THE COMBINED IMPACTS OF CONSUMER GREEN PREFERENCE AND FAIRNESS CONCERN ON THE DECISION OF THREE-PARTY SUPPLY CHAIN

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Abstract. Consumer green preference (CGP) and fairness concern have posed significant impact on supply chain, respectively. This paper study the combined impacts of CGP and fairness concern on the supply chain that consists of a manufacturer, a green retailer, and a traditional retailer. Specifically, the optimal decision-making are solved in seven cases, fairness neutrality (FN), the green retailer and the traditional retailer has vertical fairness concern (VFC) respectively, the two retailers has horizontal fairness concern (HFC) respectively, both retailers have vertical fairness concern (BVFC), both retailers have horizontal fairness concern (BHFC). Our main results via numerical simulation follow. (1) The improvement of CGP benefits the supply chain members except the traditional retailer. (2) The green retailer’s VFC benefits itself and the whole supply chain, whereas bad for the manufacturer and the traditional retailer. However, the green retailer’s HFC bad for itself, while benefits the manufacturer and the traditional retailer. (3) The traditional retailer’s profits are affected by both CGP and fairness concern. (4) The high level of BVFC benefits the two retailers, but bad for the manufacturer. Conversely, the high level of BHFC will intensify competition between retailers and thus bad for them, while the manufacturer can benefit from it.

1. Introduction. In recent years, the problem of environment pollution caused by the excessive expansion of cities and the vehicle fuel consumption has been widely concerned [30, 29]. Scientists all over the world declare greenhouse gas as the main malefactor for environmental change [11]. As a result, Countries around the world put forward the concept of “low-carbon economy” in order to protect the earth’s ecological environment and sustainable development. Besides, reducing the adverse impact of carbon emissions on the environment has become an important agenda of the government [13]. Under the government’s wide publicity and guidance, people consider not only the price but also the degree of green when they choose goods. For example, Gree Group, a Chinese air-conditioning manufacturer, obtained the European Union permit successfully due to the first fluorine-free technology of air-conditioning as early as 1998. The new type of air-conditioning that adopts new...
green technology and fluorine-free refrigerant saves 51% power contrast with traditional air-conditioning, which is very popular with people although the price is higher than that of traditional air-conditioning. In addition, products adopting green techniques contribute to environmental issues [12], so green products are favored by consumers. How can manufacturers coordinate the production of traditional products or green products in this case? Therefore, considering the behavior of consumer green preference (CGP) has a great significance for manufacturers to arrange production rationally. However, manufacturers to improve the products’ green level means that they need to invest more R&D cost and production cost. Whether manufacturer’s profits are related to CGP and how to make a reasonable decision are also a question to be discussed in this paper.

The investment of green products is often conducted by manufacturers that are usually the leader in supply chain, and the core manufacturer tends to make decisions from its own interests regardless of its supply chain members’ interests. When manufacturers increase investment in green products, it will inevitably lead to an increase in the cost of R&D and production. This also means that manufacturers will put up the wholesale price substantially, which in turn leads to an increase in the purchase cost of retailers. In consequence, retailers with uncertain demand for green products believe that the increasing of retail price will make their products difficult to sell and their profits margin is unfairly squeezed [20]. As a result, this practice of manufacturers may lead to the retailers’ unbalanced mentality of profits; that is, fairness concern. Manufacturers should consider retailers’ fairness concern to achieve a better performance in supply chain when they make decisions. The fairness concern has an important impact on supply chain. When the decision-makers of enterprises have fairness concern, enterprises will adjust their business strategy [7]. The decision-making of supply chain members under fairness concern has been widely researched by academia. However, previous research has only considered these factors separately, such as only considering the impact of CGP, or only considering the impact of fairness concern. Few scholars study both from the perspectives of consumer behavior and supply chain member behavior. In fact, consumers are also part of the end of supply chain, and market demand is largely influenced by consumer behavior, so manufacturers need to consider the consumers’ behavior. Nowadays, consumers have a growing demand for green products, and they are willing to pay higher price for them. Therefore, manufacturers should consider not only CGP but also the retailers’ fairness concern caused by the sharp increase in the retail price of green products.

The research of supply chain under fairness concern is mainly based on the traditional “one-to-one” supply chain (includes one manufacturer, one retailer). In the traditional “one-to-one” supply chain, Zhang et al. [36] found that the retailer’s fairness concern will increase its profits and reduce the whole supply chain’s profits in the closed-loop supply chain that consists of one manufacturer and one retailer. Du et al. [5] found that the retailer’s fairness concern will reduce the profits of both the manufacturer and the whole supply chain under the newsboy model that consists of one manufacturer and one retailer. However, do these conclusions still hold under the background of “one-to-many” supply chain (includes one manufacturer, many retailers)? In this paper, we find some different conclusions through numerical simulation. In general, the “one-to-many” supply chain is more common in real life. For example, in the traditional industry of automobile making, automobile manufacturers (leading manufacturer), as the core enterprises in the supply
chain, are mainly responsible for R&D as well as automobiles’ manufacturing, while many subordinate automobile brand stores (many retailers) are mainly responsible for selling automobiles. Therefore, we study the combined impacts of CGP and retailer’s fairness concern under the background of “one-to-many” supply chain. Specifically, we focus on researching the following questions:

(1) Is CGP beneficial to all supply chain members? Is it good for the whole supply chain?

(2) Under the background of “one-to-many” supply chain, do the conclusions with fairness concern in traditional “one-to-one” supply chain have new changes?

(3) How do supply chain members make decisions under the combined impacts of CGP and fairness concern? What are the changes in supply chain profits?

