THE OPTIMAL PRODUCT-LINE DESIGN AND INCENTIVE MECHANISM IN A SUPPLY CHAIN WITH CUSTOMER ENVIRONMENTAL AWARENESS

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Abstract. Due to the increasing awareness of sustainable development, the manufacturer’s product-line design gets wide attention. Nowadays, the traditional manufacturer that produces non-green products is considering whether to introduce upgraded green products. This paper studies the manufacturer’s optimal product-line design considering the quality difference between non-green and green products. Besides, our model also investigates the difference in unit production cost, green research and development (R&D) investment, and market segmentation. The results show that, from the manufacturer’s perspective, producing green products is a better choice when non-green products are of low quality. In addition, the retailer is always inclined to sell green products. Further, the consumers’ preference for non-green and green products is divided. And the consumer surplus under different product-line designs is analysed. Finally, two contracts are proposed and compared to encourage the manufacturer to produce green products.

1. Introduction. Developing the circular economy becomes the consensus of the international community, which aims to reduce waste and promote environmental sustainability [1–3]. Furthermore, series of policies are actively adopted by the government to improve the sustainability of industrial production. For instance, China has levied more than 2.9 billion yuan in punitive compensation, which has effectively promoted environmental management and the clearance of solid waste1. With the increasing public awareness of environmental protection, green consumption has become incredibly popular. As a result, a growing number of environmentally friendly consumers are willing to pay more for sustainable goods. Meanwhile, the government provides special energy-saving rebates to consumers for purchasing home appliances, electric vehicles, new energy products, etc2.

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1China Daily Website, Available online, http://www.chinadaily.com.cn/a/202007/01/WS5efbe59a31083481256579.html (accessed on 11/8/2020).

2Sina Finance Website, Available online, http://finance.sina.com.cn/egs/sr/2019-09-18/doc-iicezzrrq6685103.shtml (accessed on 13/8/2020).
To deal with the mounting pressure from the government and green consumers, enterprises have positively invested in green R&D and introduced the greener versions of products. It is widely accepted that green products meet environmental requirements and are conducive to resource regeneration and recycling. Examples of green products have been observed in various industries. For example, in the fashion industry, Uniqlo, the famous Japanese fashion retail giant, has announced that they would start to sell Dry-Ex POLO shirts made from recycled PET plastic bottles in 2020, which aims at reducing environmental pollution caused by the manufacturing process\(^3\). Furthermore, in the home appliance industry, Whirlpool, one of the world’s leading manufacturers, has offered green products that dramatically reduce energy requirements and improve performance\(^4\). The same situation can be observed in the real estate industry. As one of the well-known residential builders in Japan, Sekisui House has provided eco-friendly housing with advanced environmental technologies for carbon emission reduction\(^5\).

Nevertheless, whether the firms should engage in green practices is worthy of further exploration. On the one hand, the enterprises could meet green market trends by developing green products. On the other hand, green production needs high costs \(^4\). In practice, compared with the non-green products, both the production cost and the quality of the green products are higher owing to the sustainable raw material and advanced production technology \(^5, 6\). Table 1 summarizes some practices of green production, which reflects that green products have strong market momentum and broad development space. Hence, it is important to design an appropriate product-line that can help enterprises boost revenue and improve environmental performance. Furthermore, the coordination between the manufacturer and the retailer plays a critical role in the success of a sustainable supply chain \(^7\). Thus, it is necessary to take into account the cooperation issue.

Motivated by these issues, we specifically aim to figure out the following research questions:

1) Is it beneficial for a traditional manufacturer to replace the non-green product with the green product?

2) How does product quality influence firms’ operational decisions and product-line design?

3) Which contract is a better alternative for the retailer aiming to induce manufacturing the green product?

To address the above questions, this paper formulates a two-echelon supply chain consisting of an upstream manufacturer who is accountable for manufacturing products and undertaking the R&D expenditure, and a downstream retailer who is responsible for selling. Specifically, we investigate two scenarios: the product manufactured in the non-green version or the green version. Besides, the potential consumers are composed of two segments: the green segment is willing to pay a price premium for the product with a higher green level, and the non-green segment does not pay attention to the green performance. Our main findings suggest that producing green products is the optimal strategy when green products are high quality and non-green products are low quality or both are low quality.

\(^3\)Men DRY-EX — T-Shirts — Polo Shirts — UNIQLO, https://www.uniqlo.com/eu/en/men/featured/dry-ex.

\(^4\)whirlpool bath parts, whirlpool bath parts Manufacturers and Suppliers at everychina.com, http://www.everychina.com/m-whirlpool-bath-parts.

\(^5\)About Us — Sekisui House Australia, https://www.sekisuihouse.com.au/about-sekisui-house.
### Table 1. Practices of the enterprise’s green production

| Industry          | The practice of green production                                                                                                                                                                                                 |
|-------------------|------------------------------------------------------------------------------------------------------------|
| Automobile        | SAIC General Motors promotes the strategy of “greening the future”. Buick and Chevrolet’s 1.2L–1.6L vehicles are equipped with EcotecDVVT and S-TEC engines. Compared with the products of the same level, the manual gearboxes are high performance and fuel-efficient(https://www.saic-gm.com/www/web/saic-gm/satep.). |
| Household appliance | Philips uses green technology ranging from energy-saving lighting to TV. Compared with traditional products, its energy-saving bulbs can save 80% of electrical energy and provide sustainable lighting solutions(https://www.philips.com.cn/a-w/about-philips/sustainability.html.) |
| Commodity         | Procter & Gamble reduces the use of materials by 10% through the optimization of packaging material and the weight of each diaper is greatly decreased by technological innovation (https://www.pg.com.cn/Csr/Product.aspx.). The role of agricultural green production technologies (AGPTs) adoption rates improves low-carbon efficiency in China [8]. Green production is widely mentioned in the field of agriculture [9,10]. |
| Agriculture       | Decarburization technology leads the development of green steel [11]. |
| Steel production  | Environmental performance in the metal processing industry could be improved by green technologies (process modifications and management practices) [12]. |
| Metal processing  | H&M, Marks & Spencer, and Levi’s, have produced low-carbon products using new technology to reduce carbon emissions during production [13,14]. |

The contributions of our research lie in three aspects:

Firstly, many existing studies focus on the quality difference between the green and non-green products without considering the discrepancy in the fixed cost related to the production [15,16]. This paper considers the difference in quality and cost and investigates the influence of quality difference on decisions and profits.

Secondly, many existing studies focus on the problem of product-line design and pricing [15–18]. However, the division and coordination of customer market based on green product quality, pricing and product-line design strategy are not studied. We consider two production modes and identify the optimal product type from the manufacturer’s perspective by incorporating quality difference and market segmentation into consumer demand. Moreover, we explore the effects of the quality difference between the non-green and green products. This work not only investigates the impact of quality difference on prices, green effort and profit, but also analyses the impact of product quality on consumer surplus.

Finally, many existing studies about supply chain contracts lack the division of customer market, pricing and product-line design strategy based on green product quality [19–24]. We study customer market division and product-line design based
on green product quality and discuss two types of cooperative contracts about green innovation.

The organization is as follows. Section 2 briefly reviews relevant literature. In section 3, we present the model description, market segments, consumers' characteristics and product-line strategies. In Section 4, we carry on the Model building and analysis. Section 5 presents the extended analysis by considering cooperative contracts to induce the production of green products. In Section 6, we carry on the numerical study. Finally, we discuss the conclusion and future researches in Section 7.

2. Literature review.

2.1. Product-line design, green level and pricing strategy. Due to the rapid increase of environmental awareness, environment-friendly products are one of the sought-after among consumers [25, 26]. Hence, more traditional firms consider a managerial decision on product-line design to meet the demand of environmentally conscious consumers and strengthen their brand image. At present, Goli et al. [27] obtains that product portfolio optimization (PPO) is a strategic decision of many organizations. Goli et al [28] explore a fuzzy Mixed Integer Linear Programming model is designed for Cell Formation Problem including the scheduling of parts within cells in a Cellular Manufacturing System where several Automated Guided Vehicles are in charge of transferring the exceptional parts. Goli and Malmir [29] optimize the allocation of resources among individuals. Pahlevan Goli et al. [30] design a sustainable closed-loop supply chain network for the aluminum industry. Goli et al. [31] and Goli et al. [32] study the accurate prediction of demand for dairy products (DDP). Moreover, Chen et al. [17] look into how the production cost and output distribution of the technology impact a firm’s product line decision when operating a vertical cop-product technology. Yenipazarli and Vakharia [33] explore the pricing mechanism of a new green product that a company is considering expanding its brown product line in response to environmental pressures and market coverage. And they find that, compared with a single pricing plan, the two-tier pricing structure can achieve market coverage expansion, or even completely avoid cannibalization. Ozinci et al. [34] investigate the problem of pricing of agri-food where one retailer or two competing retailers providing organic and traditional agricultural product. And they consider the difference between product utility and product shelf life, and further investigate whether retailers can obtain benefits by investing in customer travel costs that are directly affected by product shelf life. Additionally, Zhang et al. [18] study firms’ fraudulent behavior in product’s environmental attributes and decision-making of the product choice. Their results show that the investment-to-value ratio and the unit production cost for green products have a significant impact on manufacturers’ product line decisions. Shen et al. [15] develop a differential game model to investigate the strategic choice of the manufacturer concerning offering green or traditional versions of the product under three product-line design strategies. Furthermore, Zhang et al. [35] consider the problem of the type of product and the channel structure that is the manufacturer whether to introduce the green product into the market and distribute through the same or the separate retailer. Zou et al. [16] mainly explore a firm’s optimal product line design in the presence of consumers’ anticipated regret—under-purchase regret and over-purchase regret due to the valuation of the product quality is uncertain before purchase but will be understood after purchase. Zhang et al. [36] study a
triple-channel system in which a manufacturer operates a conventional channel, a direct online channel, as well as increases its online presence with an online shopping platform. Mizgier et al. [37] study a multi-objective model for the allocation of capital for supplier development with risk. Mizgier et al. [38] introduce an agency-based supply chain network model that represents the real economic environment in which the company operates. And based on simulations, they show that agent-based modeling is a powerful tool for optimizing supply chain networks.

