, and $\Pi^c = \frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega + \rho)} - F$.

From Theorem 7, we see that unlike the case where $c_g > c_b$, if the cost of the green product is lower than the cost of the brown product, the system prefers a greener strategy. This can be understood by considering two aspects. First, when the cost of the green product is moderately low compared to that of the brown product (i.e., $c_b - (\omega - 1) \leq c_g \leq c_b$) and the fixed cost for launching the green product is not high ($F \leq \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1 - c_b)^2)$), a mix pricing strategy is applied. In addition, the strategy can only be the WGC Mix-Product strategy, and the RGC Mix-Product strategy will never be applied because the low cost of the green products encourages the system to offer it at a low retail price so that the customers in the green segment will all choose to buy the green product. Second, in contrast with the case where $c_g > c_b$, the application of the PG strategy becomes possible. Specifically, when the cost of the green product is very low compared to that of the brown product (i.e., $c_g < c_b - (\omega - 1)$), then if the fixed cost of launching the green product is affordable (i.e., $F \leq \frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega + \rho)} - \frac{(1-c_b)^2}{4}$),

the system will apply the PG strategy. Note that the PG strategy can only be applied in the case where $c_g < c_b - (\omega - 1)$.

Fig. 5. Product line and pricing strategies in the case where $c_g < c_b$ and $F = 0$

The rationale behind this result is that the low cost of the green products allows the system to offer a retail price for the green product that is even lower than that of the brown one, so that all customers in both segments choose to buy green products. Fig. 5 clearly shows these results and identifies the regions of application of the WGC mixed-product strategy and the PG strategy under the assumption of a fixed cost associated with launching the green product that is as low as zero ($F = 0$).

In the manufacturer-led decentralized system, the manufacturer's and the retailer's pricing strategies and the net profits at equilibrium are given in Theorem 8.

Theorem 8. In the manufacturer-led decentralized system, the pricing and product line strategy at equilibrium is

- PB strategy in any of the following cases:
  - $c_b - 3(\omega - 1) \leq c_g \leq c_b$ and $F > \frac{\rho((\omega - c_g)^2 - \omega(1 - c_b)^2)}{8\omega}$
  - $c_g < c_b - 3(\omega - 1)$ and $F > \frac{3(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{16\omega((1-\rho)\omega + \rho)} - \frac{(1 - c_b)^2}{4}$

Under this strategy, we have $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2}$, $p_b^{1*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{1*} = \frac{1}{4} - \frac{c_b}{4}$, $\pi_M^{1*} = \frac{(1-c_b)^2}{8}$, $\pi_R^{1*} = \frac{(1-c_b)^2}{16}$, and $\Pi^{1*} = \frac{3(1-c_b)^2}{16}$.

- WGC Mix-Product strategy when $c_b - 3(\omega - 1) \leq c_g \leq c_b$ and $F \leq \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$. Under this strategy, we have $w_g^{1*} = \frac{\omega}{2} + \frac{c_g}{2}$, $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2}$, $p_g^{1*} = \frac{3\omega}{4} + \frac{c_g}{4}$, $p_b^{1*} = \frac{3}{4} + \frac{c_b}{4}$, $D_b^{1*} = \frac{(1-\rho)(1-c_b)}{4}$, $D_g^{1*} = \frac{\rho(\omega-c_g)}{4\omega}$, $\pi_M^{1*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega} - F$, $\pi_R^{1*} = \frac{(1-c_b)^2}{16} + \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega}$ and $\Pi^{1*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega} - F$.
- PG strategy when $c_g < c_b - 3(\omega - 1)$ and $F \leq \frac{3(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{16\omega((1-\rho)\omega+\rho)} - \frac{(1-c_b)^2}{4}$. Under this strategy, $w_g^{1*} = \frac{\omega(1+c_g-\rho c_g)+\rho c_g}{2((1-\rho)\omega+\rho)}$, $p_g^{1*} = \frac{\omega(3+c_g-\rho c_g)+\rho c_g}{4((1-\rho)\omega+\rho)}$, $D_g^{1*} = \frac{\omega(1-c_g+\rho c_g)-\rho c_g}{4\omega}$, $\pi_M^{1*} = \frac{(\omega(\rho c_g-c_g+1)-\rho c_g)^2}{8\omega((1-\rho)\omega+\rho)} - F$, $\pi_R^{1*} = \frac{(\omega(\rho c_g-c_g+1)-\rho c_g)^2}{16\omega((1-\rho)\omega+\rho)}$ and $\Pi^{1*} = \frac{3(\omega(\rho c_g-c_g+1)-\rho c_g)^2}{16\omega((1-\rho)\omega+\rho)} - F$.

Similar to the centralized system, in the decentralized system where the manufacturer is the leader, the manufacturer and the retailer tend to offer more of the green product compared to the case with the higher green product cost $c_g > c_b$. We also note that the first-best pricing strategy in the centralized system is even greener than that in the decentralized system. We can see this from the fact that in the centralized system, the possibility of adopting the PG strategy is greater because it is easier to satisfy the conditions of application of this strategy $c_g < c_b - (\omega - 1)$ and $F \leq \frac{(\omega(\rho c_g-c_g+1)-\rho c_g)^2}{4\omega((1-\rho)\omega+\rho)} - \frac{(1-c_b)^2}{4}$ in the centralized system than the conditions $c_g < c_b - 3(\omega - 1)$ and $F \leq \frac{3(\omega(\rho c_g-c_g+1)-\rho c_g)^2}{16\omega((1-\rho)\omega+\rho)} - \frac{(1-c_b)^2}{4}$ in the decentralized system. Thus, we can conclude that launching the green product is less constrained in the centralized system than in the decentralized system. This conclusion is reasonable because in the centralized system, each

supply chain member's incentive is aligned, and hence, the efficiency of the system is higher, which makes launching green products easier. Hence, the analysis of the case where $c_g \leq c_b$ provides further evidence that a higher level of efficiency can be achieved by coordinating the decentralized system.

The analytical results in the decentralized system where the retailer is the leader are very similar; hence, for the sake of brevity, we omit the details. Furthermore, we can also show that the decentralized system can be coordinated under either a two-part tariff contract or a revenue-sharing contract. Again, as these analytical results do not provide new insights, we omit the details.

5 Conclusion, Managerial Insights and Limitations

To address and exploit the growing interest of customers in green products, companies are expanding their offer in the market by launching green versions of existing conventional brown products. This expansion of the product line aims to satisfy the demand of current customers for greener products, attract new environmentally conscious customers and capture the price premium that these consumers are willing to pay for the green product. However, a new green product could cannibalize the sales of the conventional brown product and requires investment in extra resources associated with product greening. Considering these issues, the question of positioning and tuning the two offerings becomes critical for obtaining full advantage from launching the green product. Moreover, even though providing the necessary resources and the investment required to launch the green product is usually the responsibility of the manufacturer, the decision to launch the product and position it on the market spans the manufacturer's borders and involves the other supply chain partners.

In this work, we study the decision to launch a green version of an existing conventional brown product and analyze the different positioning and pricing strategies of the two products' offerings in a supply chain composed of one manufacturer and one retailer. To provide the most valuable insights from our model, we based it on realistic assumptions regarding market segmentation and consumers' preferences with regard to green and brown products (Ginsberg & Bloom, 2004; Rowlands et al., 2003). Thus, the market in our study is composed of two consumer segments. A green segment comprises the consumers who are willing to pay a price premium for the green product, and a brown segment comprises the consumers who equally value the green and the brown products. We provide analytical results and managerial insights for both situations encountered in business: the situation where the manufacturer owns the brand and acts as the supply chain leader and the situation where the retailer is the brand owner and acts as the supply chain leader. Through our analysis, we develop 4 possible strategies that managers can adopt with regards to launching and positioning on the market a green version of an already existing brown product, and explicitly express the conditions under which each strategy would be chosen. The results we obtain for the centralized system confirm the findings of the previous literature for the case of a single company. For the two decentralized supply chain systems, we provided and analyzed the conditions of application of each pricing and positioning strategy and the threshold of the green consumer proportion on the market that allows for launching the green product. Our results are completely new.

We summarize the key managerial insights from our analysis as follows. The green product always cannibalizes sales from the brown one regardless of the pricing strategy. However, offering the two products never translate into lower market coverage. It is also observed that the fixed cost linked with launching the green product reduces the opportunities to

offer this product and can be prohibitive in this regard. Thus, regardless of who the supply chain leader is, unless the fixed cost of launching the green product is too high (higher than a given threshold), it is possible to exploit the green consumers' willingness to pay and calibrate the two offerings of brown and green products to obtain a maximum advantage from each consumer segment. Interestingly, we found that the manufacturer-led supply chain is better prepared to overcome the fixed cost and launch the green product than the retailer-led one, although the optimal prices of the green products and brown products are set at the same level in both the decentralized supply chains. Our analysis also demonstrates that a manufacturer-led supply chain would be able to benefit from the growth of the green consumer segment by offering them a green product at a premium price at an earlier stage than could a retailer-led supply chain. Compared to the two decentralized alternatives (the retailer-led and the manufacturer-led supply chains), a centralized supply chain exhibits higher efficiency from two perspectives. First, it allows for benefiting from a growing proportion of green consumers on the market at an earlier stage than the two alternative decentralized supply chains. Second, it allows the green product to be launched even when the related fixed cost would prohibit its launch in any of the decentralized supply chains. Thus, from a managerial point of view, it is crucial to coordinate the supply chain so that it is possible to benefit at an early stage from the growing tendency of consumers to buy green products. With this in mind, we prove that a revenue-sharing contract can coordinate the supply chain.

Because we considered a simple supply chain that consists of one manufacturer and one retailer and acts as a monopolist in the market, interesting extensions of this work would be to incorporate competition and consider different supply chain structures, such as one manufacturer with two or more competing retailers or two competing supply chains (see Zhu & He, 2017).

Another possible avenue for future research could incorporate demand uncertainty by assuming stochastic demand (see Xu et al., 2017) or fuzzy demand (see Zhao et al., 2012), and/or supply uncertainty due to the uncertain yield rate in the production process (Arifoglu et al. 2012, Yan et al. 2017). In our study, we considered noncooperative games with complete and deterministic information. Future studies may consider the same questions using cooperative games under uncertainty (see Palancı et al., 2014). Future research may also use a nonuniform distribution of consumer preference, such as a unimodal, bimodal or generalized beta distribution (see Gaur & Honhon, 2006).