To solve above questions, this paper constructs a supply chain that consists of a green retailer, a traditional retailer, and a manufacturer. We consider the combined impacts of CGP and the retailers’ fairness concern on the supply chain. Specifically, the optimal decision-makings are solved in seven cases, the supply chain members are fairness neutrality (FN), the green retailer has vertical fairness concern (R1VFC), the traditional retailer has vertical fairness concern (R2VFC), the green retailer has horizontal fairness concern (R1HFC), the traditional retailer has horizontal fairness concern (R2HFC), both retailers have vertical fairness concern (BVFC), both retailers have horizontal fairness concern (BHFC). We constructed a Stackelberg game model in which the manufacturer is the game leader, and the green retailer and the traditional retailer are the follower. Then, the optimal decisions are solved by using backward induction method and its optimality are proved by using optimization theory. Finally, some conclusions are obtained through numerical simulation with the help of Maple and Matlab mathematical software. We find that the profits of the green retailer, the manufacturer, and the whole supply chain under the high level of CGP are higher than those under the low level of CGP. Moreover, we find some different conclusions that retailers’ fairness concern can also increase the profits of the manufacturer and the whole supply chain in some cases under the “one-to-many” supply chain background. These conclusions are different from previous research [36, 5]. Finally, our results provide some insights. For instance, the green retailers and the traditional retailer may be able to cooperate with each other to improve their profits. They should turn their attention of fairness concern to the manufacturer, not each other.

The advantages of our proposed model are summarized as follows. Firstly, few scholars study both from the perspectives of consumer behavior and supply chain member behavior. However, consumers, as a part of the end of the supply chain, will pose an important impact on market demand and supply chain. Thus, our model considers the combined impacts of CGP and fairness concern on the supply chain, but the previous research has only considered these factors separately. Secondly, the previous studies are mainly based on the traditional “one-to-one” supply chain, so the horizontal fairness concern between retailers is less considered. Differently, our model extends the research background of traditional supply chain and study more situations about fairness concern (e.g., vertical and horizontal fairness concern, respective and simultaneous fairness concern) under the background of “one-to-many” supply chain. Finally, some interesting conclusions which are difficult to discover in real life are found in our models. For instance, although the manufacturer’s optimal wholesale price is affected by horizontal fairness concern of the two retailers, the unilateral horizontal fairness concern will not change their optimal retail price.
2. Literature review. At present, there are many research results indicate that consumers have a preference for green products. Vanclay et al. [31] labeled 37 products with different carbon emission labels and made sales records for three months. They found that the sales of products labeled with low carbon emission outdistanced than those labeled with high carbon emission, which indicated that consumers have a preference for green products. Ghosh and Shah [14] studied the green clothing supply chain and their research results showed that the coordination of the green clothing supply chain was affected by consumers’ sensitivity to green clothing. Besides, the demand for green clothing was not only affected by the clothing price but also affected by the green degree of clothing products to a certain extent. Ghosh and Shah [15] also studied the impacts of green cost and consumers’ sensitivity to green products on the supply chain and believed that enterprises should increase the production of green and low-carbon products to meet consumers’ demand for green and low-carbon products with the change of consumers’ environmental awareness. Moon et al. [25] proposed, by studying consumers’ willingness to pay for environment-friendly products, that residents in different regions have different expectations for environment-friendly products. What’s more, residents in some regions are willing to pay higher price for green products. Zhou et al. [42] found that consumers’ willingness to pay for green pork was higher through a large number of marketing investigation. Du et al. [6] analyzed the impacts of consumers with green and low carbon awareness on the supply chain and showed that consumers’ low carbon awareness could effectively promote the manufacturer to reduce carbon emission and improve the whole supply chain’s profits. Li et al. [19] found that the degree of CGP has a positive correlation effect on the price and green degree of products by analyzing various cooperation modes. Besides, the whole supply chain’s profits increase with the rise of CGP in the cooperation model involving green manufacturers. Zeng et al. [34] analyzed the impact of CGP on the decision-making results of the supply chain and found that the remanufacturer will get benefits when consumers think the quality of remanufactured product and the degree of green is higher than a certain critical value. Brécard [3] and Zhang [35] found that the improvement of people’s environmental awareness will increase people’s demand for green products, and manufacturers are willing to produce green products in order to obtain more profits. The above research results show that consumers have preference behavior for green products, which has caused a significant impact on supply chain.

Green supply chain management is an important research direction. Westley et al. [10] studied the cooperation between environmentalist and business in the marketing of green products. Mardani et al. [1] have provided useful insights into the development of green and sustainable supply chain management with a better understanding of the current body of knowledge in these fields. However, the decision-makers are usually assumed to be completely rational in the previous research. That is, they make decisions based on the profit maximization principle. Actually, people in real life are not only concerned about their own profits but also about the profit distribution of others. Both the decision-making and the profits of supply chain members are also affected by fairness concern. Kahneman, Nobel Laureate in economics, first proposed the concept of fairness concern in his early research on behavioral economics. The research reveals that people also pay attention to the fairness of others’ profit distribution in the process of profit distribution [18]. Cui et al. [2] introduced the concept of fairness into the two-stage
supply chain and the study found that the manufacturer will change the wholesale price in order to obtain channel profit as well as channel utility maximization when channel members concern about fairness. Moreover, the channel coordination only needs a wholesale price constant to achieve. Du et al. [4] considered the retailers’ fairness concern in the traditional two-stage supply chain and analyzed the influence of this tendency on the supply chain contract and coordination. Besides, they simplified the utility function of fairness concern. Li et al. [21] researched the influence of different business objectives and fairness concern on the complexity of dual-channel value chains and the research found that the manufacturer and the retailer with the high level of fairness concern are always bad for the leading manufacturer but not always unfavorable to the follower retailer. Zhen et al. [40] developed a supply chain that included a manufacturer producing and selling products through direct online channel and a retailer sells directly to consumers through online and offline channels. They studied how fairness concern affected the supply chain members’ decision-making under different scenarios. Li et al. [22] introduced fairness concern into the background of the low-carbon supply chain and discussed the impact of two-part tariff contract on the coordination of the low-carbon supply chain. Zhou et al. [41] discussed the decision-making problem led by the retailer in the low-carbon supply chain under fairness concern and their research showed that the utility maximization of the low-carbon supply chain system is related to the level of fairness concern when the manufacturer has fairness concern behavior. Zhang et al. [38] considered the impacts of consumer environmental awareness and retailers’ fairness concern on retail price, wholesale price, and environmental quality of green products. The above research results enrich content related to fairness concern and supply chain management. However, the above studies about fairness concern are still based on the traditional supply chain that includes a single manufacturer and a single retailer.