In the aspect of the sustainable supply chain, green level and pricing strategy, Tirkolaee et al. [39] consider environmental standards to study green supply chain management (GSCM). In order to meet the requirements and comply with environmental regulations, a hybrid method based on fuzzy logic is proposed for sustainable supplier selection [40]. At present, Sinayi and Rasti-Barzoki [41] examine the impacts of cooperation between the manufacturer and retailer towards pricing and greening level of the product from economic, social and environmental dimensions, and consider the government intervening with tax or subsidy on the final price of the product. They confirm that cooperation always leads to produce a higher green level product and different government policies can contribute to the performance of the supply chain members as well as on the environment. Chen et al. [42] formulate and solve a model for firms’ strategic decisions as well as the supply chain’s sustainability performance that incorporates the technological spillover, supply chain power relationship and green R&D cooperation behavior. Furthermore, they employ a two-part tariff contract to coordinate the green supply chain under the same setting. Moreover, Yu et al. [43] develop four types of R&D collaboration contracts, consisting of vertical R&D collaboration contracts and co-development contracts, in order to explore which collaboration mode is more valuable and efficient for green technological innovation. They show that no R&D collaboration strategy always prevails over other strategies from the marketer’s perspective. Additionally, Zhu et al. [44] study the green investment decision of the enterprises under duopoly competition to cope with the pressure of resource consumption and ecological problems. Furthermore, Zu et al. [45] study the optimal pricing strategies and the energy efficiency efforts under the governmental grading standard, and examine the influences of discontinuous market demand on the strategies of firms. Tirkolaee and Weber [46] establish a robust mixed-integer linear programming model for green vehicle routing problems with the intermediate depot, considering different urban traffic conditions, fuel consumption, service time Windows and uncertain demand for perishable products.

In this paper, product-line design, green level and pricing related research positioning are summarized in Table 2. Most of the previous studies focused on the green level of products and pricing research based on the green practices of enterprises. However, there is a lack of research on market segmentation based on customer green preferences and product quality differentiation. Our paper fills the gap of the previous research.

2.2. Quality-based model in sustainable supply chain management. The second stream of research relevant to our work is quality differentiation between green and non-green products. At present, Chen [47] focus on strategic decisions regarding the number of products introduced and their prices and qualities by considering the impact of green and non-green product quality on consumers’ purchase decision. After that, he studies the impact of the environmental standards imposed by governments and finds that improving environmental benefits may not be
achieved by implementing green product development and stricter environmental standards. Zhang et al. [48] discuss the effects of government subsidies on firms’ product strategies that can provide greater incentives for green product development. They emphasize that firms can change their primary product design through effective subsidy policies, and higher profits and total environmental quality can be achieved as well. Moreover, Gouda et al. [49] investigate an automaker’s decision in quality during the design and product development stages to separate markets without cannibalization and the effect of composite regulations. Additionally, Murali et al. [50] explore the effects of eco-labels and environmental regulation on green product development with two mechanisms. The first mechanism is voluntary external certifications and the second one is mandatory regulation. The obtained results show that it is possible to allow external certification in place of regulation if the firm is sufficiently credible, which provides insights for the formulation of government policy. Furthermore, Shen et al. [15] examine the impacts of quality difference towards the product-line design of the manufacturer from the perspective of profit, consumer surplus, environmental impact and social welfare.

In this paper, the quality-based model in sustainable supply chain management related research positioning is summarized in Table 2. Specially, the most of aforementioned studies focus on the quality differentiation between the green and non-green products without considering the fixed cost related to the production, which is the main feature that this paper differs from them. In addition, our paper fills the research on market segmentation based on customer green preferences and product quality differentiation. Moreover, we consider the variable cost related to green innovation effort if the manufacturer decides to manufacture the green product. Furthermore, we study the effect of the fixed production cost on manufacturers’ product-line design strategies.

2.3. Supply chain coordination. The last stream of studies is on the coordination mechanism among disparate partners within the supply chain, which has been widely discussed due to the double marginalization effect of the supply chain. Particularly, cost-sharing contracts have been proved to be effective in coordinating supply chains involving high investment [51, 52]. At present, Xu et al. [19] investigate the production and coordination problem with wholesale price and cost-sharing contracts of a Make-To-Order supply chain under cap-and-trade regulation. They show that both contracts can coordinate the supply chain, and wholesale price contract is stronger in terms of weakening the double marginalization. Zhou and Ye [20] analyze the cooperative advertising contract and the cooperative advertising and emission reduction cost-sharing contract, and further investigate how they impact the joint emission reduction effort in a dual-channel supply chain under a low-carbon environment. They confirm that the latter is more efficient than the former under certain conditions. Moreover, He et al. [21] establish three differential game models to explore the optimal decisions in a service supply chain consisting of a service provider and a service integrator. Their findings demonstrate that sharing SP’s emission reduction cost or service cost can benefit the entire service supply chain and its members. In addition, most previous studies apply the revenue-sharing contract to enhance the channel performance. Additionally, Li et al. [22] discuss how to make the Pareto improvement by employing a revenue-sharing contract when the retailer exhibits fairness concerns if his share of total profit is low. They find that the revenue-sharing contract can attain a win-win situation under
certain conditions. Yang et al. [23] explore the effect of revenue-sharing and cost-sharing offered by a retailer on a manufacturer’s emission abatement effort when consumers exhibit environmental awareness and carbon tax arises. Furthermore, Moon et al. [24] study the optimal investment decisions in a supply chain of fresh agricultural products under the impact of fairness indices, and revenue sharing coupled with investment cost-sharing and quantity discount contract is proposed to achieve a win-win outcome.

In this paper, supply chain coordination related research positioning are summarized in Table 2. Similar to the works above, this paper also contributes to the second group of literature. Specially, our research makes up the effect of the different cooperative schemes on manufacturers’ product-line design strategies with market segmentation based on customer green preferences and product quality differentiation. In our study, the retailer has the awareness to cooperate with the manufacturer to take on the green innovation cost generated by manufacturing green products. Besides, we analyse the advantage of cost-sharing and revenue-sharing contracts under different circumstances. The analysis results can provide insights for the retailer to set an appropriate cooperative scheme, which further stimulates green production and improves the economic benefit.

The difference between our research and the above-mentioned scholars’ research are shown in Table 2, which will also reflect our understanding and further improvement of the existing technology-intensive supply chain research issues.

Notes: Y refers to “considered”, N refers to “not considered” in Table 2.

3. Model framework.

3.1. The supply chain structure, product quality and costs. In this paper, we consider a two-echelon supply chain that consists of an upstream manufacturer (denoted as “m”) and a downstream retailer (denoted as “r”). The products can be manufactured in two versions, the non-green or the green versions. The manufacturer currently only produces non-green products and distributes them through the retailer. In response to regulatory pressure from the government and consumer preferences for green products, the manufacturer considers the product-line design, i.e., whether to produce the green version of the product. Investing in green research and development is required to launch green products. \( C(e) \) represents the R&D cost and the higher the level of the green innovation is, the greater the R&D cost is. According to Atasu and Subramanian [53] and Chen et al. [54], we define the green R&D investment cost using a quadratic function of the green level of the product, i.e., \( C(e) = ke^2 \), where \( k > 0 \) is the cost coefficient of the green investment and \( e \) is the green degree. In the meantime, we assume that the non-green products need not R&D investment because of the ample expertise in previous operations.

We use \( q_g(q_n) \) and \( c_g(c_n) \) to denote the product quality and the unit production cost of the green (non-green) products, respectively, and reasonably assume that \( q_g > q_n \). Namely, the product quality of the green products is higher than that of the non-green products. In addition, the materials used to produce green products are generally more expensive than those used to produce non-green products [33, 55]. Hence, we assume that \( c_g > c_n \). Following Lim et al. [56], this paper assumes that \( q_i > c_i \) and considers the manufacturer’s production cost only and ignores inventory or transportation cost.
### Table 2. Relative running time of the considered filters

| Paper                          | Product-line design | Green level | Pricing strategy | Quality-based model | Coordination | Game theory |
|-------------------------------|---------------------|-------------|------------------|---------------------|-------------|-------------|
| Chen et al. [17]              | Y                   | N           | Y                | N                   | N           | N           |
| Yenipazarli and Vakharia. [33]| N                   | N           | Y                | N                   | N           | Y           |
| Ozinci et al. [34]            | N                   | N           | Y                | N                   | N           | Y           |
| Zhang et al. [18]             | Y                   | Y           | Y                | N                   | N           | N           |
| Shen et al. [15]              | Y                   | N           | Y                | N                   | N           | Y           |
| Zhang et al. [35]             | N                   | N           | Y                | N                   | N           | Y           |
| Zou et al. [16]               | Y                   | N           | Y                | N                   | Y           | Y           |
| Tirkolaee et al. [39]         | N                   | Y           | N                | N                   | N           | N           |
| Sinayi and Rasti-Barzoki. [41]| N                   | Y           | Y                | N                   | Y           | Y           |
| Chen et al. [42]              | N                   | Y           | Y                | N                   | Y           | Y           |
| Yu et al. [43]                | N                   | N           | Y                | N                   | Y           | Y           |
| Zhu et al. [44]               | N                   | Y           | Y                | N                   | N           | Y           |
| Zu et al. [45]                | N                   | N           | Y                | N                   | N           | Y           |
| Chen. [47]                    | N                   | N           | Y                | N                   | N           | Y           |
| Zhang et al. [48]             | N                   | N           | Y                | N                   | N           | Y           |
| Gouda et al. [49]             | N                   | Y           | Y                | N                   | N           | Y           |
| Murali et al. [50]            | N                   | N           | Y                | N                   | N           | Y           |
| Xu et al. [19]                | N                   | N           | Y                | N                   | N           | Y           |
| Zhou and Ye. [20]             | N                   | N           | Y                | N                   | N           | Y           |
| He et al. [21]                | N                   | N           | Y                | N                   | N           | Y           |
| Li et al. [22]                | N                   | N           | Y                | N                   | N           | Y           |
| Yang et al. [23]              | N                   | N           | Y                | N                   | N           | Y           |
| Moon et al. [24]              | N                   | N           | Y                | N                   | N           | Y           |
| Our paper                     | Y                   | Y           | Y                | Y                   | Y           | Y           |

#### 3.2. Market segments and consumers’ characteristics

We consider the consumers composed of two segments: the green and the non-green segments. Due to the preference for the green characteristic of the product, the consumers in the green segment tend to purchase the green product. We consider the fraction $\theta \in [0,1]$ of the consumers are environmentally conscious and would like to pay more for the product with a higher green level. And the remaining $1-\theta$ of the market belongs to the non-green segment. They do not have a preference for the green characteristic of the product because of the price and ignorance.

Consumer’s valuation from purchasing product is $v$, which is uniformly distributed in the interval $[0,1]$, and they can purchase at most one unit of the good. Following Guo and Zhang [57] and Shen et al. [15], we incorporate quality into the consumer utility function. The non-green products are valued at $q_nv$ and the green products are valued at $q_gv$ by the consumer in both market segments.

We use notation $U_{ns}^N(U_{gs}^N)$ and $U_{gs}^N(U_{gs}^G)$ to represent the utilities of the consumers in the non-green and green segments. As a consequence, the utility function has degenerated to the following expression, $U_{ns}^N = U_{gs}^N = q_nv - p_n$, $U_{gs}^G = q_gv - p_g$ and $U_{gs}^G = q_gv - p_g + \gamma e$.

#### 3.3. Product-line strategies

There are two product-line design strategies (The product-line design is shown in Fig.2.) for the manufacturer: (1) continually selling the non-green products (N scenario) and (2) removing the non-green products and
offering the green products (G scenario). Following the method used by Hsiao and Chen [58], and Zhang et al. [59], we use \( D_n \) and \( D_r \) to denote the demand for non-green products and green products, respectively. Based on the above reasoning, we obtain the demands for each scenario.