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Appendix

Proof of Lemma 1.

Consider the case where $c_g > c_b$. We first consider the centralized system. Suppose the optimal pricing strategy is $p_b > p_g$. Now we consider the case where $p_b > p_g$ and the case where $p_b' = p_g$. Next we prove that p_b' is always better to the system than any $p_b > p_g$.

For the customers in the green segment, $U_g^G = \omega\theta - p_g$ and $U_b^G = \theta - p_b$. Since $\omega > 1$, we know at any $p_b > p_g$, the customers prefer the green product and hence the demand $d_g = \rho(1 - \frac{p_g}{\omega})$. For the same reason, at $p_b' = p_g$, the customers also prefer the green product and hence the demand $d_g' = \rho(1 - \frac{p_g}{\omega})$. Therefore, the demands are the same at any $p_b > p_g$ and at $p_b' = p_g$. In addition, at any $p_b > p_g$ and at $p_b' = p_g$, the system profits, Π and Π' respectively, are both given by $\Pi = \Pi' = \rho(1 - \frac{p_g}{\omega})(p_g - c_g)$.

For the customers in the brown segment, $U_g^B = \theta - p_g$ and $U_b^B = \theta - p_b$. At any $p_b > p_g$, the customers prefer the green product and the demand $d_g = 1 - p_g$. Therefore, the system profit $\Pi = (1-\rho)(1-p_g)(p_g - c_g)$. At $p_b' = p_g$, the customers obtain the same utility from either green products or brown products. We assume that the customers will purchase either product with 50% probability. Therefore, the total demand still equals $1 - p_g$ but half of them will purchase brown products and half of them will purchase green products. Hence, at $p_b' = p_g$, the system profit $\Pi' = (1-\rho)\left((p_b' - c_b)\frac{1-p_g}{2} + (p_g - c_g)\frac{1-p_g}{2}\right) = (1-\rho)\left((p_g - c_b)\frac{1-p_g}{2} + (p_g - c_g)\frac{1-p_g}{2}\right) = \frac{(1-\rho)(1-p_g)}{2}\left((p_g - c_b) + (p_g - c_g)\right)$. Since $c_g > c_b$, $\Pi' = \frac{(1-\rho)(1-p_g)}{2}\left((p_g - c_b) + (p_g - c_g)\right) > \frac{(1-\rho)(1-p_g)}{2}\left((p_g - c_g) + (p_g - c_g)\right) = (1-\rho)(1-p_g)(p_g - c_g)$.

From the above analysis, we see that the system profit at $p_b' = p_g$ is higher than that at any $p_b > p_g$. This contradicts with what we assume at the beginning, i.e., the optimal pricing strategy is $p_b > p_g$. Therefore, we have proved that when $c_g > c_b$, the retail prices must satisfy $p_g \geq p_b$ when both brown products and green products co-exist.

The proof of this result in the decentralized system is very similar. For the sake of brevity, we omit the details of the proof.

Proof of Theorem 1.

We first consider the centralized system under Pure Brown strategy. From Section 4.1.1, we know that under Pure Brown strategy, the system profit $\Pi = (p_b - c_b)(1 - p_b)$. Taking the first derivative of Π w.r.t. p_b, we have $\frac{\partial \Pi}{\partial p_b} = (1-\rho)(1 + c_b - 2p_b)$. Therefore the first best $p_b^c = \frac{1}{2} + \frac{c_b}{2}$. Plugging the first best pricing and product line strategy p_b^c into profit Π and demand D_b, we have the first best demand $D_b^c = \frac{1}{2} - \frac{c_b}{2}$, and the first best system profit $\Pi^c = \frac{(1-c_b)^2}{4}$.

Similarly, under WGC Mix-Product strategy (i.e., $p_g \leq \omega p_b$), we know that WGC Mix-Product strategy, the system profit $\Pi = (p_b - c_b)(1-\rho)(1-p_b) + (p_g - c_g)\rho(1 - \frac{p_g}{\omega}) - F$. Taking the first derivative of Π w.r.t. p_b, we have $\frac{\partial \Pi}{\partial p_b} = (1-\rho)(1 + c_b - 2p_b)$. Therefore the first best $p_b^c = \frac{1}{2} + \frac{c_b}{2}$. Taking the first derivative of Π w.r.t. p_g, we have $\frac{\partial \Pi}{\partial p_g} = \frac{\rho}{\omega}(\omega + c_g - 2p_g)$. Therefore the first best $p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$. Plugging the two first best pricing and product line strategies $\{p_b^c, p_g^c\}$ into the profit Π and the demand $\{D_b, D_g\}$, we have the first best demands $D_b^c = \frac{(1-\rho)(1-c_b)}{2}$, $D_g^c = \frac{(1-\rho)(\omega - c_g)}{2\omega}$, and the first best system profit $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4\omega}\left((\omega - c_g)^2 - \omega(1-c_b)^2\right) - F$. In addition, to ensure the WGC Mix-Product strategy is feasible, we must have $p_g^c \leq \omega p_b^c$, i.e., $\frac{\omega}{2} + \frac{c_g}{2} \leq \omega(\frac{1}{2} + \frac{c_b}{2})$. This is equivalent to $c_g \leq \omega c_b$. Furthermore, even if WGC Mix-Product strategy is feasible, we must also ensure that it is more beneficial than the Pure Brown strategy, which means that the first best system profit under WGC Mix-Product strategy is higher than that under Pure Brown strategy. So, we must have $\frac{(1-c_b)^2}{4} + \frac{\rho}{4\omega}\left((\omega - c_g)^2 - \omega(1-c_b)^2\right) - F \geq \frac{(1-c_b)^2}{4}$, i.e., $F \leq \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1-c_b)^2)$. Therefore, the last bullet in Theorem 1 has been proved.

Next we consider the RGC Mix-Product strategy (i.e., $p_g > \omega p_b$). Similar to the WGC Mix-Product strategy, we have the system profit $\Pi = (p_b - c_b)((1-\rho)(1-p_b) + \frac{\rho(p_g - \omega p_b)}{\omega - 1}) + (p_g - c_g)\rho(1 - \frac{p_g - p_b}{\omega - 1}) - F$. Taking the first derivative of Π w.r.t. p_b, we have

$\frac{\partial \Pi}{\partial p_b} = (1-\rho)(1+c_b-2p_b) + \frac{\rho}{\omega-1}\left(2p_g - 2\omega p_b + \omega c_b - \omega c_g\right)$. Taking the first derivative of Π w.r.t. p_g, we have $\frac{\partial \Pi}{\partial p_g} = \frac{\rho}{\omega-1}(\omega - 1 - 2p_g + 2p_g + c_g - c_b)$. By solving the two first-order equations $\left\{\frac{\partial \Pi}{\partial p_b} = 0, \frac{\partial \Pi}{\partial p_g} = 0\right\}$, we have the first best prices $p_b^c = \frac{1}{2} + \frac{c_b}{2}$, $p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$. Accordingly, the two demands at first best solution are $D_b^c = \frac{1-\rho}{2} - \frac{c_b}{2} + \frac{\rho(c_g-c_b)}{2(\omega-1)}$, $D_g^c = \frac{\rho}{2} - \frac{\rho(c_g-c_b)}{2(\omega-1)}$, and the first best system profit is $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2 - F$. In addition, to ensure the RGC Mix-Product strategy is feasible, we must have $p_g^c > \omega p_b^c$, i.e., $\frac{\omega}{2} + \frac{c_g}{2} > \omega(\frac{1}{2} + \frac{c_b}{2})$. This is equivalent to $c_g > \omega c_b$. Furthermore, we also need to ensure that both demands are nonnegative, i.e., $D_b^c = \frac{1-\rho}{2} - \frac{c_b}{2} + \frac{\rho(c_g-c_b)}{2(\omega-1)} \geq 0$ and $D_g^c = \frac{\rho}{2} - \frac{\rho(c_g-c_b)}{2(\omega-1)} \geq 0$. Since $c_g > \omega c_b$, we have $D_b^c = \frac{1-\rho}{2} - \frac{c_b}{2} + \frac{\rho(c_g-c_b)}{2(\omega-1)} > \frac{1-\rho}{2} - \frac{c_b}{2} + \frac{\rho(\omega-1)c_b}{2(\omega-1)} = \frac{1-\rho}{2}(1-c_b) \geq 0$. $D_g^c = \frac{\rho}{2} - \frac{\rho(c_g-c_b)}{2(\omega-1)} \geq 0$ is equivalent to $c_g \leq c_b + \omega - 1$. Finally, even if RGC Mix-Product strategy is feasible, we must also ensure that it is more beneficial than the Pure Brown strategy, which means that the first best system profit under RGC Mix-Product strategy is higher than that under Pure Brown strategy. So, we must have $\frac{(1-c_b)^2}{4} + \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2 - F \geq \frac{(1-c_b)^2}{4}$, i.e., $F \leq \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2$. Therefore, the second bullet in Theorem 1 has been proved.

Finally, when neither RGC Mix-Product strategy nor WGC Mix-Product strategy is the first best solution, Pure Brown strategy is the first best strategy. Therefore, Pure Brown is the first best strategy when $c_g > c_b + \omega - 1$, or $\omega c_b < c_g \leq c_b + \omega - 1$ and $F > \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2$, or $c_g \leq \omega c_b$ and $F > \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1-c_b)^2)$. Theorem 1 has been proved.

Proof of Theorem 2.

Similar to the proof of Theorem 1, we show the equilibrium solution under each strategy in the manufacturer-led decentralized system.

We first consider the decentralized system under Pure Brown strategy. From Section 3.3, we know that under Pure Brown strategy, the manufacturer's profit and the retailer's profit are $\pi_M = (w_b - c_b)(1 - p_b)$ and $\pi_R = (p_b - w_b)(1 - p_b)$. Since the manufacturer is the leader, we solve the equilibrium solution by using the backward method. Given the manufacturer's decision w_b, the retailer solves his best response $p_b^*(w_b)$ to maximize his profit π_R. Taking the first derivative of π_R w.r.t. p_b, we have $\frac{d\pi_R}{dp_b} = 1 + w_b - 2p_b$. Therefore, the retailer's best response $p_b^*(w_b) = \frac{1}{2} + \frac{w_b}{2}$. Plugging $p_b^*(w_b)$ in π_M and take the first derivative of π_M w.r.t. w_b, we have $\frac{d\pi_M}{dw_b} = \frac{1}{2} + \frac{c_b}{2} - w_b$. Therefore, the manufacturer's optimal decision $w_b^* = \frac{1}{2} + \frac{c_b}{2}$ and accordingly the retailer optimal decision at equilibrium is $p_b^* = \frac{3}{4} + \frac{c_b}{4}$. Plugging $\{w_b^*, p_b^*\}$ in the demand function and each member's profit, we have $D_b^{1*} = \frac{1}{4} - \frac{c_b}{4}$, $\pi_M^{1*} = \frac{(1-c_b)^2}{8} - F$, $\pi_R^{1*} = \frac{(1-c_b)^2}{16}$, and $\Pi^{1*} = \frac{3(1-c_b)^2}{16}$.