Savaskan et al. [28] studied the closed-loop supply chain members’ decision-making and found that the supply chain’s profits were driven by the competition interaction between retailers. Huang et al. [16], on the basis of Savaskan et al. [28], respectively constructed three remanufacturing models with the trade-in strategy and discussed the impact of the trade-in plans on the profits and on the supply chain members’ decision-making in the case of competition among one manufacturer and two retailers. Yao et al. [32] developed a product-service supply chain that included one manufacturer and two retailers and studied the equilibrium strategy of the supply chain members from the perspective of competitive services provided by the retailers. Modak et al. [24] explored the channel coordination and profit distribution in a two-layer socially responsible supply chain that consists of a manufacturer and two competitive retailers. They compared the optimal decisions of the retailers two game behaviors and analyzed the effects of social responsibility on the optimal decisions. Roy et al. [27] studied a two-echelon supply chain that consists of one manufacturer and two competing retailers with sales price dependent demand and random arrival of the customers. They researched a single-period newsvendor type model to determine the optimal order quantity, considering the competing retailers’ strategies. Lu et al. [23] considered the competitive factors among the retailers in the cooperative advertising model and solved its equilibrium ordering strategy and cooperative advertising strategy under the background of a single manufacturer and multiple competing retailers.
Table 1. The literature positioning of this paper

| Literature          | Consumer green preference | Vertical fairness concern | Horizontal fairness concern | Both fairness concern | Three-party supply chain |
|---------------------|---------------------------|---------------------------|----------------------------|----------------------|--------------------------|
| Vanclay et al. [31] | ✓                         |                           |                            |                      |                          |
| Ghosh et al. [14]   | ✓                         |                           |                            |                      |                          |
| Moon et al. [25]    | ✓                         |                           |                            |                      |                          |
| Du et al. [6]       |                           | ✓                         |                            |                      |                          |
| Cui et al. [2]      |                           |                           | ✓                          |                      |                          |
| Du et al. [4]       |                           |                           | ✓                          |                      |                          |
| Zhang et al. [38]   |                           |                           |                            | ✓                    |                          |
| Savaskan et al. [28]|                           |                           |                            | ✓                    |                          |
| Yao et al. [32]     |                           |                           |                            | ✓                    |                          |
| Modak et al. [24]   |                           |                           |                            | ✓                    |                          |
| Nie et al. [26]     | ✓                         | ✓                         |                            | ✓                    |                          |
| Ho et al. [17]      | ✓                         | ✓                         |                            | ✓                    |                          |
| Yao et al. [33]     |                           |                           |                            | ✓                    |                          |
| This paper          | ✓                         | ✓                         | ✓                           | ✓                    | ✓                        |

Nevertheless, the above research about “one-to-many” supply chain did not consider the influence of the decision-maker’s subjective behavior (e.g., fairness concern, overconfidence). Nie et al. [26] respectively considered the impacts of horizontal fairness concern and vertical fairness concern on the supply chain that consists of a single manufacturer and two retailers and proposed a coordination plan combining fixed fee and quantity discount contract. Ho et al. [17] established a duopoly supply chain game model with a single manufacturer and two retailers to research how an enterprise’s vertical fairness concern and horizontal fairness concern simultaneously affect the three-party supply chain coordination. Yao et al. [33] discussed the impacts of retailers’ fairness concern and the degree of competition between them on the closed-loop supply chain comprising of a single manufacturer, two competing retailers, and a single third-party recycler, but they assumed that the retailers are homogeneous, in other words, retailers are absolutely the same. Actually, retailers in real life are diversified such as retailers’ product types and geographic locations may be different. In addition, the above “one-to-many” supply chain do not consider the impact of consumer behavior on the supply chain. The subjective behaviors of consumers and supply chain members have an important impact on supply chain. Zhang et al. [37] analyzed the combined impacts of consumers’ environmental awareness and fairness concern on the supply chain, but their research background was “one-to-one” traditional supply chain. Zhao et al. [39] considered the low-carbon preference of consumers and the supply chain members’ fairness concern and analyzed their combined impacts on the investment strategies of carbon emission reduction and on the supply chain members’ profits. However, their research background was still “one-to-one” traditional supply chain.

In summary, we consider the combined impacts of CGP and fairness concern on the decision-making of the supply chain members and on the supply chain’s profits under the background of “one-to-many” supply chain. However, the previous research considered these two factors separately. The difference between our study and others in the literature is shown in Table 1.
3. **Model assumption and construction.** We construct a supply chain model composed of a green retailer, a traditional retailer, and a manufacturer. The diagram of proposed supply chain is shown in Figure 1.

![Proposed supply chain structure](image)

**Figure 1.** Proposed supply chain structure

The manufacturer produces two types of products, the first is green products which are sold to the market by the green retailer (retailer 1), and the other is traditional products which are sold to the market by the traditional retailer (retailer 2). The manufacturer provides products for retailer 1 and retailer 2 at different wholesale price due to different production cost. Then, retailer 1 and retailer 2 sell their products at different retail price. Table 2 summarizes the main notations used in this paper.

| Notations | Definition |
|-----------|------------|
| $c_1, c_2$ | Unit cost for the manufacturer to produce green products and traditional products, respectively |
| $w_1, w_2$ | Wholesale price of green products and traditional products, respectively |
| $p_1, p_2$ | Retail price of green products and traditional products, respectively |
| $Q$ | Potential consumers in the market |
| $\sigma$ | Consumer green preference |
| $q_1, q_2$ | Sales of green products and traditional products, respectively |
| $\pi_m$ | Profit function of the manufacturer |
| $\pi_{r1}$ | Profit function of the green retailer |
| $\pi_{r2}$ | Profit function of the traditional retailer |
| $\pi_s$ | Profit function of the whole supply chain |
| $u_{r1}(m)$ | Utility of the green retailer vertical fairness concern |
| $u_{r2}(m)$ | Utility of the traditional retailer vertical fairness concern |
| $u_{r1}(r_2)$ | Utility of the green retailer horizontal fairness concern |
| $u_{r2}(r_1)$ | Utility of the traditional retailer horizontal fairness concern |
| $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ | Coefficients of fairness concern under different scenarios |
3.1. **Model assumptions.** In order to make this study more realistic, we make the following assumptions:

1. The unit cost for the manufacturer to produce green products is $c_1$, to produce traditional products is $c_2$ ($c_1 > c_2$). The wholesale price of retailer 1 and retailer 2 are respectively $w_1$ and $w_2$.
2. The retail price of retailer 1 and retailer 2 are respectively $p_1$ and $p_2$.
3. Assume that consumers only buy one type of product according to the utility maximization principle, because consumers usually do not buy green products and traditional products at the same time. For instance, consumers who have bought the green air-conditioning will no longer buy the traditional air-conditioning.
4. The fairness concern information and market information are completely open to the members in supply chain. Besides, the supply chain members decide their pricing strategies simultaneously to maximize their own profits.