In the N scenario, consumers from both the non-green and green market segments will buy the product if and only if the utility is positive. Proof. See Appendix. Proof of A1. The market demand for non-green products is denoted as:

\[
D_n = 1 - p_n/q_n
\]

Similarly, in the G scenario, consumers from both the non-green and green market segments will buy if the utility is positive. Proof. See Appendix. Proof of A2. The market demand for green products is denoted as:

\[
D_g = \theta(1 - (p_g - \gamma e)/q_g) + (1 - \theta)(1 - p_g/q_g) = 1 - (p_g - \theta \gamma e)/q_g
\]

Table 3 summarizes the notations used in this paper.

### Table 3. Notations for model parameters

| Abbreviations | Description |
|---------------|-------------|
| \( N/n \)    | The production of the non-green product |
| \( G/g \)    | The production of the green product |
| \( m \)       | The manufacturer |
| \( r \)       | The retailer |
| Variables     |                                    |
| \( w_i \)     | The unit wholesale price of the product \( i \), where \( i = n, g \) |
| \( p_i \)     | The unit retail price of the product \( i \), where \( i = n, g \) |
| \( e \)       | Green effort of the green product |
| Parameters    |                                    |
| \( q_i \)     | Product quality for the product \( i \), where \( i = n, g \) |
| \( c_i \)     | The unit production cost for the product \( i \), where \( i = n, g \) |
| \( v \)       | Consumer’s willingness to pay for the product |
| \( k \)       | Coefficient of manufacturer’s green R&D effort cost |
| \( \gamma \)  | Sensitivity coefficient of green R&D effort to market demand, \( \gamma > 0 \) |
| \( \theta \)  | The proportion of green consumers in the market |
| Functions     |                                    |
| \( U_{ns}^j \) | Consumer’s utility obtained from the product \( j \) in the non-green segment, where \( j = N, G \) |
| \( U_{gs}^j \) | Consumer’s utility obtained from the product \( j \) in the green segment, where \( j = N, G \) |
| \( D_i \)     | Demand for the product \( i \), where \( i = n, g \) |
| \( \pi_{ms}^j \) | The profit of the manufacturer from producing the product \( j \), where \( j = N, G \) |
| \( \pi_{rs}^j \) | The profit of the retailer from selling the product \( j \), where \( j = N, G \) |
| \( CS^j \)    | Consumer surplus obtained from purchasing the product \( j \), where \( j = N, G \) |
4. **Model building and analysis.** In this paper, we use a Stackelberg game-theoretical method to solve the problem. To be specific, the leader has the first-mover advantage, and the follower must make the decisions after the leader. The game sequence can be stated as follows:

- **Step 1.** The manufacturer designs the product-line and sets the wholesale price and the green level if she decides to produce the green product.
- **Step 2.** The retailer decides the retail price.

From the firm’s perspective, green investment is more strategic and longer-term than the pricing decision. Thus, the manufacturer and the retailer sequentially make the operational decisions on price according to the green investment decision. This decision sequence assumes that the manufacturer is the leader, followed by the downstream retailer.

The problem is solved through backward induction. The specific steps are shown as follows:

1. Solve the follower’s decision to get the optimal solution;
2. Given the optimal solution of the follower, solve the decision of the dominant player and get the optimal solution.

The detail sequence of events is shown in Fig. 1.

![Figure 1. The flow diagram of implement methodology](image-url)

The specific process of green and non-green product-line design and the sequence of events are shown in Fig. 2.
4.1. N scenario: non-green product. We analyze the N scenario as a benchmark that the manufacturer only manufactures non-green products, the profit functions of the manufacturer and the retailer are as follows, respectively.

\[
\pi^N_m = (w_n - c_n)(1 - p_n/q_n) \tag{3}
\]

\[
\pi^N_r = (p_n - w_n)(1 - p_n/q_n) \tag{4}
\]

In general, companies should consider not only their economic benefits in long-term operations, but also the sense of welfare that consumers obtain from purchasing. Consumer surplus (CS) refers to the difference between the highest price that consumers are willing to spend minus the market price, which measures the additional benefits that the buyer feels and gains [60]. Therefore, it is necessary to study the influence of consumer surplus on the product type.

Following several previous studies [61, 62], consumer surplus in the N scenario can be formulated as follows:

\[
\int_{p_n/q_n}^{q_n} (q_n v - p_n) dv = (q_n v - p_n) dv = (q_n - p_n)^2/(2q_n) \tag{5}
\]

Proposition 1. In the N scenario, the optimal equilibrium solutions are shown as follows: Proof. See Appendix. Proof of Proposition 1.

\[
w_n = (q_n + c_n)/2; p_n = (3q_n + c_n)/4; D_n = (q_n - c_n)/(4q_n); \pi^N_m = (q_n - c_n)^2/(8q_n); \pi^N_r = (q_n - c_n)^2/(16q_n); CS^N = (q_n - c_n)^2/(32q_n).
\]

Under the non-green product scenario, we can see that the supply chain members’ pricing and profits are functions of the product quality \( q_n \).

Corollary 1. For the N scenario, the influence of parameter \( q_n \) on the optimal decisions and profits are shown as follows: Proof. See Appendix. Proof of Corollary 1. \( \partial w_n/\partial q_n > 0; \partial p_n/\partial q_n > 0; \partial D_n/\partial q_n > 0; \partial \pi^N_m/\partial q_n > 0; \partial \pi^N_r/\partial q_n > 0. \)
Corollary 1 shows that the influence of $q_n$ on the prices, production quantity and the firm’s profit is consistent. Because the demand is influenced by the product quality and the retail price, and the negative impact of the retail price on demand $(1/q_n)$ is greater than the positive impact of quality on demand $(3q_n + c_n)/(4q^2_n)$. Meanwhile, the retail price increases with the product quality. As the positive impact of the product quality on retail price weakens its negative impact on demand $(1/q_n \rightarrow 3/(4q^3_n))$, the positive impact of quality on demand occupies a dominant position. Therefore, the higher the product quality is, the more products will be sold. In addition, the increasing product quality increases the manufacturer’s desire to gain profit from the retailer by setting a higher wholesale price, and in turn, leads to a higher retail price. Accordingly, the market share has expanded and more profit has been achieved by the improvement of the product quality. It illustrates that higher product quality may always be desirable.

4.2. G scenario: Green product. In the G scenario, the manufacturer only produces green products. The profit functions of the manufacturer and the retailer are as follows, respectively.

$$\pi^G_m = (w_g - c_g)(1 - (p_g - \theta \gamma e)/q_g) - ke^2$$

$$\pi^G_r = (p_g - w_g)(1 - (p_g - \theta \gamma e)/q_g)$$

Meanwhile, consumer surplus contains the surpluses from the purchase decision by environmentally conscious and ordinary consumers, which can be formulated as follows:

$$\theta \int_{(p_g-\gamma e)/q_g}^{1} (q_g v - p_g + \gamma e) dv + (1 - \theta) \int_{p_g/q_g}^{1} (q_g v - p_g) dv$$

$$= ((q_g - p_g)^2 + \theta(\gamma e)^2 + 2\theta \gamma e(q_g - p_g))/(2q_g)$$

Proposition 2. In the G scenario, given $\rho > \rho_0$, the optimal equilibrium solutions are as follows: Proof. See Appendix. Proof of Proposition 2.

$$e = \theta q_g - c_g)/(8kq_g - \gamma^2 \theta^2); w_g = (4kq_g^2 + (4kq_g - \gamma^2 \theta^2)c_g)/(8kq_g - \gamma^2 \theta^2); p_g = (6kq_g + (2kq_g - \gamma^2 \theta^2)c_g)/(8kq_g - \gamma^2 \theta^2); D_g = (2kq_g - c_g)/(8kq_g - \gamma^2 \theta^2); \pi^G_m = (k(q_g - c_g)^2)/(8kq_g - \gamma^2 \theta^2); \pi^G_r = (4k^2q_g(q_g - c_g)^2)/(8kq_g - \gamma^2 \theta^2); CS^G = ((q_g - c_g)^2(\gamma(1 - \theta)^2 + 4kq_g^2))/(2q_g(8kq_g - \gamma^2 \theta^2)^2)$$

To derive structural results, we refer to $\rho \equiv k/r^2$ as the investment return or the investment-to-value ratio for green products. A low value of $\rho$ indicates a higher level of green investment return, meaning that the smaller is the cost of green investment, and the greater is the consumer willingness to pay. We denote $\rho_0 \equiv \theta^2/(8q_g)$, thus $\rho > \rho_0$ is the feasible condition for the G scenario.

Next, we analyze how the product quality impacts the supply chain members’ performances in the following Corollary 2.

Corollary 2. For the G scenario, the influence of parameter $q_n$ on the optimal decisions and profits are as follows: Proof. See Appendix. Proof of Corollary 2.

1. $\partial e/\partial q_n > 0$ and $\partial D_g/\partial q_n > 0$ if $\rho > \rho_1$; otherwise, $\partial e/\partial q_n < 0$ and $\partial D_g/\partial q_n < 0$ if $\rho_0 < \rho < \rho_1$.
2. $\partial w_g/\partial q_n > 0$ and $\partial p_g/\partial q_n > 0$ if $\rho > \rho_2$; otherwise, $\partial w_g/\partial q_n < 0$ and $\partial p_g/\partial q_n < 0$ if $\rho_0 < \rho < \rho_2$.
3. $\partial \pi^G_m/\partial q_n > 0$ if $\rho > \rho_3$; otherwise, $\partial \pi^G_m/\partial q_n < 0$ if $\rho_0 < \rho < \rho_3$.
4. $\partial \pi^G_r/\partial q_n > 0$ if $\rho > \rho_4$; otherwise, $\partial \pi^G_r/\partial q_n < 0$ if $\rho_0 < \rho < \rho_4$. 
where \( \rho_1 = \theta^2/(8c_g) \), \( \rho_2 = 2\theta^2/(8q_g^2) \), \( \rho_3 = 2\theta^2/(8q_g^2) \), \( \rho_4 = 2\theta^2/((q_g + c_g)) \).

Different from Corollary 1, Corollary 2 illustrates that a higher product quality may not always be desirable. For green products, it shows that the impact of the product quality on the optimal decision and profit depends on the efficiency of the R&D. When environmentally-minded consumers obtain an additional valuation from purchasing green products, both the optimal prices and the order quantity increase with the product quality if the investment-to-value ratio is sufficiently high. This finding reveals that when the efficiency of the R&D is sufficiently low, enhancing product quality makes the manufacturer raise the wholesale price for chasing more profit. And the retailer sets an increased retail price for the sake of transferring the cost of wholesale trading. Meanwhile, raising product quality improves green innovation efforts, and it also promotes sales volume. Thus, the profits of both enterprises rise. Otherwise, product quality will reduce the prices, sales volume and profits.