We consider WGC Mix-Product strategy (i.e., $p_g \le \omega p_b$) . Under this strategy, we have $\pi_M = (w_b - c_b)(1-\rho)(1 - p_b) + \rho(w_g - c_g)\left(1 - \frac{p_g}{\omega}\right) - F$ and $\pi_R = (p_b - w_b)(1-\rho)(1 - p_b) + \rho(p_g - w_g)(1 - \frac{p_g}{\omega})$. Given the manufacturer's decisions $\{w_b, w_g\}$, we take the first derivative of π_R w.r.t. p_b and p_g, we have $\frac{\partial \pi_R}{\partial p_b} = (1-\rho)(1 + w_b - 2p_b)$ and $\frac{\partial \pi_R}{\partial p_g} = \rho\left(1 + \frac{w_g}{2} - \frac{2p_g}{\omega}\right)$. Therefore, we solve the retailer's best response $p_b^{1*} = \frac{1}{2} + \frac{w_b}{2}$ and $p_g^{1*} = \frac{\omega}{2} + \frac{w_g}{2}$. Plugging the best response $\{p_b^*, p_g^*\}$ into the manufacturer's profit π_M and take the first derivative of π_M w.r.t. w_b and w_g, we have $\frac{\partial \pi_M}{\partial w_b} = \frac{1-\rho}{2}(1 + c_b - 2w_b)$ and $\frac{\partial \pi_M}{\partial w_g} = \frac{\rho}{\omega}(\frac{\omega}{2} + \frac{c_g}{2} - w_g)$. Solving $\left\{\frac{\partial \pi_M}{\partial w_b} = 0, \frac{\partial \pi_M}{\partial w_g} = 0\right\}$, we have $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2}$ and $w_g^{1*} = \frac{\omega}{2} + \frac{c_g}{2}$. Therefore, $p_b^{1*} = \frac{3}{4} + \frac{c_b}{4}$ and $p_g^{1*} = \frac{3\omega}{4} + \frac{c_g}{4}$. Accordingly, we have $D_b^{1*} = \frac{(1-\rho)(1-c_b)}{4}$, $D_g^{1*} = \frac{(1-\rho)(\omega - c_g)}{4\omega}$, $\pi_M^{1*} = \frac{1}{8}(1 - c_b)^2 + \frac{\rho((\omega - c_g)^2 - \omega(1-c_b)^2)}{8\omega} - F$, $\pi_R^{1*} = \frac{(1-c_b)^2}{16} + \frac{\rho((\omega - c_g)^2 - \omega(1-c_b)^2)}{16\omega}$ and $\Pi^{1*} = \frac{3}{16}(1 - c_b)^2 + \frac{3\rho((\omega - c_g)^2 - \omega(1-c_b)^2)}{16\omega} - F$. Finally, to ensure that $p_g^{1*} \le \omega p_b^{1*}$, we must have $\frac{3\omega}{4} + \frac{c_g}{4} \le \omega\left(\frac{3}{4} + \frac{c_b}{4}\right)$. This condition is equivalent to $c_g \le \omega c_b$. In addition, to ensure the mix

strategy is better than the Pure Brown strategy, the manufacturer's profit, who is the leader of the game, should obtain a profit higher under the WGC strategy. Therefore, we must have $\frac{1}{8}(1-c_b)^2+\frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}-F\geq\frac{(1-c_b)^2}{8}$, i.e., $F\leq\frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$. Hence, we know that when $c_g\leq\omega c_b$ and $F\leq\frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$, WGC Mix-Product strategy is the equilibrium solution. The last bullet of Theorem 2 has been proved.

Next we consider RGC Mix-Product strategy (i.e., $p_g>\omega p_b$) . Under this strategy, we have $\pi_M=(w_b-c_b)((1-\rho)(1-p_b)+\frac{\rho}{\omega-1}(p_g-\omega p_b))+\rho(w_g-c_g)(1-\frac{p_g-p_b}{\omega-1})-F$ and $\pi_R=(p_b-w_b)((1-\rho)(1-p_b)+\frac{\rho}{\omega-1}(p_g-\omega p_b))+(p_g-w_g)\rho(1-\frac{p_g-p_b}{\omega-1})$. Given the manufacturer's decisions $\{w_b,w_g\}$, we take the first derivative of π_R w.r.t. p_b and p_g, we have $\frac{\partial\pi_R}{\partial p_b}=(1-\rho)(1+w_b-2p_b)+\frac{\rho}{\omega-1}(2p_g-2\omega p_b-w_g+\omega w_b)$ and $\frac{\partial\pi_R}{\partial p_g}=\frac{\rho}{\omega-1}(2p_b-2p_g+w_g-w_b+\omega-1)$. Therefore, we solve the retailer's best response $p_b^{1*}=\frac{1}{2}+\frac{w_b}{2}$ and $p_g^{1*}=\frac{\omega}{2}+\frac{w_g}{2}$. Plugging the best response $\{p_b^*,p_g^*\}$ into the manufacturer's profit π_M and take the first derivative of π_M w.r.t. w_b and w_g, we have $\frac{\partial\pi_M}{\partial w_b}=\frac{1}{2}(1+c_b-2w_b)+\frac{\rho}{2(\omega-1)}(1-\omega+c_b-c_g-2w_b+2w_g)$ and $\frac{\partial\pi_M}{\partial w_g}=\frac{\rho}{2(\omega-1)}(\omega-c_b+c_g+2w_b-2w_g-1)$. Solving $\left\{\frac{\partial\pi_M}{\partial w_b}=0,\frac{\partial\pi_M}{\partial w_g}=0\right\}$, we have $w_b^{1*}=\frac{1}{2}+\frac{c_b}{2}$ and $w_g^{1*}=\frac{\omega}{2}+\frac{c_g}{2}$. Therefore, $p_b^{1*}=\frac{3}{4}+\frac{c_b}{4}$ and $p_g^{1*}=\frac{3\omega}{4}+\frac{c_g}{4}$. Accordingly, we have $D_b^{1*}=\frac{1-\rho}{4}-\frac{c_b}{4}+\frac{\rho(c_g-c_b)}{4(\omega-1)}$, $D_g^{1*}=\frac{\rho}{4}-\frac{\rho(c_g-c_b)}{4(\omega-1)}$, $\pi_M^{1*}=\frac{1}{8}(1-c_b)^2+\frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}-F$, $\pi_R^{1*}=\frac{1}{16}(1-c_b)^2+\frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)}$, and $\Pi^{1*}=\frac{3}{16}(1-c_b)^2+\frac{3\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)}-F$. Finally, to ensure that $p_g^{1*}>\omega p_b^{1*}$, we must have $\frac{3\omega}{4}+\frac{c_g}{4}>\omega\left(\frac{3}{4}+\frac{c_b}{4}\right)$. This condition is equivalent to $c_g>\omega c_b$. Furthermore, we also need to ensure that both demands are nonnegative, i.e., $D_b^{1*}=\frac{1-\rho}{4}-\frac{c_b}{4}+\frac{\rho(c_g-c_b)}{4(\omega-1)}\geq 0$ and $D_g^{1*}=\frac{\rho}{4}-\frac{\rho(c_g-c_b)}{4(\omega-1)}\geq 0$. Since $c_g>\omega c_b$, we have $D_b^{1*}=\frac{1-\rho}{4}-\frac{c_b}{4}+\frac{\rho(c_g-c_b)}{4(\omega-1)}>\frac{1-\rho}{4}-\frac{c_b}{4}+\frac{\rho(\omega-1)c_b}{4(\omega-1)}=\frac{1-\rho}{4}(1-c_b)\geq 0$. $D_g^{1*}=\frac{\rho}{4}-\frac{\rho(c_g-c_b)}{4(\omega-1)}\geq 0$ is equivalent to $c_g\leq c_b+\omega-1$. Therefore, we must have

$\frac{1}{8}(1-c_b)^2+\frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}-F\geq\frac{(1-c_b)^2}{8}$, i.e., $F\leq\frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}$. In addition, to ensure RGC Mix-Product strategy is better than the Pure Brown strategy, the manufacturer's profit, who is the leader of the game, should obtain a profit higher under the RGC strategy. Hence, we know that when $c_g>\omega c_b$ and $F\leq\frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}$, RGC Mix-Product strategy is the equilibrium solution. The second bullet of Theorem 2 has been proved.

Finally, when neither RGC Mix-Product strategy nor WGC Mix-Product strategy is the first best solution, Pure Brown strategy is the first best strategy. Therefore, Pure Brown is the first best strategy when $c_g>c_b+\omega-1$, or $\omega c_b<c_g\leq c_b+\omega-1$ and $F>\frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}$, or $c_g\leq\omega c_b$ and $F>\frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$. Theorem 2 has been proved.

Proof of Theorem 3.

Similar to the proof of Theorem 2, we first consider the decentralized system under Pure Brown strategy. From Section 3.3, we know that under Pure Brown strategy, the manufacturer's profit and the retailer's profit are $\pi_M=(w_b-c_b)(1-w_b-m_b)$ and $\pi_R=m_b(1-p_b)$. Since the retailer is the leader, we solve the equilibrium solution by using the backward method. Given the retailer's decision m_b, the manufacturer solves her best response $w_b^{2*}(m_b)$ to maximize her profit π_M. Taking the first derivative of π_M w.r.t. w_b, we have $\frac{d\pi_M}{dm_b}=1-2w_b-m_b+c_b$. Therefore, the mfr's best response $w_b^{2*}(m_b)=\frac{1}{2}-\frac{m_b}{2}+\frac{c_b}{2}$. Plugging $w_b^{2*}(m_b)$ in π_R and take the first derivative of π_R w.r.t. m_b, we have $\frac{d\pi_R}{dm_b}=\frac{1}{2}-\frac{c_b}{2}-m_b$. Therefore, the retailer's optimal decision $m_b^{2*}=\frac{1}{2}-\frac{c_b}{2}$ and accordingly $w_b^{2*}=\frac{1}{4}+\frac{3c_b}{4}$. Plugging $\{w_b^{2*},p_b^{2*}\}$ in the demand function and each member's profit, we have $p_b^{2*}=\frac{3}{4}+\frac{c_b}{4}$, $D_b^{2*}=\frac{1}{4}-\frac{c_b}{4}$, $\pi_R^{2*}=\frac{(1-c_b)^2}{8}$, $\pi_M^{2*}=\frac{(1-c_b)^2}{16}$, and $\Pi^{2*}=\frac{3(1-c_b)^2}{16}$.