3.2. **Model construction.** Based on the above assumptions and previous research [8], we suppose that there be $Q$ potential consumers in the market, characterized by the variable $v \in (0, Q)$ uniformly distributed in this domain, according to their valuation of traditional products. Let $\sigma (\sigma > 1)$ indicate the consumer green preference (i.e., CGP). Large value of $\sigma$ means that the level of consumer’s preference for green products higher than if $\sigma$ is small. The utility that a consumer gets when buying green products is $U_1 = \sigma v - p_1$ and buying traditional products is $U_2 = v - p_2$. Assume that the consumer gets same utility for buying green products and traditional products at point $v_1$, and gets the same utility for buying traditional products as they do not buying any products at point $v_2$. Then, we can conclude $v_1 = \frac{p_1 - p_2}{\sigma - 1}$, $v_2 = p_2$. Consumers buy green products when $v_1 \leq v \leq Q$, consumers buy traditional products when $v_2 \leq v \leq v_1$, consumers do not buy any products when $0 \leq v \leq v_2$. The diagram is as follows in figure 2.

![Figure 2. The potential demand distribution of consumers in the market](image)

From Figure 2, the demand of green products and traditional products are respectively $\frac{Q - v_1}{Q}Q$ and $\frac{v_2 - v}{Q}Q$. Then, the demand function of green products and traditional products purchased by consumers are respectively as follows:

$$q_1 = Q - \frac{p_1 - p_2}{\sigma - 1}$$

$$q_2 = \frac{p_1 - p_2}{\sigma - 1} - p_2$$

The profits functions of the manufacturer, retailer 1, and retailer 2 are respectively as follows:

$$\pi_m = (w_1 - c_1)q_1 + (w_2 - c_2)q_2$$

$$\pi_r1 = (p_1 - w_1)q_1$$

$$\pi_r2 = (p_2 - w_2)q_2$$
4. Decisions of supply chain under different scenarios.

4.1. The baseline model: Fairness neutral (FN). Without consideration of fairness concern, supply chain members do not concern about the fairness of their profit distribution in the supply chain and make decisions to maximize their own profits. In the market competition, manufacturers are usually more powerful than retailers. Therefore, supposed that the manufacturer is a game leader, retailer 1 and retailer 2 are the follower, and the game equilibrium is called Stackelberg equilibrium. In the game model, the manufacturer firstly decides the wholesale price \( w_1 \) and \( w_2 \), according to the profit maximization principle. Then, retailer 1 and retailer 2 decide the retail price \( p_1 \) and \( p_2 \) respectively, according to the profit maximization principle. Based on the above game order, the backward induction method is adopted to solve this problem.

First of all, retailer 1 and retailer 2 determine the response functions of their respective retail price. Setting \( \frac{\partial \pi_{r1}}{\partial p_1} = 0 \) and \( \frac{\partial \pi_{r2}}{\partial p_2} = 0 \), the response functions are as follows:

\[
p_{1\text{FN}} = \frac{\sigma(2Q\sigma - 2Q + 2w_1 + w_2)}{4\sigma - 1} \quad (6)
\]

\[
p_{2\text{FN}} = \frac{Q\sigma - 2\sigma w_2 - Q + w_1}{4\sigma - 1} \quad (7)
\]

Since \( \sigma > 1 \), \( \frac{\partial^2 \pi_{r1}}{\partial p_1^2} = -\frac{2}{\sigma - 1} < 0 \), \( \frac{\partial^2 \pi_{r2}}{\partial p_2^2} = -\frac{2}{\sigma - 1} - 2 < 0 \), the second-order derivative of the profit function of retailer 1 and retailer 2 are less zero, which indicate they can get the optimal solutions. \( p_{1\text{FN}} \) and \( p_{2\text{FN}} \) are the global optimal solutions of retailer 1 and retailer 2, respectively.

Secondly, taking (6)(7) into (3), the manufacturer’s profit function \( \pi_m \) can be acquired. Setting \( \frac{\partial \pi_m}{\partial w_1} = 0 \) and \( \frac{\partial \pi_m}{\partial w_2} = 0 \), the manufacturer’s optimal wholesale prices are as follows:

\[
w_{1\text{FN}} = \frac{1}{2}(Q\sigma + c_1) \quad (8)
\]

\[
w_{2\text{FN}} = \frac{1}{2}(Q + c_2) \quad (9)
\]

The Hessian matrix of the manufacturer’s profit function is

\[
H = \begin{pmatrix}
\frac{4\sigma - 2}{(4\sigma - 1)(\sigma - 1)} & \frac{2\sigma}{(4\sigma - 1)(\sigma - 1)} \\
\frac{2\sigma}{(4\sigma - 1)(\sigma - 1)} & \frac{4\sigma - 2}{(4\sigma - 1)(\sigma - 1)}
\end{pmatrix}
\]

Since \( \sigma > 1 \), \( H_{11} = -\frac{4\sigma - 2}{(4\sigma - 1)(\sigma - 1)} < 0 \), \( \text{det}(H) = \frac{4\sigma}{(4\sigma - 1)(\sigma - 1)} > 0 \), the Hessian matrix is negative definite, which indicates \( w_{1\text{FN}}, w_{2\text{FN}} \) are the global optimal solutions of the manufacturer.

Lastly, taking (8)(9) into (6)(7) meanwhile, the optimal retail prices are as follows:

\[
p_{1\text{FN}} = \frac{1}{2} \sigma \left(6Q\sigma - 3Q + 2c_1 + c_2\right) \quad (10)
\]

\[
p_{2\text{FN}} = \frac{1}{2} \sigma \left(5Q\sigma + 2c_2\sigma - 2Q + c_1\right) \quad (11)
\]
Taking (8)(9)(10)(11) into (3)(4)(5), the profit functions of supply chain members can be expressed as follows:

\[
\pi_{m,\text{FN}} = \frac{\frac{1}{4}2Q^2\sigma^3 + A_1\sigma^2 + A_2\sigma - c_1^2}{(4\sigma - 1)(\sigma - 1)} \\
\pi_{r_1,\text{FN}} = \frac{\frac{1}{4}(2Q^2\sigma^2 - 2Q\sigma - 2c_1\sigma + c_2\sigma + c_1)^2}{(4\sigma - 1)^2(\sigma - 1)} \\
\pi_{r_2,\text{FN}} = \frac{\frac{1}{4}(Q\sigma - 2c_2\sigma - Q + c_1 + c_2)^2\sigma}{(4\sigma - 1)^2(\sigma - 1)}
\]

Where \(A_1, A_2\) are shown in appendix A.