Corollary 3. For the G scenario, the influence of other parameters on the optimal decisions and profits are shown as follows: Proof. See Appendix. Proof of Corollary 3. (1) \( \partial e/\partial k < 0, \partial w_g/\partial k < 0, \partial p_g/\partial k < 0, \partial D_g/\partial k < 0, \partial q_g^G/\partial k < 0, \partial \pi^G_r/\partial k < 0 \).

(2) \( \partial e/\partial \gamma > 0, \partial w_g/\partial \gamma > 0, \partial p_g/\partial \gamma > 0, \partial D_g/\partial \gamma > 0, \partial q_g^G/\partial \gamma > 0, \partial \pi^G_r/\partial \gamma > 0 \).

(3) \( \partial e/\partial \theta > 0, \partial w_g/\partial \theta > 0, \partial p_g/\partial \theta > 0, \partial D_g/\partial \theta > 0, \partial q_g^G/\partial \theta > 0, \partial \pi^G_r/\partial \theta > 0 \).

It can be seen from Corollary 3 that both parties will benefit from a decreased \( k \), an increased \( \gamma \) and an increased \( \theta \). When the R&D investment coefficient \( k \) is greater, it means that R&D requires more investment to achieve the same degree of green. Consequently, the manufacturer tends to set a lower green level. At the same time, a lower pricing strategy is strategically chosen, which serves as a reminder that a higher green investment may not always be desirable. In contrast, when \( \gamma \) or \( \theta \) is greater, the additional demand arising from the green attributes of the product can always promote the green effort. In response, the supply chain members will set a higher price to increase revenue, which implies that consumer education regarding green awareness is essential.

4.3. Comparative analysis of product-line strategies. In this section, we use the notation \( \Delta q = q_g - q_n \), \( \Delta c = c_g - c_n \) to represent the differentiation of the quality and the unit production, respectively.

Corollary 4. Proof. See Appendix. Proof of Corollary 4.

(1) The wholesale prices are related as follows:

(i) when \( q_n \geq 2c_g - c_n, w_g > w_n \).

(ii) when \( q_n < 2c_g - c_n, w_g \geq w_n \) if \( 0 < \gamma \leq t_1 \), otherwise, \( w_g < w_n \) if \( \gamma > t_1 \).

where \( t_1 = 1/\theta \sqrt{(-(8kq_g(\Delta q + \Delta c))/(q_n + c_n - 2c_g))} \).

(2) The retail prices are related as follows:

(i) when \( 3q_n \geq 4c_g - c_n, p_g > p_n \).

(ii) when \( 3q_n < 4c_g - c_n, p_g \geq p_n \) if \( 0 < \gamma \leq t_2 \), otherwise, \( p_g < p_n \) if \( \gamma > t_2 \).

where \( t_2 = 1/\theta \sqrt{(-(8kq_g(3\Delta q + \Delta c))/(3q_n + c_n - 4c_g))} \).

(3) The demands are related as follows:

if \( 0 < \gamma \leq t_3 \), \( D_g \geq D_n \), otherwise \( D_g < D_n \) if \( \gamma > t_3 \).

where \( t_3 = \sqrt{(8k(q_gc_n + q_n c_g)/((\theta^2(q_n + c_n)))} \).

Corollary 4 (1), (2) confirms that a threshold exists such that the prices of the green products are smaller than those of the non-green products. A lower price for
green products is enjoyed by the supply chain members when the product quality of the non-green product is relatively low and consumers’ sensitivity to green level is relatively high. While the unit production cost of a green product is higher, the manufacturer has an incentive to provide them for the consumers’ acceptance of green products is relatively high. Otherwise, it is better to manufacture non-green products. Corollary 4 (3) particularly implies that the sales volume of the green product may be larger when consumers’ sensitivity to the green level is relatively small.

Now, we turn our attention to the profit. For notational convenience, let \( \Delta m_g = q_g - c_g, \Delta m_n = q_n - c_n \) and it is apparent that \( \Delta m_g > 0 \) and \( \Delta m_n > 0 \).

Corollary 5. Proof. See Appendix. Proof of Corollary 5.

1) The manufacturer’s profits are related as follows:
   \[ \frac{\Delta m_g}{\Delta m_n} > t_4, \pi^G_m > \pi^N_m, \text{otherwise, if } 0 < \frac{\Delta m_g}{\Delta m_n} \leq t_4, \pi^G_m \leq \pi^N_m. \]
where \( t_4 = \sqrt{(8kq_g - \gamma^2\theta^2) / (8kq_n)} \).

2) The retailer’s profits are related as follows:
   \[ \frac{\Delta m_g}{\Delta m_n} > t_5, \pi^G_r > \pi^N_r, \text{otherwise, if } 0 < \frac{\Delta m_g}{\Delta m_n} \leq t_5, \pi^G_r \leq \pi^N_r. \]
where \( t_5 = (8kq_g - \gamma^2\theta^2) / 8k \sqrt{1 / (q_g q_n)} \).

Corollary 5(1), (2) illustrates that the parameter \( \frac{\Delta m_g}{\Delta m_n} \) plays a significant role in the product-line design. From the point of the manufacturer, manufacturing green products is desirable when the threshold is relatively large, i.e., \( \frac{\Delta m_g}{\Delta m_n} > t_4 \). It is notable that \( t_4 \) is always larger than \( t_5 \). That is, comparing with the manufacturer, the retailer will be more likely to choose green products and obtain higher profit since the equilibrium region of the green products is larger. The result also implies that the high cost of green technology is one of the main reasons why the manufacturer is reluctant to manufacture green products. And it is better to sell non-green products for both of them when the threshold is relatively small, i.e., \( \frac{\Delta m_g}{\Delta m_n} < t_5 \).

Corollary 6. The comparison of consumer surplus is shown as follows: Proof. See Appendix. Proof of Corollary 6.

If \( \frac{\Delta m_g}{\Delta m_n} > t_6, CS^G > CS^N \), otherwise, if \( 0 < \frac{\Delta m_g}{\Delta m_n} \leq t_6 \), \( CS^G \leq CS^N \).

where \( t_6 = (q_g (8kq_g - \gamma^2\theta^2)^2) / (16q_n (\gamma^4 (1 - \theta)\theta^3 + 4k^2q_n^2)) \).

Similar to Corollary 5, Corollary 6 shows that the parameter \( \frac{\Delta m_g}{\Delta m_n} \) plays an important role in product-line design when the firms care about consumer welfare. If \( \frac{\Delta m_g}{\Delta m_n} \) is less than the certain threshold, non-green products will be chosen by the manufacturer. Conversely, it will be more likely to encourage the firms to engage in green manufacturing.

5. Cooperative contract to induce production of green product. There is a possible split happening in product type preference for the supply chain members. And we explore the condition that the supply chain members agree with each other on product type.

Corollary 7. The product type preference of the manufacturer and the retailer are related as follows: The proof is the same as Corollary 5.

1) if \( \frac{\Delta m_g}{\Delta m_n} > t_4, \pi^G_m > \pi^N_m, \pi^G_r > \pi^N_r \).
2) if \( t_5 < \frac{\Delta m_g}{\Delta m_n} < t_4, \pi^N_m > \pi^G_m, \pi^G_r > \pi^N_r \).
3) if \( 0 < \frac{\Delta m_g}{\Delta m_n} < t_5, \pi^N_m > \pi^G_m, \pi^G_r > \pi^N_r \).

It can be concluded that there are two situations: (1) they both prefer the same type of products, (2) the manufacturer prefers non-green products while the retailer

\[ \]
prefers green products. In a special case that the supply chain members are divided based on the preference of the product when the threshold falls in a certain interval.

Corollary 8. Comparing with the manufacturer, the retailer is more inclined to obtain profit from green products. Proof. See Appendix. Proof of Corollary 8.

With respect to the distribution of profit, it clearly shows that the G scenario is better for the retailer due to \( \frac{\pi^G_m}{\pi^G_r} = \frac{\pi^N_r}{\pi^N_m} \), and the reason is that the green investment cost is borne by the manufacturer alone. The retailer can design contracts to prompt the traditional manufacturer to participate in green production. And we study the cost-sharing and the revenue-sharing contracts under the premise of the production of green products. The timeline of decision-making is as follows.

The retailer firstly decides the sharing ratio of the cooperation contract. Secondly, the manufacturer determines green innovation efforts and then sets the wholesale price. Finally, the retailer decides the retail price.

5.1. Cost-sharing contract. When the retailer and the manufacturer enter into a cost-sharing agreement (denoted as "CS"), the profit functions of the manufacturer and the retailer are denoted as follows:

\[
\begin{align*}
\pi^CS_m &= (w_g - c_g)(1 - (p_g - \theta \gamma e)/q_g) - (1 - \phi^CS)ke^2  \\
\pi^CS_r &= (p_g - w_g)(1 - (p_g - \theta \gamma e)/q_g) - \phi^CS ke^2
\end{align*}
\]

Proposition 3. For the given sharing parameter, if \( \rho > \theta^2/(8q_g(1 - \phi^CS)) \), the optimal equilibrium solutions are shown as follows: Proof. See Appendix. Proof of Proposition 3.

\[
e^{CS} = (\gamma \theta(q_g - c_g))/(8kq_g(1 - \phi^CS) - \gamma^2 \theta^2); w^{CS} = (4kq_g(1 - \phi^CS) - \gamma^2 \theta^2 c_g)/(8kq_g(1 - \phi^CS) - \gamma^2 \theta^2); p^{CS} = (2kq_g(3q_g + c_g)(1 - \phi^CS) - \gamma^2 \theta^2 c_g)/(8kq_g(1 - \phi^CS) - \gamma^2 \theta^2); D^{CS} = (2k(q_g - c_g)(1 - \phi^CS))/(8kq_g(1 - \phi^CS) - \gamma^2 \theta^2); \pi^{CS}_m = (k(q_g - c_g)^2(1 - \phi^CS))/(8kq_g(1 - \phi^CS) - \gamma^2 \theta^2); \pi^{CS}_r = (k(q_g - c_g)^2(4kq_g(1 - \phi^CS)^2 - \gamma^2 \theta^2))/(8kq_g(1 - \phi^CS) - \gamma^2 \theta^2)
\]

Corollary 9. When the retailer adopts the cost-sharing contract: Proof. See Appendix. Proof of Corollary 9.

\[
\begin{align*}
(1) &\partial \pi^CS / \partial \phi^CS > 0, \partial w^CS / \partial \phi^CS > 0, \partial p^CS / \partial \phi^CS > 0, \partial D^CS / \partial \phi^CS > 0, \partial \pi^CS_m / \partial \phi^CS > 0, \partial \pi^CS_r / \partial \phi^CS > 0. \\
(2) &\partial \pi^CS / \partial \phi^CS > 0 \quad \text{if} \quad \rho < \theta^2/(16q_g \phi^CS); \text{otherwise}, \partial \pi^CS / \partial \phi^CS < 0.
\end{align*}
\]

From Corollary 9, it can be concluded that the optimal green effort level always monotonously increases in the value of the cost-sharing parameter. Furthermore, a higher green effort level will lead to higher prices and demand. On the other hand, a higher sharing parameter is always beneficial for the manufacturer, but bad for the retailer sometimes. If the investment-to-value ratio is relatively low, the profit of the retailer increases. The reason is that the increase in the profit due to higher demand exceeds the amount of the R&D cost-shared by the retailer with the manufacturer. Otherwise, a higher cost-sharing parameter hurts the retailer’s profit. We further calculate the optimal cost-sharing parameter.