We consider WGC Mix-Product strategy (i.e., $p_g\leq\omega p_b$). Under this strategy, we have $\pi_M=(w_b-c_b)(1-\rho)(1-w_b-m_b)+\rho(w_g-c_g)\left(1-\frac{w_g+m_g}{\omega}\right)-F$ and $\pi_R=m_b(1-\rho)(1-w_b-m_b)+\rho m_g(1-\frac{w_g+m_g}{\omega})$. Given the retailer's decisions $\{m_b,m_g\}$, we take the

first derivative of π_M w.r.t. w_b and w_g, we have $\frac{\partial \pi_M}{\partial w_b} = (1-\rho)(1+w_b-m_b) - (w_b - c_b)(1-\rho)$ and $\frac{\partial \pi_M}{\partial w_g} = \rho\left(1 - \frac{w_g+m_g}{\omega} - \frac{w_g-c_g}{\omega}\right)$. Therefore, we solve the mfr's best response $w_b^{2*} = \frac{1}{2} - \frac{m_b}{2} + \frac{c_b}{2}$ and $w_g^{2*} = \frac{\omega}{2} - \frac{m_g}{2} + \frac{c_g}{2}$. Plugging the best response $\{w_b^{2*}, w_g^{2*}\}$ into the retailer's profit π_R and take the first derivative of π_R w.r.t. m_b and m_g, we have $\frac{\partial \pi_R}{\partial m_b} = \frac{1-\rho}{2}(1 - c_b - 2m_b)$ and $\frac{\partial \pi_R}{\partial m_g} = \frac{\rho}{2\omega}(\omega - c_g - 2m_g)$. Solving $\left\{\frac{\partial \pi_R}{\partial m_b} = 0, \frac{\partial \pi_R}{\partial m_g} = 0\right\}$, we have $m_b^{2*} = \frac{1}{2} - \frac{c_b}{2}$ and $m_g^{2*} = \frac{\omega}{2} - \frac{c_g}{2}$. Therefore, $p_b^{2*} = \frac{3}{4} + \frac{c_b}{4}$ and $p_g^{2*} = \frac{3\omega}{4} + \frac{c_g}{4}$. Accordingly, we have $D_b^{2*} = \frac{(1-\rho)(1-c_b)}{4}$, $D_g^{2*} = \frac{(1-\rho)(\omega-c_g)}{4\omega}$, $\pi_M^{2*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho((\omega-c_g)^2 - \omega(1-c_b)^2)}{16\omega} - F$, $\pi_R^{2*} = \frac{(1-c_b)^2}{8} + \frac{\rho((\omega-c_g)^2 - \omega(1-c_b)^2)}{8\omega}$ and $\Pi^{2*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho((\omega-c_g)^2 - \omega(1-c_b)^2)}{16\omega} - F$. Finally, to ensure that $p_g^{2*} \le \omega p_b^{2*}$, we must have $\frac{3\omega}{4} + \frac{c_g}{4} \le \omega\left(\frac{3}{4} + \frac{c_b}{4}\right)$. This condition is equivalent to $c_g \le \omega c_b$. In addition, to ensure the mix strategy is better than the Pure Brown strategy, the manufacturer's profit, who is the leader of the game, should obtain a profit higher under the WGC strategy. Therefore, we must have $\frac{1}{16}(1-c_b)^2 + \frac{\rho((\omega-c_g)^2 - \omega(1-c_b)^2)}{16\omega} - F \ge \frac{(1-c_b)^2}{16}$, i.e., $F \le \frac{\rho((\omega-c_g)^2 - \omega(1-c_b)^2)}{16\omega}$. Hence, we know that when $c_g \le \omega c_b$ and $F \le \frac{\rho((\omega-c_g)^2 - \omega(1-c_b)^2)}{16\omega}$, WGC Mix-Product strategy is the equilibrium solution. The last bullet of Theorem 3 has been proved.

Next we consider RGC Mix-Product strategy (i.e., $p_g > \omega p_b$) . Under this strategy, we have $\pi_M = (w_b - c_b)((1-\rho)(1-w_b-m_b) + \frac{\rho}{\omega-1}(w_g + m_g - \omega(w_b+m_b))) + \rho(w_g - c_g)(1 - \frac{w_g+m_g-w_b-m_b}{\omega-1}) - F$ and $\pi_R = m_b((1-\rho)(1-w_b-m_b) + \frac{\rho}{\omega-1}(w_g + m_g - \omega(w_b + m_b))) + m_g\rho(1 - \frac{w_g+m_g-w_b-m_b}{\omega-1})$. Given the retailer's decisions $\{m_b, m_g\}$, we take the first derivative of π_M w.r.t. w_b and w_g, we have $\frac{\partial \pi_M}{\partial w_b} = \frac{\rho}{\omega-1}(c_b - c_g - m_b + m_g - 2w_b + 2w_g) - \rho + c_b - m_b - 2w_b + 1$ and $\frac{\partial \pi_M}{\partial w_g} = \rho + \frac{\rho}{\omega-1}(2w_b - 2w_g + m_b - m_g - c_b + c_g)$. Therefore, we solve the manufacturer's best response $w_b^{2*} = \frac{c_b}{2} - \frac{m_b}{2} + \frac{1}{2}$ and $w_g^{2*} = \frac{\omega}{2} + \frac{c_g}{2} - \frac{m_g}{2}$. Plugging the best response $\{w_b^{2*}, w_g^{2*}\}$ into the retailer's profit π_R and take the first derivative of π_R w.r.t. m_b and m_g, we have $\frac{\partial \pi_R}{\partial m_b} = \frac{1}{2}(1 - c_b - 2m_b) + \frac{\rho}{2(\omega-1)}(1 - \omega - c_b + c_g - 2m_b + 2m_g)$ and

$\frac{\partial \pi_R}{\partial m_g} = \frac{\rho}{2(\omega-1)}(\omega + c_b - c_g + 2m_b - 2m_g - 1)$. Solving $\left\{\frac{\partial \pi_R}{\partial m_b} = 0, \frac{\partial \pi_R}{\partial m_g} = 0\right\}$, we have $m_b^{2*} = \frac{1}{2} - \frac{c_b}{2}$ and $m_g^{2*} = \frac{\omega}{2} - \frac{c_g}{2}$. Therefore, $p_b^{2*} = \frac{3}{4} + \frac{c_b}{4}$ and $p_g^{2*} = \frac{3\omega}{4} + \frac{c_g}{4}$. Accordingly, we have $D_b^{2*} = \frac{1-\rho}{4} - \frac{c_b}{4} + \frac{\rho(c_g-c_b)}{4(\omega-1)}$, $D_g^{2*} = \frac{\rho}{4} - \frac{\rho(c_g-c_b)}{4(\omega-1)}$, $\pi_M^{2*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)} - F$, $\pi_R^{2*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho(\omega-1+c_b-c_g)^2}{8(\omega-1)}$, and $\Pi^{2*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)} - F$. Finally, to ensure that $p_g^{2*} > \omega p_b^{2*}$, we must have $\frac{3\omega}{4} + \frac{c_g}{4} > \omega\left(\frac{3}{4} + \frac{c_b}{4}\right)$. This condition is equivalent to $c_g > \omega c_b$. Furthermore, we also need to ensure that both demands are nonnegative, i.e., $D_b^{2*} = \frac{1-\rho}{4} - \frac{c_b}{4} + \frac{\rho(c_g-c_b)}{4(\omega-1)} \geq 0$ and $D_g^{2*} = \frac{\rho}{4} - \frac{\rho(c_g-c_b)}{4(\omega-1)} \geq 0$. Since $c_g > \omega c_b$, we have $D_b^{2*} = \frac{1-\rho}{4} - \frac{c_b}{4} + \frac{\rho(c_g-c_b)}{4(\omega-1)} > \frac{1-\rho}{4} - \frac{c_b}{4} + \frac{\rho(\omega-1)c_b}{4(\omega-1)} = \frac{1-\rho}{4}(1-c_b) \geq 0$. $D_g^{2*} = \frac{\rho}{4} - \frac{\rho(c_g-c_b)}{4(\omega-1)} \geq 0$ is equivalent to $c_g \leq c_b + \omega - 1$. Finally, we must ensure the manufacturer obtains a higher profit than under the Pure Brown strategy, i.e., we must have $\frac{1}{16}(1-c_b)^2 + \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)} - F \geq \frac{(1-c_b)^2}{16}$, i.e., $F \leq \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)}$. Hence, we know that when $\omega c_b < c_g \leq c_b + \omega - 1$ and $F \leq \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)}$, RGC Mix-Product strategy is the equilibrium solution. The second bullet of Theorem 3 has been proved.

Finally, when neither RGC Mix-Product strategy nor WGC Mix-Product strategy is the first best solution, Pure Brown strategy is the first best strategy. Therefore, Pure Brown is the first best strategy when $c_g > c_b + \omega - 1$, or $\omega c_b < c_g \leq c_b + \omega - 1$ and $F > \frac{\rho(\omega-1+c_b-c_g)^2}{16(\omega-1)}$, or $c_g \leq \omega c_b$ and $F > \frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega}$. Theorem 3 has been proved.

Proofs of Corollary 1 and Corollary 2.

From Theorems 1-3, we already know that under Pure Brown strategy, $p_b^{1*} = p_b^{2*} = \frac{3}{4} + \frac{c_b}{4} > p_b^c = \frac{1}{2} + \frac{c_b}{2}$, since $p_b^{1*} - p_b^c = \frac{1-c_b}{4} > 0$ (otherwise if $c_b \geq 1$, $D_b^c = \frac{1}{2} - \frac{c_b}{2} \leq 0$, which is a trivial case). $\Pi^c = \frac{(1-c_b)^2}{4} > \Pi^{c1} = \Pi^{c2} = \frac{3(1-c_b)^2}{16}$. In addition, $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2} > w_b^{2*} = \frac{1}{4} + \frac{3c_b}{4}$ because $w_b^{1*} - w_b^{2*} = \frac{1-c_b}{4} > 0$. $\pi_M^{1*} = \frac{(1-c_b)^2}{8} > \pi_M^{2*} = \frac{(1-c_b)^2}{16}$, and $\pi_R^{1*} = \frac{(1-c_b)^2}{16} < \pi_R^{2*} = \frac{(1-c_b)^2}{8}$.