**Theorem 4.1.** In FN scenario, the optimal retail prices of retailer 1 and retailer 2 are \(p_{1,\text{FN}}\) and \(p_{2,\text{FN}}\) respectively, and the manufacturer’s optimal wholesale prices are \(w_{1,\text{FN}}\) and \(w_{2,\text{FN}}\).

4.2. Retailer 1 vertical fairness concern model (R1VFC). In reality, supply chain members often have fairness concern. They will pay attention to their own profits and care about the fairness of profits distribution. When the manufacturer improves products’ green level, which often leads to retailers’ fairness concern. Therefore, we consider the retailers’ fairness concern in the above baseline model. Firstly, we propose that retailer 1 has vertical fairness concern with the manufacturer (i.e., R1VFC), retailer 2 is fairness neutral. According to the previous research [4], the profits of retailer 1 and the manufacturer as a reference point to describe fairness concern utility, and the utility function of R1VFC is

\[
u_{r_1}(m) = \pi_{r_1} - \lambda_1(\pi_m - \pi_{r_1})
\]

Where \(\pi_m\) and \(\pi_{r_1}\) are the profits of the manufacturer and retailer 1 respectively, the coefficient of R1VFC denoted by \(\lambda_1(0 < \lambda_1 < 1)\), \(\lambda_1(\pi_m - \pi_{r_1})\) is the fairness utility of retailer 1. If \(\pi_m > \pi_{r_1}\), the utility of retailer 1 decreases as \(\lambda_1\) increases. Conversely, the utility of retailer 1 increases as \(\lambda_1\) decreases if \(\pi_m < \pi_{r_1}\).

In R1VFC scenario, the step of game is as follows:

First of all, retailer 1 determines the response function of retail price according to the utility maximization principle, and retailer 2 determines the response function of retail price according to the profit maximization principle. Setting \(\frac{\partial u_{r_1}(m)}{\partial p_1} = 0\) and \(\frac{\partial u_{r_2}}{\partial p_2} = 0\), the response functions are as follows:

\[
p_{1,\text{R1VFC}} = \frac{\sigma[(2Q\sigma - 2Q - 2c_1 + 2c_2 + 4w_1 - w_2)\lambda_1 + 2Q(\sigma - 1) + 2w_1 + w_2]}{(4\sigma - 1)(\lambda_1 + 1)}
\]

\[
p_{2,\text{R1VFC}} = \frac{(Q\sigma + 2\sigma w_2 - Q - c_1 + c_2 + 2w_1 - w_2)\lambda_1 + Q(\sigma - 1) + 2\sigma w_2 + w_2}{(4\sigma - 1)(\lambda_1 + 1)}
\]

Since \(\sigma > 1\), \(0 < \lambda_1 < 1\), \(\frac{\partial^2 u_{r_1}(m)}{\partial p_1^2} = -\frac{2}{\sigma - 1} - 2 < 0\), \(\frac{\partial^2 \pi_{r_2}}{\partial p_2^2} = -\frac{2}{\sigma - 1} - 2 < 0\), the second-order derivative of the utility function of retailer 1 and the profit function of retailer 2 are less zero, which indicate they can get the optimal solutions. \(p_{1,\text{R1VFC}}\) and \(p_{2,\text{R1VFC}}\) are the global optimal solutions of retailer 1 and retailer 2, respectively.
Secondly, taking (16)(17) into (3), the manufacturer’s profit function $\pi_m$ can be acquired. Setting $\frac{\partial \pi_m}{\partial w_1} = 0$ and $\frac{\partial \pi_m}{\partial w_2} = 0$, the manufacturer’s optimal wholesale prices are as follows:

$$w_{1R2VFC} = \frac{[B_1 \lambda_1^2 + B_2 \lambda_1 + 2\sigma(4Q\sigma^2 - Q\sigma + 4c_1 - c_1)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}$$

$$w_{2R2VFC} = \frac{[B_3 \lambda_1^2 + B_4 \lambda_1 + 2\sigma(4Q\sigma - Q + 4c_2 + c_2)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}$$

Where $B_1, B_2, \ldots, B_4$ are shown in appendix B.

The Hessian matrix of the manufacturer’s profit function is

$$H = \begin{pmatrix}
\left(\frac{2(2\sigma - 1)(2\lambda_1 + 1)}{(4\sigma - 1)(\lambda_1 + 1)(\sigma - 1)}\right) & -\frac{3\lambda_1\sigma + \lambda_1 - 2\sigma}{(4\sigma - 1)(\lambda_1 + 1)(\sigma - 1)} \\
-\frac{5\lambda_1\sigma + 2\sigma - 2\sigma}{(4\sigma - 1)(\lambda_1 + 1)(\sigma - 1)} & -\frac{\lambda_1\sigma^2 + \lambda_1 - 2\sigma}{(4\sigma - 1)(\lambda_1 + 1)(\sigma - 1)}
\end{pmatrix}
$$

$$H_{11} = -\frac{2(2\sigma - 1)(2\lambda_1 + 1)}{(4\sigma - 1)(\lambda_1 + 1)(\sigma - 1)} < 0$$

$$\det(H) = \frac{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}{(4\sigma - 1)^2(\lambda_1 + 1)^2(\sigma - 1)} > 0$$

Since $\sigma > 1$, $0 < \lambda_1 < 1$, $H_{11} < 0$, $\det(H) > 0$, the Hessian matrix is negative definite, which indicate $w_{1R2VFC}$, $w_{2R2VFC}$ are the global optimal solutions of the manufacturer.