Proposition 4. If \( \rho > (3\theta^2)/(16q_g) \), the optimal equilibrium solutions are shown as follows: Proof. See Appendix. Proof of Proposition 4.

\[
\begin{align*}
\phi^{CS*} &= \gamma^2 \theta^2/(16kq_g); e^{CS*} = 2\gamma \theta(q_g - c_g)/(16kq_g - 3\gamma^2 \theta^2); w^{CS*} = (16kq_g(q_g + c_g) - \gamma^2 \theta^2(q_g + 3c_g))/(2(16kq_g - 3\gamma^2 \theta^2)); p^{CS*} = (q_g - c_g)(16kq_g - 3\gamma^2 \theta^2)/(4(16kq_g - 3\gamma^2 \theta^2)); \pi^{CS*}_m = (q_g - c_g)\n\end{align*}
\]
c_j^2(16kq_g-\gamma^2\theta^2)/(8q_g(16kq_g-3\gamma^2\theta^2)); \pi^{RS}_M = (q_g-c_g)^2(16kq_g+\gamma^2\theta^2)/(16q_g(16kq_g-3\gamma^2\theta^2)).

It is straightforward to show that as the R&D cost $k$ decreases or as the demand sensitivity to the green effort level $\gamma$ and the percentage of eco-concerned consumers $\theta$ increases, the green effort level, prices, demand and profit would increase.

5.2. Revenue-sharing contract. When the retailer and manufacturer enter into a revenue-sharing agreement (denoted as “RS”), the profit functions of the manufacturer and the retailer are denoted as follows:

$$\pi^{RS}_M = (w_g-c_g)(1-(p_g-\theta\gamma e)/q_g) + \phi^{RS}(p_g-w_g)(1-(p_g-\theta\gamma e)/q_g) - ke^2 \tag{11}$$

$$\pi^{RS}_r = (1-\phi^{RS})(p_g-w_g)(1-(p_g-\theta\gamma e)/q_g) \tag{12}$$

Proposition 5. For the given sharing parameter, if $\rho > \theta^2/(4q_g(2-\phi^{RS}))$, the optimal equilibrium solutions are shown as follows: Proof. See Appendix. Proof of Proposition 5.

$$e^{RS} = \gamma\theta(q_g-c_g)/(4kq_g(2-\phi^{RS})-\gamma^2\theta^2); w^{RS} = (4kq_g(1-\phi^{RS})q_g + c_g) - \gamma^2\theta^2\epsilon_c)/(4kq_g(2-\phi^{RS})-\gamma^2\theta^2); p^{RS} = (2kq_g((3-2\phi^{RS})q_g+c_g)-\gamma^2\theta^2\epsilon_c)/(4kq_g(2-\phi^{RS})-\gamma^2\theta^2); D^{RS} = k(q_g-c_g)/(4kq_g(2-\phi^{RS})-\gamma^2\theta^2); \pi^{RS}_M = k(q_g-c_g)^2/(4kq_g(2-\phi^{RS})-\gamma^2\theta^2)^2.$$.

Corollary 10. When the retailer adopts the revenue-sharing contract, the sensitivity analysis are as follows: Proof. See Appendix. Proof of Corollary 10.

(1) $\partial e^{RS}/\partial q_g > 0, \partial w^{RS}/\partial q_g < 0, \partial D^{RS}/\partial \phi^{RS} > 0, \partial \pi^{RS}_M/\partial \phi^{RS} > 0$.
(2) $\partial p^{RS}/\partial \phi^{RS} > 0$ if $\rho < \theta^2/(2q_g)$; otherwise, $\partial p^{RS}/\partial \phi^{RS} < 0$.
(3) $\partial \pi^{RS}_r/\partial \phi^{RS} > 0$ if $\rho < \theta^2/(4q_g\phi^{RS})$; otherwise, $\partial \pi^{RS}_r/\partial \phi^{RS} < 0$.

Corollary 10 indicates that the green effort level and demand always monotonously increase in the value of revenue sharing parameter. Furthermore, the manufacturer can reduce the wholesale price to secure additional profit-sharing from the retailer. Note that when the investment-to-value ratio is relatively low, the retail price is increasing as the value of the revenue sharing parameter increases. Conversely, the retailer would decrease the retail price in response to maintaining the demand for the product. In addition, a higher sharing parameter is not beneficial for the retailer. The profit of the retailer increases if the investment-to-value ratio is sufficiently low. This outcome occurs because the increase in the profit due to higher demand exceeds the profit shared by the retailer with the manufacturer. We further calculate the optimal revenue sharing parameter.

Proposition 6. If $\rho > \theta^2/(4q_g)$, the optimal equilibrium solutions are shown as follows: Proof. See Appendix. Proof of Proposition 6.

$$\phi^{RS} = \gamma^2\theta^2/(4kq_g); e^{RS} = \theta(3q_g-c_g)/(2(4kq_g-\gamma^2\theta^2)); w^{RS} = (q_g+c_g)/2; p^{RS} = (2kq_g(3q_g+c_g)-\gamma^2\theta^2)/(2(4kq_g-\gamma^2\theta^2)); D^{RS} = (k(q_g-c_g))/((4kq_g-\gamma^2\theta^2))^2; \pi^{RS}_M = (k(q_g-c_g)^2)/(4(4kq_g-\gamma^2\theta^2)).$$

It can easily verify that a decrease in R&D cost $k$ or an increase in demand sensitivity to the green effort level $\gamma$ and the percentage of eco-concerned consumers $\theta$ would lead to an increment in the green effort level, equilibrium retail price, demand and profit.

5.3. Performance comparison of cooperative contracts. In this section, we examine the efficiency of the two contracts and find the results that crucially depend on the green investment efficiency.
Corollary 11. The equilibrium results are related as follows: Proof. See Appendix. Proof of Corollary 11.

(1) $\phi_{RS}^* > \phi_{CS}^*$.
(2) $e_{RS}^* > e_{CS}^*$.
(3) $w_{CS}^* > w_{RS}^*$.
(4) $p_{RS}^* > p_{CS}^*$ if $\rho < (3\theta^2)/(8q_g)$; otherwise, $p_{CS}^* > p_{RS}^*$.
(5) $D_{CS}^* > D_{RS}^*$ if $\rho < \theta^2/(8q_g)$; otherwise, $D_{RS}^* > D_{CS}^*$.
(6) $\pi_{m}^{RS} > \pi_{m}^{CS}$, $\pi_{r}^{RS} > \pi_{r}^{CS}$.

Corollary 11(1) shows that the optimal sharing parameter of the revenue-sharing contract is always higher. In addition, Corollary 11(2) and (3) indicate that the wholesale price under the revenue-sharing contract is lower while the green effort is higher, respectively. The rationale lies in the fact that under the cost-sharing contract, the enhancement of the green effort will correspondingly result in a higher wholesale price than the manufacturer charges. However, under the revenue-sharing contract, the manufacturer can incentivize the retailer to raise the revenue sharing ratio, consequently, leading to a lower wholesale price. Corollary 11(4) and (5) demonstrate that when the investment-to-value ratio is low, the retailer has more incentive to set a lower price under the cost-sharing contract. Hence, the demand for the product is higher. By contrast, when the investment-to-value ratio is high, the revenue-sharing contract will generate a lower retail price and a higher demand. Corollary 11(6) further concludes that both the manufacturer and the retailer prefer the revenue-sharing contract which brings the highest profit.

6. Numerical study. In this section, we provide a set of numerical studies to illustrate the theoretic results obtained in previous sections. Detailed product-line design strategy, pricing, green innovation effort comparison have been deduced and explained in Corollaries 1-11. In order to make readers further understand the strategy clearly, we selected some specific data for numerical simulation research. And the specific datasets do not affect the final analysis results. The values of the parameters are selected according to the earlier studies [15, 50, 63]. Furthermore, we set $c_g=0.6q_g$, $c_n=0.3q_n$, $\theta=0.5$, $\gamma=5$, $k=10$.

6.1. Impact of parameters $q_g$ and $q_n$. As shown in Fig.3, it can be observed that the green and non-green product’s quality differences play a more significant role in affecting the player’s product-line selection and product preference. The diagonal line indicates that there is no difference in the product quality. When the threshold is relatively large, i.e., $\triangle m_g/\triangle m_n>\tau_4$, it is beneficial to manufacture green products. As shown in the lower parameter region of Fig.3, when the quality of green products is low, the quality gap between green products and non-green products is larger with the increase of the quality of green products. Therefore, customers prefer green products, and the green product-line strategy will be superior. However, the non-green product will be the optimal choice when the threshold is relatively low. To be specific, as shown in the upper parameter region of Fig.3, it is better to manufacture non-green products if both products hold high quality.

Furthermore, the manufacturer and the retailer disagree on product preference when the threshold falls in a certain interval, i.e., $\tau_5<\triangle m_g/\triangle m_n<\tau_4$. And the manufacturer’s optimal product-line strategy may come at the expense of the retailer’s profit. Conversely, both of them are in favor of the same product type.

From Fig.4, it can be seen that when the quality of both products is relatively low, selling green products will generate a higher consumer surplus. Green products
are more likely to enable environmentally conscious consumers to obtain additional utility. On the contrary, when the two products are high quality or the quality of the two products differs significantly, it is more desirable to sell non-green products.

It is known from Fig.5 that the green effort decreases as the product quality increases. It shows that enhancing product quality is not conducive to promote the
green effort. Furthermore, the negative effect of product quality on the green effort in the cost-sharing contract is larger, and the green effort under the revenue-sharing contract is higher. However, according to Fig.6, more profit can be obtained if the product quality is enhanced. Furthermore, the profits under the revenue-sharing contract are higher, but the cost-sharing contract may be better for the retailer concerning the distribution of profit due to $\pi_{CS}^* / \pi_{m}^* > \pi_{RS}^* / \pi_{m}^*$.

6.2. Impact of parameters $k$, $\gamma$ and $\theta$. As shown in Fig.7-9, it is desirable to design green products only if the cost coefficient of the green investment is relatively low, consumers’ green preference, or the proportion of environmentally conscious consumers is relatively high. In addition, the profit threshold value $t_4$ always decreases with $\gamma$ and $\theta$, that is, the higher the consumers’ green preference and proportion of environmentally aware consumers are, the higher the profit that the manufacturer can obtain from green products. By contrast, $t_4$ always increases with $k$ and the manufacturer is easier to benefit from the green product-line design if the cost coefficient of the green investment is relatively low. Therefore, the government should strengthen publicity propaganda to improve the consumers’ environmental awareness. In addition, the government can subsidize the green technology investment to conduct green production.