Under WGC Mix-Product strategy, $p_b^{1*} = p_b^{2*} = \frac{3}{4} + \frac{c_b}{4} > p_b^c = \frac{1}{2} + \frac{c_b}{2}$. $p_g^{1*} = p_g^{2*} = \frac{3\omega}{4} + \frac{c_g}{4} > p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$ because $p_g^{1*} - p_g^c = \frac{\omega - c_g}{4} > 0$ (otherwise $D_g^c = \frac{(1-\rho)(\omega - c_g)}{2\omega} \leq 0$, which is a trivial case). In addition, $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4\omega}\left(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2\right) - F > \Pi^{1*} = \Pi^{2*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2)}{16\omega} - F$. In addition, $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2} > w_b^{2*} = \frac{1}{4} + \frac{3c_b}{4}$, $w_g^{1*} = \frac{\omega}{2} + \frac{c_g}{2} > w_g^{2*} = \frac{\omega}{4} + \frac{3c_g}{4}$ since $w_g^{1*} - w_g^{2*} = \frac{\omega - c_g}{4} > 0$. $\pi_M^{1*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2)}{8\omega} - F > \pi_M^{2*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2)}{16\omega} - F$, and $\pi_R^{1*} = \frac{(1-c_b)^2}{16} + \frac{\rho(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2)}{16\omega} < \pi_R^{2*} = \frac{(1-c_b)^2}{8} + \frac{\rho(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2)}{8\omega}$.

Under RGC Mix-Product strategy, $p_b^{1*} = p_b^{2*} = \frac{3}{4} + \frac{c_b}{4} > p_b^c = \frac{1}{2} + \frac{c_b}{2}$. $p_g^{1*} = p_g^{2*} = \frac{3\omega}{4} + \frac{c_g}{4} > p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$. In addition, $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4(\omega-1)}(\omega - 1 - c_g + c_b)^2 - F > \Pi^{1*} = \Pi^{2*} = \frac{3}{16}(1-c_b)^2 + \frac{3\rho(\omega - 1 + c_b - c_g)^2}{16(\omega-1)} - F$. In addition, $w_b^{1*} = \frac{1}{2} + \frac{c_b}{2} > w_b^{2*} = \frac{1}{4} + \frac{3c_b}{4}$, $w_g^{1*} = \frac{\omega}{2} + \frac{c_g}{2} > w_g^{2*} = \frac{\omega}{4} + \frac{3c_g}{4}$. $\pi_M^{1*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho(\omega - 1 + c_b - c_g)^2}{8(\omega-1)} - F > \pi_M^{2*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho(\omega - 1 + c_b - c_g)^2}{16(\omega-1)} - F$, and $\pi_R^{1*} = \frac{1}{16}(1-c_b)^2 + \frac{\rho(\omega - 1 + c_b - c_g)^2}{16(\omega-1)} < \pi_R^{2*} = \frac{1}{8}(1-c_b)^2 + \frac{\rho(\omega - 1 + c_b - c_g)^2}{8(\omega-1)}$.

Corollary 1 has been proved.

Next we prove Corollary 2. First, under Pure Brown strategy, $D_b^{2*} = D_b^{1*} = \frac{1}{2}D_b^c = \frac{1}{4} - \frac{c_b}{4}$. Under WGC Mix-Product strategy, $D_b^{2*} = D_b^{1*} = \frac{1}{2}D_b^c = \frac{(1-\rho)(1-c_b)}{4}$ and $D_g^{2*} = D_g^{1*} = \frac{1}{2}D_g^c = \frac{(1-\rho)(\omega - c_g)}{4\omega}$. Under RGC Mix-Product strategy, $D_b^{2*} = D_b^{1*} = \frac{1}{2}D_b^c = \frac{1-\rho}{4} - \frac{c_b}{4} + \frac{\rho(c_g - c_b)}{4(\omega-1)}$ and $D_g^{2*} = D_g^{1*} = \frac{1}{2}D_g^c = \frac{\rho}{4} - \frac{\rho(c_g - c_b)}{4(\omega-1)}$.

Furthermore, in the centralized sytem, the demand of the brown product $D_b^c = \frac{1}{2} - \frac{c_b}{2}$, which is higher than the demand of brown product under the RGC Mix-Product strategy, $D_b^c = \frac{1-\rho}{2} - \frac{c_b}{2} + \frac{\rho(c_g - c_b)}{2(\omega-1)}$, since $D_b^c + D_g^c = \frac{1}{2} - \frac{c_b}{2}$. Also the demand of the brown product under the PB strategy, $D_b^c = \frac{1}{2} - \frac{c_b}{2}$, is higher than that under WGC Mix-Product strategy, $D_b^c = \frac{(1-\rho)(1-c_b)}{2}$,

since $\frac{1}{2}-\frac{c_b}{2}-\left(\frac{(1-\rho)(1-c_b)}{2}\right)=\frac{\rho(1-c_b)}{2}>0$. Similarly, we can show that this result is true in the manufacturer-led system and the retailer-led system. Here for the sake of brevity we omit the details.

In the centralized system, the demand of the two products under RGC Mix-Product strategy, $D_b^c+D_g^c=\frac{1}{2}-\frac{c_b}{2}$, which is same as the demand of brown product under PB strategy. In addition, the demand for the two products under WGC Mix-Product strategy, $D_b^c+D_g^c=\frac{(1-\rho)(1-c_b)}{2}+\frac{\rho(\omega-c_g)}{2\omega}$. Since under WGC Mix-Product strategy, $c_g\leq\omega c_b$, we have $D_b^c+D_g^c\geq\frac{(1-\rho)(1-c_b)}{2}+\frac{\rho(\omega-\omega c_b)}{2\omega}=\frac{1}{2}-\frac{c_b}{2}$.Therefore, the total demand of brown products and green products is higher than the demand of brown products under pure brown strategy.

The proofs of the results in the two decentralized systems are very similar to that in the centralized system. For the sake of brevity, we omit the details.

Proof of Corollary 3

Theorem 1-3 provide the conditions of each pricing and product line strategy to be adopted as the first-best strategy or equilibrium strategy in the three systems. First we consider WGC Mix-Product strategy. This strategy will be adopted in the centralized system, manufacturer-led decentralized system, and retailer-led decentralized system when the following conditions are satisfied:

- Centralized system: $c_g\leq\omega c_b$ and $F\leq\frac{\rho}{4\omega}((\omega-c_g)^2-\omega(1-c_b)^2)$.
- Manufacturer-led system: $c_g\leq\omega c_b$ and $F\leq\frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{8\omega}$.
- Retailer-led system: $c_g\leq\omega c_b$ and $F\leq\frac{\rho((\omega-c_g)^2-\omega(1-c_b)^2)}{16\omega}$.

We see that if the fixed cost of launching the green product $F=0$, the conditions of all three systems are $c_g\leq\omega c_b$. Therefore, the area where WGC strategy would be applied is the same in the three systems. The proofs for the other pricing and product line strategies are similar and hence we omit the details.

If $F > 0$, we see that for the second condition in the three systems, since $\frac{\rho}{4\omega}\left(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2\right) > \frac{\rho(\left(\omega-c_g\right)^2-\omega(1-c_b)^2)}{8\omega} > \frac{\rho(\left(\omega-c_g\right)^2-\omega(1-c_b)^2)}{16\omega}$, the second condition in the centralized is the easiest to be satisfied, then the condition in the manufacturer-led system, and then the retailer-led system. Hence, the area where a Mixed-Product strategy would be applied is smaller in the decentralized system than in the centralized case, and it is smaller in the retailer-led decentralized system than in the manufacturer-led system.

Proofs of Theorems 4-6.

We first prove Theorem 4. Suppose that the price-only contract with $\{w_g, w_b\}$ can coordinate the manufacturer-led system. Then at least under the RGC Mix-Product strategy, the decisions should be aligned with the first-best decisions. Since the under the RGC Mix-Product strategy, the retailer's profit is given by $\pi_R = (p_b - w_b)((1-\rho)(1-p_b) + \frac{\rho}{\omega-1}(p_g - \omega p_b)) + (p_g - w_g)\rho(1 - \frac{p_g - p_b}{\omega-1})$. Taking the first-derivative of π_R w.r.t. p_b and p_g, we have $\frac{\partial \pi_R}{\partial p_b} = (1-\rho)(1 + w_b - 2p_b) + \frac{\rho}{\omega-1}\left(2p_g - 2\omega p_b - w_g + \omega w_b\right)$ and $\frac{\partial \pi_R}{\partial p_g} = \frac{\rho}{\omega-1}\left(2p_b - 2p_g + w_g - w_b + \omega - 1\right)$. We can solve the retailer's optimal response is $p_b^* = \frac{1}{2} + \frac{w_b}{2}$ and $p_g^* = \frac{\omega}{2} + \frac{w_g}{2}$. To ensure that the two retail prices are aligned with the first-best solution, obviously we have to set $w_b = c_b$ and $w_g = c_g$. However, in this case, we have the manufacturer's profit $\pi_M = (w_b - c_b)\left((1-\rho)(1-p_b) + \frac{\rho}{\omega-1}\left(p_g - \omega p_b\right)\right) + \rho\left(w_g - c_g\right)\left(1 - \frac{p_g - p_b}{\omega-1}\right) - F = -F < 0$. Therefore, there is no way for us to ensure that $\pi_M^{1*} = (1-\chi)\Pi^c > 0$. Theorem 4 has been proved.