Lastly, taking (18)(19) into (16)(17) meanwhile, the optimal retail prices are as follows:

$$p_{1R2VFC} = \frac{\sigma[B_5 \lambda_1^2 + B_6 \lambda_1 + 2\sigma(6Q\sigma - 3Q + 2c_1 + c_2)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}$$

$$p_{2R2VFC} = \frac{[B_7 \lambda_1^2 + \sigma B_8 \lambda_1 + 2\sigma(5Q\sigma + 2c_2 - 2Q + c_1)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}$$

Where $B_5, B_6, \ldots, B_8$ are shown in appendix B.

**Theorem 4.2.** In R1VFC scenario, the optimal retail prices of retailer 1 and retailer 2 are $p_{1R1VFC}$ and $p_{2R1VFC}$ respectively, and the manufacturer’s optimal wholesale prices are $w_{1R1VFC}$ and $w_{2R1VFC}$.

### 4.3. Retailer 2 vertical fairness concern model (R2VFC)

As a member of the supply chain, retailer 2 will also concern about the profit distribution between itself and the manufacturer. We propose that retailer 2 has vertical fairness concern with the manufacturer (i.e., R2VFC), the manufacturer and retailer 1 are fairness neutral. The utility function of R2VFC is

$$u_{r_2}(m) = \pi_{r_2} - \lambda_2(\pi_m - \pi_{r_2})$$

Where $\pi_m$ and $\pi_{r_2}$ are the profits of the manufacturer and retailer 2 respectively, the coefficient of R2VFC denoted by $\lambda_2(0 < \lambda_2 < 1)$, $\lambda_2(\pi_m - \pi_{r_2})$ is the fairness utility of retailer 2. As $\lambda_2$ increase, retailer 2 is more concerned about the inequality of profits between itself and the manufacturer.

In R2VFC scenario, the step of game is as follows:

First of all, retailer 1 determines the response function of retail price according to the profit maximization principle, and retailer 2 determines the response function
of price according to the utility maximization principle. Setting \( \frac{\partial \pi_1}{\partial p_1} = 0 \) and \( \frac{\partial w_2}{\partial p_2} = 0 \), the response functions are as follows:

\[
p_1^{R2VFC} = \frac{2\sigma(2Q\sigma - Q + w_1 + w_2) - c_2\sigma + c_1 - w_1 \lambda_2 + 2\sigma(Q\sigma - Q + w_1) + \sigma w_2}{(4\sigma - 1)(\lambda_2 + 1)}
\]

\[
p_2^{R2VFC} = \frac{(Q\sigma - 2c_2\sigma + 4\sigma w_2 - Q + 2c_1 - w_1)\lambda_2 + Q(\sigma - 1) + 2\sigma w_2 + w_1}{(4\sigma - 1)(\lambda_2 + 1)}
\] (23)

Since \( \sigma > 1 \), \( 0 < \lambda_2 < 1 \), \( \frac{\partial^2 \pi_1}{\partial p_1^2} = -\frac{2}{\sigma - 1} < 0 \), \( \frac{\partial^2 w_2}{\partial p_2^2} = -\frac{2\sigma(1 + \lambda_2)}{\sigma - 1} < 0 \), the second-order derivative of the profit function of retailer 1 and the utility function of retailer 2 are less zero, which indicate they can get the optimal solutions. \( p_1^{R2VFC} \) and \( p_2^{R2VFC} \) are the global optimal solutions of retailer 1 and retailer 2, respectively.

Secondly, taking (23)(24) into (3), the manufacturer’s profit function \( \pi_m \) can be acquired. Setting \( \frac{\partial \pi_m}{\partial w_1} = 0 \) and \( \frac{\partial \pi_m}{\partial w_2} = 0 \), the manufacturer’s optimal wholesale price are as follows:

\[
w_1^{R2VFC} = \frac{[C_1\lambda_2^2 + C_2\lambda_2 + 2\sigma(4Q\sigma^2 - Q\sigma + 4c_1\sigma - c_1)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}
\] (25)

\[
w_2^{R2VFC} = \frac{[(C_3\lambda_2^2 + C_4)\lambda_2 + 2\sigma(4Q\sigma - Q + 4c_2\sigma - c_2)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}
\] (26)

Where \( C_1, C_2, \ldots, C_4 \) are shown in appendix C.

The Hessian matrix of the manufacturer’s profit function is

\[
H = \begin{pmatrix}
-\frac{4\sigma(\lambda_2 + 1) - 2}{(\sigma - 1)(\lambda_2 + 1)(\sigma - 1)} & -\frac{-5\lambda_2\sigma + \lambda_2 - 2\sigma}{(4\sigma - 1)(\lambda_2 + 1)(\sigma - 1)} \\
-\frac{-5\lambda_2\sigma + \lambda_2 - 2\sigma}{(4\sigma - 1)(\lambda_2 + 1)(\sigma - 1)} & -\frac{4\lambda_2(\lambda_2 + 1) + 4\sigma(2\sigma - 1)}{(4\sigma - 1)(\lambda_2 + 1)(\sigma - 1)}
\end{pmatrix}
\]

\[
H_{11} = -\frac{4\sigma(\lambda_2 + 1) - 2}{(\sigma - 1)(\lambda_2 + 1)(\sigma - 1)} < 0
\]

\[
det(H) = \frac{(32\sigma^2 - 9\sigma + 1)\lambda_2^2 + (48\sigma^2 - 12\sigma)\lambda_2 + 4\sigma(4\sigma - 1)}{(4\sigma - 1)^2(\lambda_2 + 1)^2(\sigma - 1)} > 0
\]

Since \( \sigma > 1 \), \( 0 < \lambda_2 < 1 \), \( H_{11} < 0 \), \( det(H) > 0 \), the Hessian matrix is negative definite, which indicate \( w_1^{R2VFC}, w_2^{R2VFC} \) are the global optimal solutions of the manufacturer.

Lastly, taking (25)(26) into (23)(24) meanwhile, the optimal retail prices are as follows:

\[
p_1^{R2VFC} = \frac{\sigma[C_5\lambda_2^2 + C_6\lambda_1 + 2\sigma(6Q\sigma - 3Q + 2c_1 + c_2)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}
\] (27)

\[
p_2^{R2VFC} = \frac{[C_7\lambda_2^2 + \sigma C_6\lambda_2 + 2\sigma(5Q\sigma + 2c_2\sigma - 2Q + c_1)]}{(32\sigma^2 - 9\sigma + 1)\lambda_1^2 + (48\sigma^2 - 12\sigma)\lambda_1 + 4\sigma(4\sigma - 1)}
\] (28)

Where \( C_5, C_6, \ldots, C_8 \) are shown in appendix C.