7. Managerial insights and practical application. By comparing the manufacturer’s optimal product-line design strategy and optimal incentive mechanism, we derive several interesting managerial insights.

(1) The quality and the unit production cost differentiation affect the product pricing and wholesale price under the manufacturer’s different product-line strategies. Furthermore, the sales volume of the green product may be larger when
consumers' sensitivity to the green level is relatively small. Moreover, either green products are high quality and non-green products are low quality, or both are low quality, the manufacturer is more likely to obtain a higher profit from green products. Besides, the optimal green effort is always positively proportional to the green consumer segmentation and the consumers' green preference, negatively related to the coefficient of the R&D cost. Hence, the government and the firms should strengthen the propagation of environmental protection and green consumption.

(2) We refer to \( \rho \equiv k/r^2 \) as the investment return or the investment-to-value ratio for green products. A low value of \( \rho \) indicates a higher level of green investment return, meaning that the smaller the cost of green investment is and the greater the consumer's willingness to pay is. It shows that the impact of the product quality on the optimal decisions and profit depends on the efficiency of the R&D.

(3) Additionally, the retailer is inclined to obtain profit from green products. The revenue-sharing is a better incentive mechanism in terms of increasing the green innovation effort. If the investment-to-value ratio is relatively low, the profit of the retailer would increases, but a higher cost-sharing parameter hurts the retailer's profit. In addition, a higher sharing parameter is not beneficial for the retailer.

Next, we take Philips, an electronic and electrical enterprise with green design, as an example to illustrate our managerial insights.

To be specific, Philips is an electrical and electronic manufacturer belonging to Dutch brand, including color televisions, lighting, electric shavers, medical diagnostic images and patient monitoring devices. Since the 1990s, Philips has been continuously carrying out life cycle assessment (LCA), which measures the environmental impact of the enterprise on the whole society through the environmental profit and loss (EP&L) table, and uses the results of life cycle assessment to guide
the green design of products and obtain green solutions. The main practices are as follows:

Firstly, Philips continues to increase investment in green design and technologies, which verifies Management inspiration 2. In 2019, Philips invested 235 million euros in green design, in order to continuously increase the proportion of renewable and recyclable raw materials, strictly limiting the use of harmful substances. Lots of green products that do not contain polyvinyl chloride (PVC) and Brominated flame retardants (BFR) are developed, such as shavers, electric toothbrushes, air purifiers, maternal and child care, which reduces energy consumption. Moreover, the developed patient monitor consumes 18% less energy than its predecessor and reduces product and package weight by 11% and 25%, respectively. According to the annual report of Philips Group in 2019, the revenue of Philips’ green design products was 13.1 billion euros, accounting for 67.2% of the total sales, which is shown in Figure.10.

Secondly, Philips has strengthened the publicity and disclosure of information related to green design, which testifies Management inspiration 1. For example, Philips has set up an environment column on the enterprise website, introducing the green design concept, technology research and development progress, green production measures and emission data. Furthermore, Philips releases regular annual reports to publicize some information and data including the performance indicators of green products, green requirements on suppliers, green innovation and environmental performance. Besides, Philips also encourages the public to participate in green design, green manufacturing and green consumption as well as supervising enterprises.

8. **Conclusion.** In the context of increasing environmental pressure and green consumption, the product-line choice is influenced by consumer awareness of environmental protection and production conditions. In this study, we take quality
differentiation and market segmentation into account under two production strategies. Focusing on the optimal product-line design strategy and pricing decision, we derive the equilibrium solutions under each scenario and discuss the effect of the product quality on the decision-making of the supply chain. Based on the results, we analyze the product preference of the members and discuss two different cooperative contracts to induce the production of the green product. We also analyze the customer surplus under different product-line designs. Finally, we conduct numerical analysis to discuss the impacts of the product quality, market segmentation and cost coefficient of the green investment on production strategies.

The main conclusions and suggestions that are worth attention for the traditional manufacturer are as follows. The manufacturer is more likely to obtain a higher profit from green products. Both manufacturers and retailers prefer green product-line design strategy. Furthermore, the optimal green effort is always positively proportional to the green consumer segmentation and the consumers’ green preference, negatively related to the coefficient of the R&D cost. Hence, the government and the firms should strengthen the propagation of information regarding environmental protection. Additionally, the retailer is more inclined to obtain profit from green products. Furthermore, the revenue-sharing is more appropriate for collaboration in terms of the green innovation effort.

There are still some limitations in this paper and further research can be done in the following several avenues. First, our paper is restricted to a bilateral monopoly setting that consists of one manufacturer and one retailer. However, it would be interesting to examine how the competitive interactions between multiple manufacturers and retailers affect the manufacturer’s behavior in product-line design. Second, our models are established by assuming completely symmetric information and deterministic demand. It would be valuable to incorporate information asymmetry and demand uncertainty among supply chain members in future analyses. Finally, the government has implemented various regulatory policies to address environmental issues, such as cap-and-trade regulation and the carbon tax regulation. It would be worthy of examining the impact of different policies on the manufacturer’s product-line design.

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Appendix. Proof of A1. In the N scenario, consumers from both non-green and green market segment will buy the product if and only if the utility they derive from it is positive (i.e., \( q_n v - p_n > 0 \)). That is, only the customers with \( v > p_n / q_n \) will purchase.

Proof of A2. Similarly, in the G scenario, consumers from both non-green and green market segment will buy if the utility they derive from it is positive (i.e., \( q_g v - p_g > 0 \) and \( q_g v - p_g + \gamma e > 0 \)). That is, environmentally aware consumers with \( v > (p_g - \gamma e)/q_g \) will purchase and remaining consumers only purchase if and only if \( v \geq p_g / q_g \).

Proof of A3. In order to ensure that the relevant variables are non-negative, and the profit functions are concave for the decision variables, we make the following inequality assumptions, \( q_i > p_i > c_i (i = n, g) \), \( 8kq_g > \gamma^2 \theta^2 \), \( 8kq_g (1 - \phi^{CS}) > \gamma^2 \theta^2 \), and \( 4kq_g (2 - \phi^{RS}) > \gamma^2 \theta^2 \).

Proof of Proposition 1. In the Stackelberg game where the manufacturer is a leader and the retailer is a follower. The manufacturer determines the wholesale price and then the retailer sets the retail price. Following backward induction to obtain the equilibrium solutions of supply chain members, the response of the follower should be determined at first, the leader then determines the optimal decisions according to the follower’s response.

In this setting, the retailer first decides the optimal retail price \( p_n \) to maximize its own profit. From Equation(4), we can derive that \( \frac{\partial^2 \pi^N}{\partial p_n^2} = 2/q_n < 0 \)
\( \pi^N_r \) is a strict concave function for \( p_n \), and \( \pi^N_r \) has an optimal solution on \( p_n \). The first order derivative of profit \( \pi^N_r \) to retail price is shown as follows \( \partial \pi^N_r / \partial p_n = (q_n - 2p_n + w_n)/q_n \), let \( \partial \pi^N_r / \partial p_n = 0 \), we can get

\[
 p_n = (q_n + w_n)/2 \tag{A.1}
\]

Next, the manufacturer decides the wholesale price. We substitute the value of \( p_n(w_n) \) into the Equation (3), we obtain the second order derivative \( \partial^2 \pi^N_r / \partial w_n = -1/q_n < 0 \), so \( \pi^N_r \) is a strict concave function for \( w_n \), and it has an optimal solution on \( w_n \), let \( \partial \pi^N_r / \partial w_n = (c_n + q_n - 2w_n)/(2q_n) = 0 \), then we can get that

\[
 w_n = (q_n + c_n)/2 \tag{A.2}
\]

Substituting (A.2) into (A.1) and simplifying, we have

\[
 p_n = (3q_n + c_n)/4 \tag{A.3}
\]

Therefore, substituting them into the corresponding equations, we get the equilibrium results for \( N \) scenario as shown in Proposition 1.

Proof of Corollary 1. Under the \( N \) scenario, taking first order derivatives of optimal decisions and profits with respect to the quality of the non-green product \( q_n \), we can yield the following results:

Obviously, (1) \( \partial q_n / \partial q_n = 1/2 > 0 \), (2) \( \partial p_n / \partial q_n = 3/4 > 0 \), (3) \( \partial D_n / \partial q_n = c_n/(4q^2_n) > 0 \), (4) \( \partial \pi^N_r / \partial q_n = 1/(8q^2_n)(q^2_n - c^2_n) \), (5) \( \partial \pi^N_r / \partial q_n = 3/(16q^2_n)(q^2_n - c^2_n) \),

according to Assumption 2 that \( q_n > c_n \), we have \( q^2_n - c^2_n > 0 \), thus, \( \partial \pi^N_r / \partial q_n > 0, \partial \pi^N_r / \partial q_n > 0 \).

Proof of Proposition 2. Similar to the proof of Proposition 1, we first solve for the retailer’s profit to get the optimal retail price. From Equation (13), the second order derivative of the retailer’s profit \( \pi^G_r \) to the retail price \( p_g \) is shown as follows, \( \partial^2 \pi^G_r / \partial p_g^2 = -2/q_g < 0 \), hence, the retailer’s profit is strictly concave for \( p_g \). Using the first order conditions of \( \pi^G_r \), we can derive that \( \partial \pi^G_r / \partial p_g = (e\gamma \theta - 2p_g + q_g + w_g)/q_g \). Let \( \partial \pi^G_r / \partial p_g = 0 \), we can get

\[
 p_g = (e\gamma \theta + q_g + w_g)/2 \tag{A.4}
\]

Next, the manufacturer decides the wholesale price. We substitute the value of \( p_g(w_g) \) into the Equation (12), we obtain the second order derivative \( \partial^2 \pi^G_r / \partial w_g^2 = -1/q_g < 0 \), so \( \pi^G_r \) is a strict concave function for \( w_g \), and it has an optimal solution on \( w_g \), let \( \partial \pi^G_r / \partial w_g = (e\gamma \theta + c_g + q_g - 2w_g)/(2q_g) = 0 \), then we can get that

\[
 w_g = (e\gamma \theta + c_g + q_g)/2 \tag{A.5}
\]

Substituting (A.5) into (A.4) and simplifying, we have

\[
 p_g = (c_g + 3(e\gamma \theta + q_g))/4 \tag{A.6}
\]

Finally, the manufacturer decides the green level. Plugging Equation (A.5) and (A.6) into Equation (12), we get manufacturer’s profit \( \pi^G_m \) as follows, \( \pi^G_m = ((-e\gamma \theta + c_g)^2 - 2(e(4c_k - \gamma \theta + c_g)q_g + q^2_g)/(8q_g) \), the second order derivative of profit \( \pi^G_m \) to the green level is shown as follows \( \partial^2 \pi^G_m / \partial e^2 = (\gamma^2 \theta^2 - 8kq_g)/(4q_g) \), to guarantee a unique optimal solution, we need the condition \( \partial^2 \pi^G_m / \partial e^2 < 0 \), i.e., \( \gamma^2 \theta^2 < 8kq_g \).