Next we prove Theorem 5. First we show if the two-part tariff contract with $\{w_g, w_b, \Omega\}$, we must set $w_g = c_g$, $w_b = c_b$, and $\Omega = (1-\chi)\Pi^c + F$. This is because under the RGC Mix-Product strategy, the retailer's profit is given by $\pi_R = (p_b - w_b)((1-\rho)(1-p_b) + \frac{\rho}{\omega-1}(p_g - \omega p_b)) + (p_g - w_g)\rho(1 - \frac{p_g - p_b}{\omega-1}) - \Omega$. Similar to the proof of Theorem 4, we have $\frac{\partial \pi_R}{\partial p_b} = (1-\rho)(1 + w_b - 2p_b) + \frac{\rho}{\omega-1}\left(2p_g - 2\omega p_b - w_g + \omega w_b\right)$ and $\frac{\partial \pi_R}{\partial p_g} = \frac{\rho}{\omega-1}\left(2p_b - 2p_g + w_g - w_b + \omega - 1\right)$. We can solve the retailer's optimal response is $p_b^* = \frac{1}{2} + \frac{w_b}{2}$ and $p_g^* = \frac{\omega}{2} + \frac{w_g}{2}$.

Therefore, to ensure the two retail prices are aligned with the first-best solution, obviously we have to set $w_b = c_b$ and $w_g = c_g$. So, the retailer's profit $\pi_R^{1*} = (p_b^c - c_b)\left((1-\rho)(1-p_b) + \frac{\rho}{\omega-1}\left(p_g^c - \omega p_b^c\right)\right) + \left(p_g^c - c_g\right)\rho\left(1 - \frac{p_g^c - p_b^c}{\omega-1}\right) - \Omega = \Pi^c + F - \Omega$. Thus, to satisfy the coordination condition C2, i.e., $\pi_R^{1*} = \chi\Pi^c$, we must have $\Omega = (1-\chi)\Pi^c + F$.

Next we prove that $w_g = c_g$, $w_b = c_b$, and $\Omega = (1-\chi)\Pi^c + F$ does ensure coordination is achieved. Under these parameters, under the Pure Brown strategy, the manufacturer's profit and the retailer's profit are given by $\pi_M = \Omega$ and $\pi_R = (p_b - c_b)(1-p_b) - \Omega = \Pi - \Omega$. Therefore, the retailer's profit is aligned with the system profit except for the constant payment Ω Since the constant payment won't impact the retailer's incentives for the price decision p_b, his optimal decision p_b^{1*} is the same as the first-best solution p_b^c. In addition, the retailer profit is $\pi_R = \Pi^c - \Omega$. If $\Omega = (1-\chi)\Pi^c$, $\pi_R = \chi\Pi^c$. Similarly, we can also show that under the other two mix strategies, the retailer's optimal price decisions are the same as the first-best solution and under the constant payment, the retailer's profit is equal to $\chi\Pi^c$. Thus, we have proved that coordination can be achieved under the parameters $w_g = c_g$, $w_b = c_b$, and $\Omega = (1-\chi)\Pi^c + F$.

Finally we prove Theorem 6. Let's first consider WGC Mix-Product strategy, $\pi_R^R = ((1-\gamma)p_b - w_b)(1-\rho)(1-p_b) + ((1-\gamma)p_g - w_g)\rho(1 - \frac{p_g}{\omega})$. Given the manufacturer's wholesale prices $\{w_b, w_g\}$, taking the first derivative of π_R^R w.r.t. p_b and p_g, we have $\frac{\partial \pi_R}{\partial p_b} = (1-\rho)((1-\gamma) + w_b - 2(1-\gamma)p_b)$ and $\frac{\partial \pi_R}{\partial p_g} = \rho\left((1-\gamma) + \frac{w_g}{\omega} - \frac{2(1-\gamma)}{\omega}p_g\right)$. We can solve the retailer's optimal response is $p_b^* = \frac{1}{2} + \frac{w_b}{2(1-\gamma)}$ and $p_g^* = \frac{\omega}{2} + \frac{w_g}{2(1-\gamma)}$. To ensure that the two retail prices are aligned with the first-best solution, if and only if we set $w_b = (1-\gamma)c_b$ and $w_g = (1-\gamma)c_g$. Plugging $p_b^* = \frac{1}{2} + \frac{w_b}{2(1-\gamma)}$ and $p_g^* = \frac{\omega}{2} + \frac{w_g}{2(1-\gamma)}$ in the retailer's profit, we have $\pi_R^R = ((1-\gamma)p_b - w_b)(1-\rho)(1-p_b) + ((1-\gamma)p_g - w_g)\rho(1 - \frac{p_g}{\omega}) = (1-\gamma)\left((p_b^c - c_b)(1-\rho)(1-p_b^c) + \left(p_g^c - c_g\right)\rho\left(1 - \frac{p_b^c}{\omega}\right)\right) = (1-\gamma)(\Pi^c + F)$. So, to ensure $\pi_R = \chi\Pi^c$, if and only if $\gamma = 1 - \frac{\chi\Pi^c}{\Pi^c + F}$. Similarly, we can also show the necessary and sufficient condition of coordination

under the Pure-Brown strategy and RGC strategy. Here for the sake of brevity, we omit the details.

Proof of Theorem 7 and Theorem 8.

From the proof of Theorem 1, we know that under RGC Mix-Product strategy (i.e., $p_g > \omega p_b$), the first-best pricing strategy is $p_b^c = \frac{1}{2} + \frac{c_b}{2}$, $p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$. Therefore, the existence of RGC Mix-Product strategy requires that $c_g > \omega c_b$. This contradicts with the fact that $c_g \leq c_b$. Therefore, RGC Mix-Product strategy is not possible.

Similar to the proof of Theorem 1, we can also show that in the centralized system under Pure Brown strategy, the system profit $\Pi = (p_b - c_b)(1 - p_b)$. Taking the first derivative of Π w.r.t. p_b, we have $\frac{d\Pi}{dp_b} = (1-\rho)(1 + c_b - 2p_b)$. Based on the first-order equation $\frac{d\Pi}{dp_b} = 0$, we can solve the first best $p_b^c = \frac{1}{2} + \frac{c_b}{2}$, the first best demands $D_b^c = \frac{1}{2} - \frac{c_b}{2}$, and the first best system profit $\Pi^c = \frac{(1-c_b)^2}{4}$.

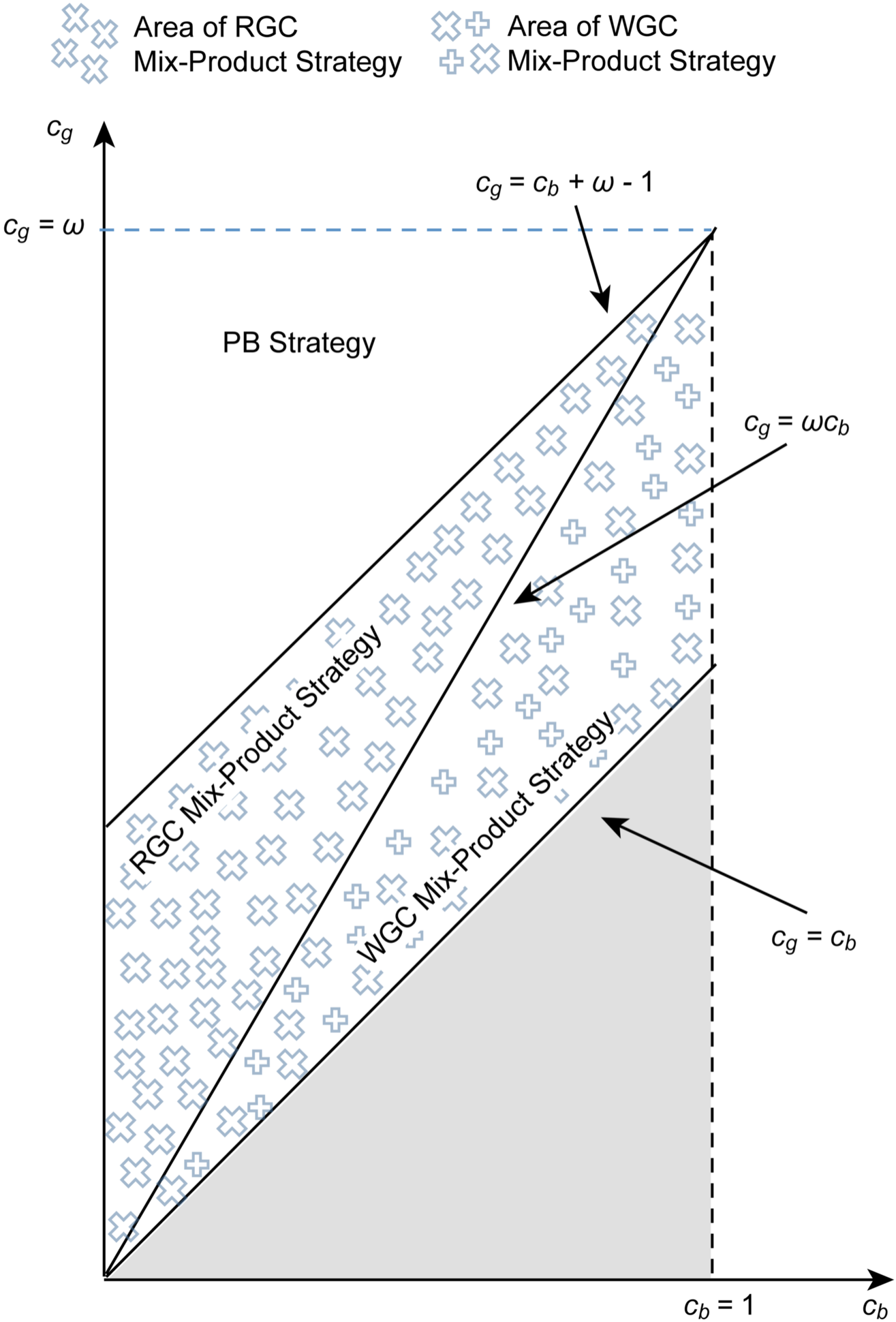
Similarly, under WGC Mix-Product strategy (i.e., $p_g \leq \omega p_b$), we know that WGC Mix-Product strategy, the system profit $\Pi = (p_b - c_b)(1-\rho)(1 - p_b) + (p_g - c_g)\rho(1 - \frac{p_g}{\omega}) - F$. Taking the first derivative of Π w.r.t. p_b, we have $\frac{\partial \Pi}{\partial p_b} = (1-\rho)(1 + c_b - 2p_b)$. Based on the first-order equation $\frac{\partial \Pi}{\partial p_b} = 0$, we can solve the first best $p_b^c = \frac{1}{2} + \frac{c_b}{2}$. Taking the first derivative of Π w.r.t. p_g, we have $\frac{\partial \Pi}{\partial p_g} = \frac{\rho}{\omega}(\omega + c_g - 2p_g)$. Based on the first-order equation $\frac{\partial \Pi}{\partial p_g} = 0$, we can solve the first best $p_g^c = \frac{\omega}{2} + \frac{c_g}{2}$. Plugging the two first best pricing strategies $\{p_b^c, p_g^c\}$ into the profit Π and the demand $\{D_b, D_g\}$, we have the first best demands $D_b^c = \frac{(1-\rho)(1-c_b)}{2}$, $D_g^c = \frac{(1-\rho)(\omega - c_g)}{2\omega}$, and the first best system profit $\Pi^c = \frac{(1-c_b)^2}{4} + \frac{\rho}{4\omega}\left(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2\right) - F$. In addition, to ensure the WGC Mix-Product strategy is feasible, we must have $p_g^c \leq \omega p_b^c$, i.e., $\frac{\omega}{2} + \frac{c_g}{2} \leq \omega(\frac{1}{2} + \frac{c_b}{2})$. This is equivalent to $c_g \leq \omega c_b$. Since $c_g \leq c_b$, the condition $c_g \leq \omega c_b$ is automatically ensured. In addition, we know that when $p_g^c < p_b^c$, all customers in the green segment will prefer green products and hence Pure Green pricing strategy is applied instead of