**Theorem 4.3.** In R2VFC scenario, the optimal retail prices of retailer 1 and retailer 2 are \( p_1^{R2VFC} \) and \( p_2^{R2VFC} \) respectively, and the manufacturer’s optimal wholesale prices are \( w_1^{R2VFC} \) and \( w_2^{R2VFC} \).
4.4. Retailer 1 horizontal fairness concern model (R1HFC). There are multiple retailers in the market. If one retailer’s profits are higher than those of others, it will often lead to fairness concern among retailers. Therefore, we consider that retailer 1 has horizontal fairness concern with retailer 2 (i.e., R1HFC), the manufacturer and retailer 2 are fairness neutral. The utility function of R1HFC is

\[ u_{r1}(r_2) = \pi_{r1} - \lambda_3(\pi_{r2} - \pi_{r1}) \]  

(29)

Where \( \pi_{r1} \) and \( \pi_{r2} \) are the profits of retailer 1 and retailer 2 respectively, the coefficient of R1HFC denoted by \( \lambda_3(0 < \lambda_3 < 1) \), \( \lambda_3(\pi_{r2} - \pi_{r1}) \) is the horizontal fairness utility of retailer 1. As \( \lambda_3 \) increases, retailer 1 is more concerned about the inequality of profits between itself and retailer 2.

In R1HFC scenario, the step of game is as follows:

First of all, retailer 1 determines the response function of retail price according to the utility maximization principle, while retailer 2 determines the response function of retail price according to the profit maximization principle. Setting \( \frac{\partial u_{r1}(r_2)}{\partial p_{r1}} = 0 \) and \( \frac{\partial u_{r2}}{\partial p_{r2}} = 0 \), the response functions are as follows:

\[ p_{1R1HFC} = \frac{\sigma(2Q\sigma - 2Q - 2w_1 + 2w_2\lambda_3 + 2Q(\sigma - 1) + 2w_1 + w_2)}{4\sigma(\lambda_3 + 1) - 1} \]  

(30)

\[ p_{2R1HFC} = \frac{(Q\sigma + 2\sigma w_2 - Q + w_1 + w_2\lambda_3 + Q(\sigma - 1) + 2\sigma w_2 + w_1)}{4\sigma(\lambda_3 + 1) - 1} \]  

(31)

Since \( \sigma > 1, 0 < \lambda_3 < 1 \), \( \frac{\partial^2 u_{r1}(r_2)}{\partial p_{r1}^2} = \frac{\partial^2 u_{r2}}{\partial p_{r2}^2} = -2(1 + \lambda_3) < 0 \), the second-order derivative of the utility function of retailer 1 and the profit function of retailer 2 are less zero, which indicate they can get the optimal solutions. \( p_{1R1HFC} \) and \( p_{2R1HFC} \) are the global optimal solutions of retailer 1 and retailer 2, respectively.

Secondly, taking (30)(31) into (3), the manufacturer’s profits function \( \pi_m \) can be acquired. Setting \( \frac{\partial \pi_m}{\partial w_2} = 0 \) and \( \frac{\partial \pi_m}{\partial w_1} = 0 \), the manufacturer’s optimal wholesale prices are as follows:

\[ w_{1R1HFC} = \frac{[D_1\lambda_3^2 + D_2\lambda_3 + 2\sigma(4Q\sigma^2 - Q\sigma + 4c_1\sigma - c_1)]}{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)} \]  

(32)

\[ w_{2R1HFC} = \frac{[D_3\lambda_3^2 + D_4\lambda_3 + 2\sigma(4Q\sigma - Q + 4c_2\sigma - c_2)]}{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)} \]  

(33)

Where \( D_1, D_2, \ldots, D_4 \) are shown in appendix D. The Hessian matrix of the manufacturer’s profit function is

\[ H = \begin{pmatrix}
\frac{(4\sigma - 2)(\lambda_3 + 1)}{(4\lambda_3\sigma + 4\sigma - 1)(\sigma - 1)} & -\frac{-\lambda_3\sigma - \lambda_3 - 2\sigma}{(4\lambda_3\sigma + 4\sigma - 1)(\sigma - 1)} \\
-\frac{\lambda_3\sigma - \lambda_3 - 2\sigma}{(4\lambda_3\sigma + 4\sigma - 1)(\sigma - 1)} & \frac{-\lambda_3\sigma - \lambda_3 - 2\sigma}{(4\lambda_3\sigma + 4\sigma - 1)(\sigma - 1)}
\end{pmatrix} \]

H_{11} = \frac{(4\sigma - 2)(\lambda_3 + 1)}{(4\lambda_3\sigma + 4\sigma - 1)(\sigma - 1)} < 0

\[ \det(H) = \frac{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)}{(4\lambda_3\sigma + 4\sigma - 1)^2(\sigma - 1)} > 0 \]

Since \( \sigma > 1, 0 < \lambda_3 < 1 \), \( H_{11} < 0, \det(H) > 0 \), the Hessian matrix is negative definite, which indicate \( w_{1R1HFC}, w_{2R1HFC} \) are the global optimal solutions of the manufacturer.
Lastly, taking (32)(33) into (30)(31) meanwhile, the optimal retail prices are as follows:

\[ p_1^{R1HFC} = \frac{\sigma[D_5\lambda_3^2 + D_6\lambda_3 + 2\sigma(6Q\sigma - 3Q + 2c_1 + c_2)]}{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)} \]  

\[ p_2^{R1HFC} = \frac{D_7\lambda_3^2 + \sigma D_8\lambda_3 + 2\sigma(5Q\sigma + 2c_2\sigma - 2Q + c_1)}{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)} \]  

Where \( D_5, D_6, \ldots, D_8 \) are shown in appendix D.

**Theorem 4.4.** In R1HFC scenario, the optimal retail prices of retailer 1 and retailer 2 are \( p_1^{R1HFC} \) and \( p_2^{R1HFC} \) respectively, and the manufacturer’s optimal wholesale prices are \( w_1^{R1HFC} \) and \( w_2^{R1HFC} \).