Thus, all the following analyses will be conducted under this condition. To this end, the unique optimal green level can be obtained from the first-order condition, let \( \partial \pi^G_m / \partial e = (e\gamma^2 \theta^2 - \gamma \theta c_g + (-8ek + \gamma \theta)q_g)/(4q_g) = 0 \), then we can get that

\[
 e = \gamma \theta(q_g - c_g)/(8kq_g - \gamma^2 \theta^2) \tag{A.7}
\]
Therefore, substituting e into the corresponding equations, the optimal results for G scenario are summarized in Proposition 2.

Proof of Corollary 2. Under the G scenario, the value of $\rho \equiv k/r^2$ as the prerequisite, it should meet $\rho > \rho_0 \equiv \theta^2/(8gq_g)$, By taking first order derivatives of optimal decisions and profits with respect to the quality of the green product $q_g$, we can obtain:

1. $\partial \pi_g/\partial q_g = (\gamma^2\theta^2 q_g - \gamma^2\theta^2)/\gamma^2\theta^2$, thus when $\rho > \rho_1 \equiv \theta^2/(8c_g)$, derive that $\partial \pi_g/\partial q_g > 0$, conversely as $\rho < \rho_1$, $\partial \pi_g/\partial q_g < 0$. As $\rho_1 - \rho_0 = (\theta^2(q_g - c_g))/(8gq_g)^2 > 0$, so $\rho_1 > \rho_0$. So we have $\partial \pi_g/\partial q_g > 0$ if $\rho > \rho_1$; otherwise, $\partial \pi_g/\partial q_g < 0$ if $\rho_0 < \rho < \rho_1$.

2. $\partial w_g/\partial q_g = (4k(\gamma^2\theta^2 q_g - 2\gamma^2\theta^2 q_g + 8kq_g^2))/(8gq_g - \gamma^2\theta^2)^2$, thus when $\rho > \rho_2 \equiv (\theta^2(q_g - c_g))/(8gq_g^2)$, derive that $\partial w_g/\partial q_g > 0$, conversely as $\rho < \rho_2$, $\partial w_g/\partial q_g < 0$. As $\rho_2 - \rho_0 = (\theta^2(q_g - c_g))/(8gq_g^2) > 0$, so $\rho_2 > \rho_0$. So we have $\partial w_g/\partial q_g > 0$ if $\rho > \rho_2$; otherwise, $\partial w_g/\partial q_g < 0$ if $\rho_0 < \rho < \rho_2$.

3. $\partial \pi_g/\partial q_g = (6k(\gamma^2\theta^2 q_g - 2\gamma^2\theta^2 q_g + 8kq_g^2))/(8gq_g - \gamma^2\theta^2)^2$, the proof of this are similar to (2), thus, we omit them.

4. $\partial \pi_m/\partial q_g = (2k(8c_gq_g - \gamma^2\theta^2))/(8gq_g - \gamma^2\theta^2)^2$, the proof of this are similar to (1), thus, we omit them.

5. $\partial \pi_m/\partial q_g = (2k(q_g - c_g)(4kq_g + 4kq_g - \gamma^2\theta^2))/(8gq_g - \gamma^2\theta^2)^2$, thus when $\rho > \rho_3 \equiv \theta^2/(4q_g + c_g)$, derive that $\partial \pi_m/\partial q_g > 0$, conversely as $\rho < \rho_3$, $\partial \pi_m/\partial q_g < 0$. As $\rho_3 - \rho_0 = (\theta^2(q_g - c_g))/(8gq_g^2) > 0$, so $\rho_3 > \rho_0$. So we have $\partial \pi_m/\partial q_g > 0$ if $\rho > \rho_3$; otherwise, $\partial \pi_m/\partial q_g < 0$ if $\rho_0 < \rho < \rho_3$.

6. $\partial \pi_m/\partial q_g = (4k(2q_g - c)(q_g - 3\gamma^2\theta^2 + 8kq_g) + 2q_g - 2\gamma^2\theta^2 + 3kq_g^2))/(8gq_g - \gamma^2\theta^2)^3$, thus when $\rho > \rho_4 \equiv \theta^2/(8gq_g^2 + c_g)$, derive that $\partial \pi_m/\partial q_g > 0$, conversely as $\rho < \rho_4$, $\partial \pi_m/\partial q_g < 0$. As $\rho_4 - \rho_0 = (2\theta^2(q_g - c_g))/(8gq_g^2(q_g + c_g)) > 0$, so $\rho_4 > \rho_0$. So we have $\partial \pi_m/\partial q_g > 0$ if $\rho > \rho_4$; otherwise, $\partial \pi_m/\partial q_g < 0$ if $\rho_0 < \rho < \rho_4$.

Proof of Corollary 3. Under the G scenario, by taking first order derivatives of optimal decisions and profits with respect to the parameters $k$, $\gamma$ and $\theta$, we can obtain:

1. $\partial \pi_g/\partial k = (8\gamma^2\theta^2 q_g)/(8gq_g - \gamma^2\theta^2)^2$, according to Assumption 2 that $q_g > c_g$. We have $\rho > c_g > 0$, $\partial \pi_g/\partial k > 0$, $\partial \pi_g/\partial k < 0$, $\partial \pi_g/\partial k = -4\gamma^2\theta^2 q_g(q_g - c_g)/(8gq_g - \gamma^2\theta^2)^2 < 0$, $\partial \pi_m/\partial k = \gamma^2\theta^2 q_g(q_g - c_g)/(8gq_g - \gamma^2\theta^2)^2 < 0$, $\partial \pi_m/\partial k = (4k\gamma^2\theta^2 q_g(q_g - c_g))/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial k = -(4k\gamma^2\theta^2 q_g(q_g - c_g))/(8gq_g - \gamma^2\theta^2)^2 < 0$, $\partial \pi_m/\partial k = -(4k\gamma^2\theta^2 q_g(q_g - c_g))/(8gq_g - \gamma^2\theta^2)^3 < 0$.

2. The proofs of (2) is similar to (1), thus, $\partial \pi_g/\partial \gamma = (\theta^2(q_g - c_g))/(8gq_g + \gamma^2\theta^2)^2/(8gq_g - \gamma^2\theta^2)^2$, thus when $\rho > \rho_2 \equiv \theta^2/(8gq_g^2)$, $\partial \pi_m/\partial \gamma > \gamma^2\theta^2 q_g(q_g - c_g)/(4k\gamma^2\theta^2 q_g^2(q_g - c_g)^2)/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial \gamma = (4k\gamma^2\theta^2 q_g(q_g - c_g))/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial \gamma = (2k\gamma^2\theta^2 q_g(q_g - c_g)^2)/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial \gamma = (4k\gamma^2\theta^2 q_g(q_g - c_g))/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial \gamma = (2k\gamma^2\theta^2 q_g(q_g - c_g)^2)/(8gq_g - \gamma^2\theta^2)^2 > 0$.

3. The proofs of (3) is similar to (1), thus, $\partial \pi_g/\partial \theta = \gamma^2\theta^2 q_g/(8gq_g + \gamma^2\theta^2)^2/(8gq_g - \gamma^2\theta^2)^2$, thus when $\rho > \rho_2 \equiv \theta^2/(8gq_g^2)$, $\partial \pi_m/\partial \theta = (4k\gamma^2\theta^2 q_g(q_g - c_g))/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial \theta = (2k\gamma^2\theta^2 q_g(q_g - c_g)^2)/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial \theta = (4k\gamma^2\theta^2 q_g(q_g - c_g))/(8gq_g - \gamma^2\theta^2)^2 > 0$, $\partial \pi_m/\partial \theta = (2k\gamma^2\theta^2 q_g(q_g - c_g)^2)/(8gq_g - \gamma^2\theta^2)^2 > 0$.

Proof of Corollary 4.

1. We have $\omega_g - \omega_n = ((c_n - 2c_g + q_n)\gamma^2\theta^2 + 8kq_g(q_g - q_n + c_g - c_n))/(2(8gq_g - \gamma^2\theta^2)^2)$, as when $\rho > \rho_0$, the denominator of the above expression is positive, so the sign of the above expression is determined by the numerator. We denote $t \equiv \gamma^2\theta^2$, define $f(t) = (c_n - 2c_g + q_n)t^2 + 8kq_g(q_g - q_n + c_g - c_n)$.

(i) when $q_n \geq 2c_g - c_n$, we know that $f(t) > 0$, so $\omega_g > \omega_n$. 

(ii) when $q_n < 2c_g - c_n$, we know that $f(t) < 0$, so $\omega_g < \omega_n$.
(ii) when \( q_n < 2c_g - c_n \), by solving the equation \( f(t) = 0 \), we can get \( t_0 = -\sqrt{-(8kq_g(\Delta q + \Delta c))/(q_n + c_n - 2c_g)} \), and \( t_1 = \sqrt{-(8kq_g(\Delta q + \Delta c))/(q_n + c_n - 2c_g)} \). Further, if \( 0 < t_1 \leq t \leq t_0 \), then \( w_g \geq w_n \), while \( w_g < w_n \) if \( t > t_1 \). Thus, if \( 0 < \gamma \leq t_1/\theta \), then \( w_g \geq w_n \); while \( w_g < w_n \) if \( \gamma > t_1/\theta \).

(2) We have \( p_g - p_n = ((c_n - 4c_g + 3q_n)\gamma^2\theta^2 + 8kq_g(3(q_n - q_n) + c_n - c_n))/((48kq_g - \gamma^2\theta^2)) \), as when \( \rho > \rho_0 \), the denominator of the above expression is positive, so the sign of the above expression is determined by the numerator. We denote \( t \equiv \gamma\theta \), define \( f(t) = (c_n - 4c_g + 3q_n)t^2 + 8kq_g(3(q_n - q_n) + c_n - c_n) \).

(i) when \( 3q_n \geq 4c_g - c_n \), we know that \( f(t) > 0 \), so \( p_g > p_n \);

(ii) when \( 3q_n < 4c_g - c_n \), by solving the equation \( f(t) = 0 \), we can get \( t_0 = -\sqrt{-(8kq_g(3\Delta q + \Delta c))/(3q_n + c_n - 4c_g)} \) and \( t_2 = \sqrt{-(8kq_g(3\Delta q + \Delta c))/(3q_n + c_n - 4c_g)} \). Further, if \( 0 < t \leq t_2 \), then \( p_g \geq p_n \); while \( p_g < p_n \) if \( t > t_2 \). Thus, if \( 0 < \gamma \leq t_2/\theta \), then \( p_g \geq p_n \); while \( p_g < p_n \) if \( \gamma > t_2/\theta \).

(3) We have \( D_g - D_n = (8k(q_g c_n + q_n c_g) - \gamma^2\theta^2(q_n + c_n))/((4q_n(8kq_g - \gamma^2\theta^2)) \), as when \( \rho > \rho_0 \), the denominator of the above expression is positive, so the sign of the above expression is determined by the numerator. It can be derived that when \( 0 < \gamma \leq t_3 \equiv \sqrt{((8k(q_g c_n + q_n c_g))/((\theta^2)(q_n + c_n)))} \), \( D_g \geq D_n \) and when \( \gamma > t_3 \), then \( D_g < D_n \).