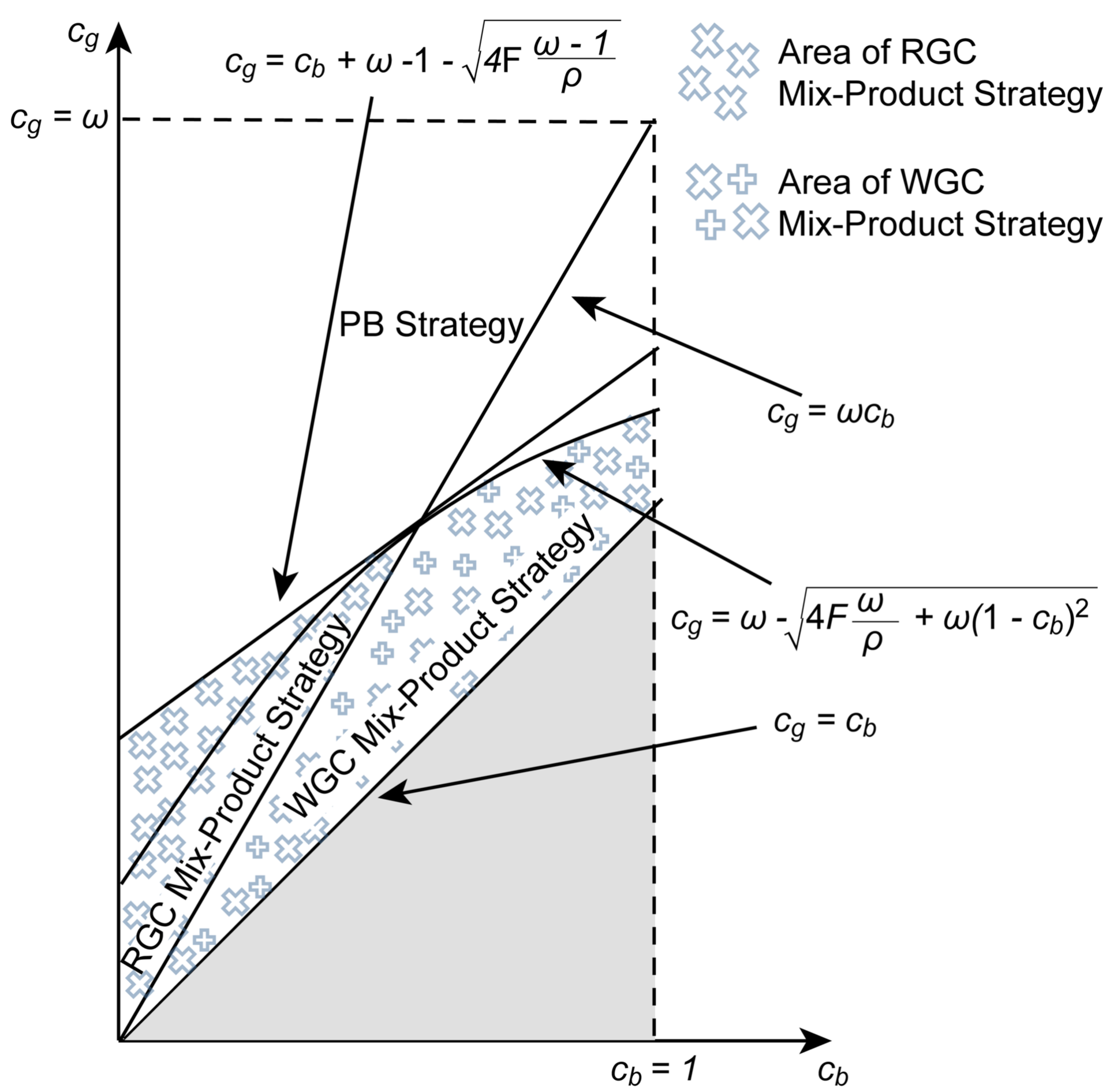
WGC strategy. Therefore WGC strategy also requires that $p_g^c \geq p_b^c$, i.e., $\frac{\omega}{2} + \frac{c_g}{2} \geq \omega(\frac{1}{2} + \frac{c_b}{2})$. This condition can be rewritten as $c_b - (\omega - 1) \leq c_g$. Finally, even if WGC Mix-Product strategy is feasible, we must also ensure that it is more beneficial than the Pure Brown strategy, which means that the first best system profit under WGC Mix-Product strategy is higher than that under Pure Brown strategy. So, we must have $\frac{(1-c_b)^2}{4} + \frac{\rho}{4\omega}\left(\left(\omega - c_g\right)^2 - \omega(1-c_b)^2\right) - F \geq \frac{(1-c_b)^2}{4}$, i.e., $F \leq \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1-c_b)^2)$. Therefore, the second bullet of Theorem 7 about WGC pricing strategy is proved.

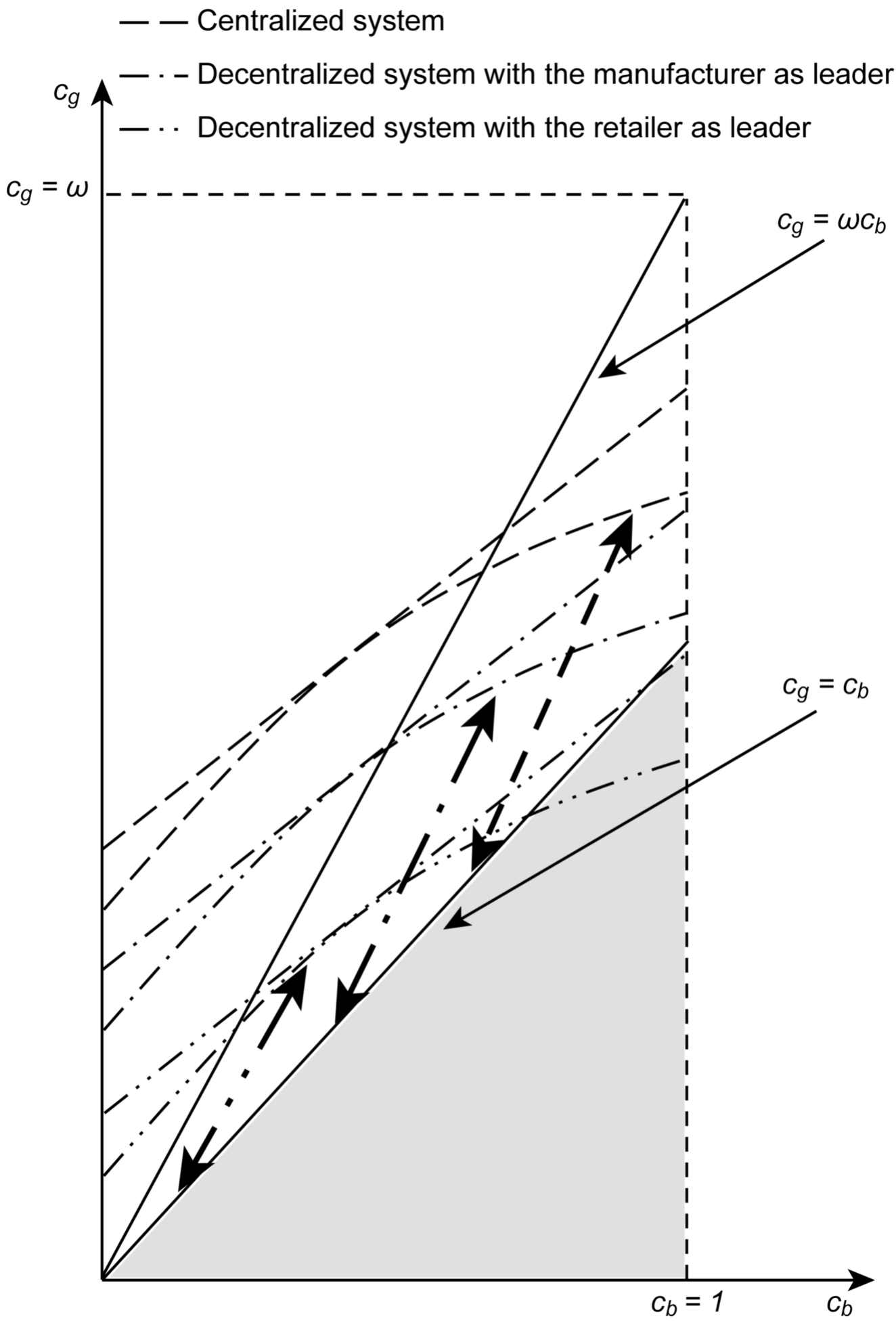
From the proof of WGC pricing strategy, we know that Pure Green strategy is feasible only when $c_g < c_b - (\omega - 1)$ (Otherwise WGC strategy will be applied). Under this case, only green products will be produced. Under this case, the system profit is given by $\Pi = \left(p_g - c_g\right)\left((1-\rho)\left(1-p_g\right) + \rho\left(1 - \frac{p_g}{\omega}\right)\right) - F$. Solving the first-order equation $\frac{d\Pi}{dp_g} = 0$, we solve the first best price $p_g^c = \frac{\omega(1+c_g-\rho c_g)+\rho c_g}{2\omega((1-\rho)\omega+\rho)}$, the first-best demand $D_g^c = \frac{\omega(1-c_g+\rho c_g)-\rho c_g}{2\omega}$, and the first-best system profit $\Pi^c = \frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega+\rho)} - F$. However, even if the Pure Green strategy is feasible, we must also ensure that it is more beneficial than the Pure Brown strategy, which means that the first best system profit under Pure Green strategy is higher than that under Pure Brown strategy. So, we must have $\frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega+\rho)} - F \geq \frac{(1-c_b)^2}{4}$, i.e., $F \leq \frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega+\rho)} - \frac{(1-c_b)^2}{4}$. Therefore, the last bullet of Pure Green pricing strategy is proved.