Proof of Corollary 5.

(1) We have \( \pi_m^G - \pi_m^N = (8kq_n(q_g - c_g)^2 - (8kq_g - \gamma^2\theta^2)(q_n - c_n)^2)/(8q_n(8kq_g - \gamma^2\theta^2)) \), as when \( \rho > \rho_0 \), the denominator of the above expression is positive, so the sign of the above expression is determined by the numerator. It can be derived that when \( (q_g - c_g)/(q_n - c_n) > t_4 \equiv \sqrt{(8kq_g - \gamma^2\theta^2)/(8kq_n)} \), namely \( \Delta m_g/\Delta m_n > t_4 \), then \( \pi_m^G > \pi_m^N \) and \( \pi_m^G \leq \pi_m^N \) when \( 0 < \Delta m_g/\Delta m_n \leq t_4 \).

(2) We have \( \pi_r^G - \pi_r^N = (16k^2q_g q_n(q_g - c_g)^2 - (8kq_g - \gamma^2\theta^2)(q_n - c_n)^2)/(16q_n(8kq_g - \gamma^2\theta^2)) \), as when \( \rho > \rho_0 \), the denominator of the above expression is positive, so the sign of the above expression is determined by the numerator. It can be derived that when \( (q_g - c_g)/(q_n - c_n) > t_5 \equiv \sqrt{(8kq_g - \gamma^2\theta^2)/(8kq_n)} \), namely \( \Delta m_g/\Delta m_n > t_5 \), then \( \pi_r^G > \pi_r^N \) and \( \pi_r^G \leq \pi_r^N \) when \( 0 < \Delta m_g/\Delta m_n \leq t_5 \).

Proof of Corollary 6.

We have \( CS^G - CS^N = (16q_n(q_g - c_g)^2(\gamma^4(1 - \theta)\theta^3 + 4k^2q_g^2) - q_g(8kq_g - \gamma^2\theta^2)(q_n - c_n)^2)/(32q_g q_n(8kq_g - \gamma^2\theta^2)) \), as when \( \rho > \rho_0 \), the denominator of the above expression is positive, so the sign of the above expression is determined by the numerator. It can be derived that when \( (q_g - c_g)/(q_n - c_n) > t_6 \equiv \sqrt{(8kq_g - \gamma^2\theta^2)/(16q_n(\gamma^4(1 - \theta)\theta^3 + 4k^2q_g^2))} \), namely \( \Delta m_g/\Delta m_n > t_6 \), then \( CS^G > CS^N \) and \( CS^G \leq CS^N \) when \( 0 < \Delta m_g/\Delta m_n \leq t_6 \).

Proof of Corollary 8. From Proposition 1, we can get that \( \pi^N_m/\pi^N_m = 1/2 \). And from Proposition 2, we can get that \( \pi^C_m/\pi^C_m \geq 1/2 \). Therefore, the retailer is more inclined to obtain profit from green product due to \( \pi^C_m/\pi^C_m \geq \pi^N_m/\pi^N_m \).

Proof of Proposition 3. Under the cost-sharing contract, following backward induction, firstly, the retailer decides the retail price. Secondly, the manufacturer decides the wholesale price. The decision consequences of the manufacturer and the retailer are consistent with the proof of the Proposition 2.

Thirdly, the manufacturer decides the green level. Plugging Equation (A.5) and (A.6) into Equation (22), we get manufacturer’s profit \( \pi^C_m \) as follows, \( \pi^C_m = (1/2(e\gamma + c_g + q_g) - c_g) ((e\gamma + c_g + q_g)/(4q_g)) - (1 - \phi^C)k\varepsilon^2 \), we obtain \( \partial^2\pi^C_m/\partial e^C = \)
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(γ^2θ^2 - 8kq_g(1 - φ^{CS}))/4q_g, to guarantee a unique optimal solution, we need the condition ∂^2π_m/∂e^2 < 0, i.e., γ^2θ^2 < 8kq_g(1 - φ^{CS}). Thus, all the following analyses will be conducted under this condition. To this end, The unique optimal green level can be obtained from the first order condition, which is given by e^{CS} = (γθ(q_g - c_g))/(8kq_g(1 - φ^{CS}) - γ^2θ^2).

Hence, for the given sharing parameter, substituting e^{CS} into the corresponding equations, the optimal results for the cost-sharing contract are summarized in Proposition 3.

Proof of Corollary 9. Under the cost-sharing contract, by taking first order derivatives of optimal decisions and profits with respect to the sharing parameter φ^{CS}, we can obtain:

\[ \frac{\partial c}{\partial \phi^{CS}} = \frac{\partial w}{\partial \phi^{CS}} = 0, \frac{\partial w}{\partial \phi^{CS}} = (4kq^2θφ^2φ_g(1 - φ^{CS}) - γ^2θ^2)^2 > 0, \frac{\partial \pi^{CS}}{\partial \phi^{CS}} = (8kq^2θφ^2φ_g(1 - φ^{CS}) - γ^2θ^2)^2 > 0, \frac{\partial D}{\partial \phi^{CS}} = (2kq^2θφ^2φ_g(1 - φ^{CS}) - γ^2θ^2)^2 > 0, \frac{\partial \pi^{RS}}{\partial \phi^{CS}} = (2kq^2θφ^2φ_g(1 - φ^{CS}) - γ^2θ^2)^2 > 0. \]

Thus, all the following analyses will be conducted under this condition. To this end, The unique optimal green level can be obtained from the first order condition, which is given by e^{RS} = (γθ(q_g - c_g))/4q_g(2 - φ^{RS}) - γ^2θ^2).
Hence, for the given sharing parameter, substituting $e^{RS}$ into the corresponding equations, the optimal results for the revenue-sharing contract are summarized in Proposition 5.

Proof of Corollary 10. Under the revenue-sharing contract, by taking first order derivatives of optimal decisions and profits with respect to the sharing parameter $\phi^{RS}$, we can obtain:

1. $\partial e^{RS}/\partial \phi^{RS} = (4kq_\gamma(q_\gamma - c_\gamma))/(4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2 > 0$, $\partial w^{RS}/\partial \phi^{RS} = -(4kq_\gamma(q_\gamma - c_\gamma)(4kq_\gamma - \gamma^2\theta^2))/(4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2 < 0$, $\partial D^{RS}/\partial \phi^{RS} = (8k^2q_\gamma(q_\gamma - c_\gamma))/(4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2 > 0$, $\partial \pi^{RS}/\partial \phi^{RS} = (4k^2q_\gamma(q_\gamma - c_\gamma)^2)/(4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2 > 0$.

2. $\partial p^{RS}/\partial \phi^{RS} = (4kq_\gamma(q_\gamma - c_\gamma)(\gamma^2\theta^2 - 2kq_\gamma))/(4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2$, thus when $\rho < \theta^2/(2kq_\gamma)$, derivethat $\partial p^{RS}/\partial \phi^{RS} > 0$, otherwise, $\partial p^{RS}/\partial \phi^{RS} < 0$.

3. $\partial \pi^{RS}/\partial \phi^{RS} = (4k^2q_\gamma(q_\gamma - c_\gamma)(\gamma^2\theta^2 - 4kq_\gamma\phi^{RS}))/(4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2$, thus when $\rho < \theta^2/(4kq_\gamma\phi^{RS})$, derivethat $\partial \pi^{RS}/\partial \phi^{RS} > 0$, otherwise, $\partial \pi^{RS}/\partial \phi^{RS} < 0$.

Proof of Proposition 6. Under the revenue-sharing contract, when the retailer tries to maximize its profit and decides the sharing ratio, the optimal profit of the retailer can be expressed as follows, $\pi^{RS}_r = (4k^2q_\gamma(q_\gamma - c_\gamma)^2(1 - \phi^{RS}))/4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2$, and the second order derivative $\partial^2 \pi^{RS}_r/\partial \phi^{RS} = -\gamma^2\theta^2(2kq_\gamma(q_\gamma - c_\gamma)^2(1 - \phi^{RS}))/4kq_\gamma(2 - \phi^{RS}) - \gamma^2\theta^2)^2$, thus when $\rho < (3\theta^2)/(8kq_\gamma)$, derivethat $\partial^2 \pi^{RS}_r/\partial \phi^{RS} > 0$, otherwise, $\partial^2 \pi^{RS}_r/\partial \phi^{RS} < 0$.

Hence, substituting $\phi^{RS*}$ into the corresponding equations, the optimal results for the revenue-sharing contract are summarized in Proposition 6.

Proof of Corollary 11. Comparing the equilibrium results under the revenue-sharing contract with that under the cost-sharing contract, we can confirm that:

1. $\phi^{RS*} - \phi^{CS*} = (3\gamma^2\theta^2)/(16kq_\gamma) > 0$.
2. $e^{RS*} - e^{CS*} = (\gamma^3\theta^3(q_\gamma - c_\gamma))^2/(16kq_\gamma) - 3\gamma^2\theta^2(4kq_\gamma - \gamma^2\theta^2) > 0$.
3. $w^{RS*} - w^{CS*} = -(\gamma^2\theta^2(q_\gamma - c_\gamma))/(16kq_\gamma - 3\gamma^2\theta^2) < 0$.
4. $p^{RS*} - p^{CS*} = (\gamma^2\theta^2(4kq_\gamma - \gamma^2\theta^2)/(4kq_\gamma(16kq_\gamma - 3\gamma^2\theta^2)(4kq_\gamma - \gamma^2\theta^2))$, then when $\rho < (3\theta^2)/(8kq_\gamma)$, derivethat $p^{RS*} > p^{CS*}$, otherwise, $p^{CS*} < p^{RS*}$.
5. $D^{RS*} - D^{CS*} = (\gamma^2\theta^2(q_\gamma - c_\gamma)/(8kq_\gamma - \gamma^2\theta^2))/(4kq_\gamma(16kq_\gamma - 3\gamma^2\theta^2)(4kq_\gamma - \gamma^2\theta^2))$, then when $\rho < \theta^2/(8kq_\gamma)$, derivethat $D^{CS*} > D^{RS*}$, otherwise, $D^{RS*} > D^{CS*}$.
6. $\pi^{RS*} - \pi^{CS*} = \gamma^2\theta^2(q_\gamma - c_\gamma)^2/(8kq_\gamma - \gamma^2\theta^2)/(16kq_\gamma(16kq_\gamma - 3\gamma^2\theta^2)(4kq_\gamma - \gamma^2\theta^2)) > 0$, $\pi^{RS*} - \pi^{CS*} = \gamma^2\theta^2(q_\gamma - c_\gamma)^2/(16kq_\gamma(16kq_\gamma - 3\gamma^2\theta^2)(4kq_\gamma - \gamma^2\theta^2)) > 0$.

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