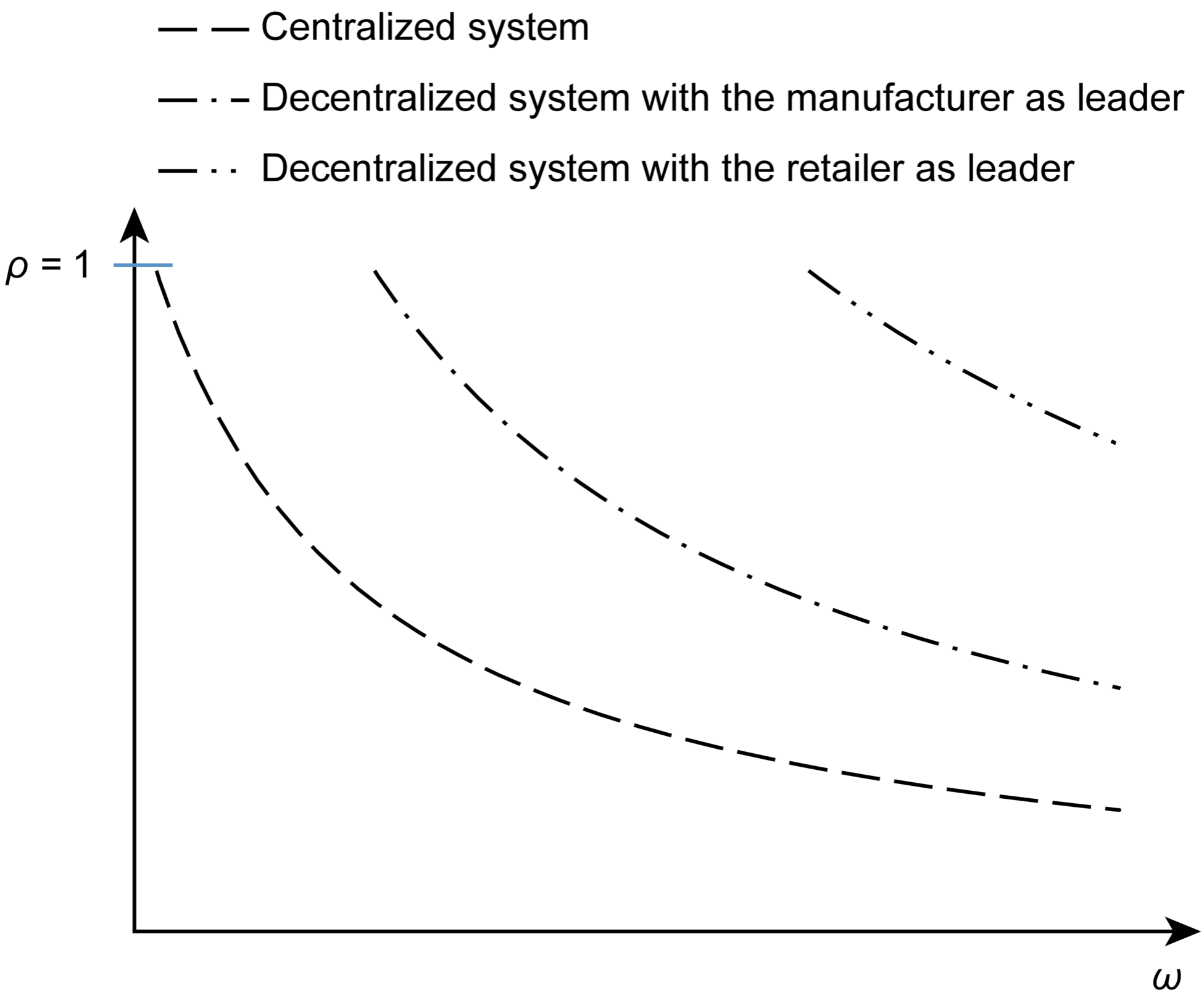
Finally, when neither WGC Mix-Product strategy nor Pure Green strategy is the first best solution, Pure Brown strategy is the first best strategy. Therefore, Pure Brown is the first best strategy when $c_b - (\omega - 1) \leq c_g \leq c_b$ and $F > \frac{\rho}{4\omega}((\omega - c_g)^2 - \omega(1-c_b)^2)$, or $c_g < c_b - (\omega - 1)$ and $F > \frac{(\omega(\rho c_g - c_g + 1) - \rho c_g)^2}{4\omega((1-\rho)\omega+\rho)} - \frac{(1-c_b)^2}{4}$. Theorem 7 has been proved.

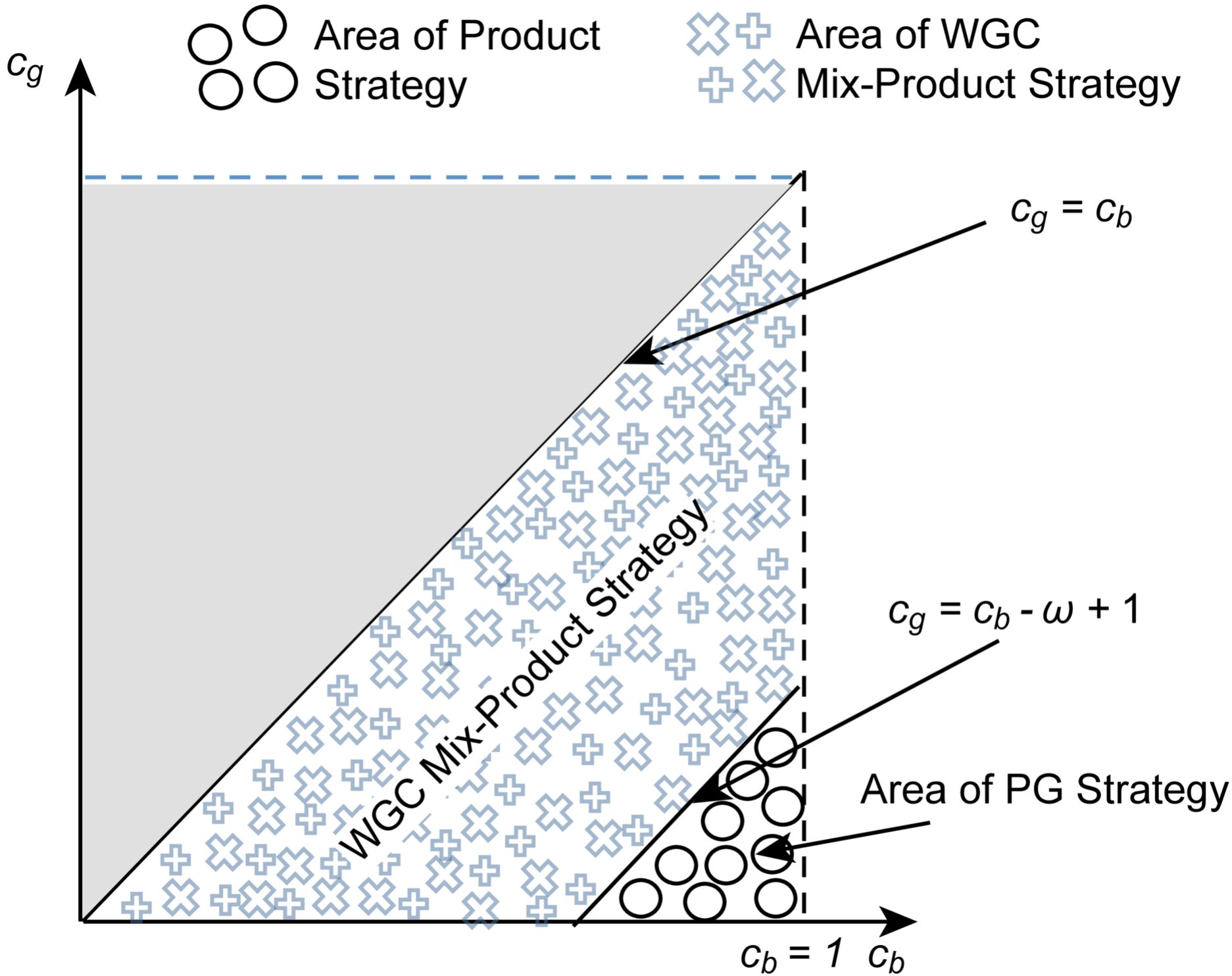
Using the same methods as in the above proof and the proof of Theorem 2, we can also prove Theorem 8 in the manufacturer-leading decentralized system. Here for the sake of brevity, we omit the details of the proof.


Area of RGC Mix-Product Strategy
Area of WGC Mix-Product Strategy
c_g
$c_g = \omega$
$c_g = c_b + \omega - 1$
PB Strategy
$c_g = \omega c_b$
RGC Mix-Product Strategy
WGC Mix-Product Strategy
$c_g = c_b$
$c_b = 1$
c_b


c_g
$c_g = c_b + \omega - 1 - \sqrt{4F\frac{\omega - 1}{\rho}}$
$c_g = \omega$
Area of RGC Mix-Product Strategy
Area of WGC Mix-Product Strategy
PB Strategy
$c_g = \omega c_b$
$c_g = \omega - \sqrt{4F\frac{\omega}{\rho} + \omega(1 - c_b)^2}$
$c_g = c_b$
RGC Mix-Product Strategy
WGC Mix-Product Strategy
$c_b = 1$
c_b


Centralized system
Decentralized system with the manufacturer as leader
Decentralized system with the retailer as leader
c_g
$c_g = \omega$
$c_g = \omega c_b$
$c_g = c_b$
$c_b = 1$
c_b


Centralized system
Decentralized system with the manufacturer as leader
Decentralized system with the retailer as leader
ρ = 1
ω


Area of Product Strategy
Area of WGC Mix-Product Strategy
c_g
$c_g = c_b$
WGC Mix-Product Strategy
$c_g = c_b - \omega + 1$
Area of PG Strategy
$c_b = 1$
c_b