4.5. **Retailer 2 horizontal fairness concern model (R2HFC).** As a competitor of retailer 1, retailer 2 will also horizontally concern about the profits of retailer 1. We consider that retailer 2 has horizontal fairness concern with retailer 1 (i.e., R2HFC), the manufacturer and retailer 1 are fairness neutral. The utility function of retailer 2 is

\[ u_{r2}(r_1) = \pi_{r2} - \lambda_4(\pi_{r1} - \pi_{r2}) \]  

Where \( \pi_{r1} \) and \( \pi_{r2} \) are the profits of retailer 1 and retailer 2 respectively, the coefficient of R2HFC denoted by \( \lambda_4(0 < \lambda_4 < 1) \), \( \lambda_4(\pi_{r1} - \pi_{r2}) \) is the horizontal fairness utility of retailer 2. As \( \lambda_4 \) increases, retailer 2 is more concerned about the inequality of profits between itself and retailer 1.

In R2HFC scenario, the step of game is as follows:

First of all, retailer 1 determines the response function of retail price according to the profit maximization principle, while retailer 2 determines the response function of retail price according to the utility maximization principle. Setting \( \frac{\partial \pi_{r1}}{\partial p_1} = 0 \) and \( \frac{\partial u_{r2}(r_1)}{\partial p_2} = 0 \), the response functions are as follows:

\[ p_1^{R2HFC} = \frac{(2Q\sigma^2 - 2Q\sigma - 2\sigma w_1 + \sigma w_2 + w_1)\lambda_4 + [2Q(\sigma - 1) + 2w_1 + w_2]\sigma}{4\sigma(\lambda_4 + 1) - 1} \]  

\[ p_2^{R2HFC} = \frac{(2\sigma w_2 + 2w_1)\lambda_4 + Q(\sigma - 1) + 2\sigma w_2 + w_1}{4\sigma(\lambda_4 + 1) - 1} \]  

Since \( \sigma > 1, 0 < \lambda_4 < 1 \), \( \frac{\partial^2 \pi_{r1}}{\partial p_1^2} = -\frac{2}{\sigma - 1} < 0, \frac{\partial^2 u_{r2}(r_1)}{\partial p_2^2} = -\frac{2\sigma(1 + \lambda_4)}{\sigma - 1} < 0 \), the second-order derivative of the profit function of retailer 1 and the utility function of retailer 2 are less zero, which indicate they can get the optimal solutions. \( p_1^{R2HFC} \) and \( p_2^{R2HFC} \) are the global optimal solutions of retailer 1 and retailer 2, respectively.

Secondly, taking (37)(38) into (31), the manufacturer’s profits function \( \pi_m \) can be acquired. Setting \( \frac{\partial \pi_m}{\partial w_1} = 0 \) and \( \frac{\partial \pi_m}{\partial w_2} = 0 \), the manufacturer’s optimal wholesale prices are as follows:

\[ w_1^{R2HFC} = \frac{\sigma[E_1\lambda_4^2 + E_2\lambda_4 + 2(4Q\sigma^2 - Q\sigma + 4c_1\sigma - c_1)]}{(16\sigma^2 - \sigma + 1)\lambda_4^2 + (32\sigma^2 - 4\sigma)\lambda_4 + 4\sigma(4\sigma - 1)} \]  

\[ w_2^{R2HFC} = \frac{[E_3\lambda_4^2 + E_4\lambda_4 + 2\sigma(4Q\sigma - Q + 4c_2\sigma - c_2)]}{(16\sigma^2 - \sigma + 1)\lambda_4^2 + (32\sigma^2 - 4\sigma)\lambda_4 + 4\sigma(4\sigma - 1)} \]  

Where \( E_1, E_2, \ldots, E_4 \) are shown in appendix E.
The Hessian matrix of the manufacturer’s profit function is

\[
H = \begin{pmatrix}
\frac{(4\sigma - 2)(\lambda_4 + 1)}{(4\lambda_3 \sigma + 4\sigma - 1)(\sigma - 1)} & \frac{-\lambda_4 \sigma - \lambda_4 - 2\sigma}{(4\lambda_3 \sigma + 4\sigma - 1)(\sigma - 1)} \\
\frac{-\lambda_4 \sigma - \lambda_4 - 2\sigma}{(4\lambda_3 \sigma + 4\sigma - 1)(\sigma - 1)} & \frac{-\lambda_4 \sigma - \lambda_4 - 2\sigma}{(4\lambda_3 \sigma + 4\sigma - 1)(\sigma - 1)}
\end{pmatrix}
\]

\[
H_{11} = \frac{(4\sigma - 2)(\lambda_4 + 1)}{(4\lambda_3 \sigma + 4\sigma - 1)(\sigma - 1)} < 0
\]

\[
\det(H) = \frac{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)}{(4\lambda_3 \sigma + 4\sigma - 1)^2(\sigma - 1)} > 0
\]

Since \( \sigma > 1, 0 < \lambda_4 < 1, H_{11} < 0, \) \( \det(H) > 0, \) the Hessian matrix is negative definite, which indicate \( w_1^{R2HFC}, w_2^{R2HFC} \) are the global optimal solutions of the manufacturer.

Lastly, taking (39)(40) into (37)(38) meanwhile, the optimal retail prices are as follows:

\[
p_1^{R2HFC} = \frac{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)}{(16\sigma^2 - \sigma + 1)\lambda_4^2 + (32\sigma^2 - 4\sigma)\lambda_4 + 4\sigma(4\sigma - 1)}
\]

(41)

\[
p_2^{R2HFC} = \frac{(16\sigma^2 - \sigma + 1)\lambda_3^2 + (32\sigma^2 - 4\sigma)\lambda_3 + 4\sigma(4\sigma - 1)}{(16\sigma^2 - \sigma + 1)\lambda_4^2 + (32\sigma^2 - 4\sigma)\lambda_4 + 4\sigma(4\sigma - 1)}
\]

(42)

Where \( E_5, E_6, \ldots, E_8 \) are shown in appendix E.

**Theorem 4.5.** In R2HFC scenario, the optimal retail prices of retailer 1 and retailer 2 are \( p_1^{R2HFC} \) and \( p_2^{R2HFC} \) respectively, and the manufacturer’s optimal wholesale prices are \( w_1^{R2HFC} \) and \( w_2^{R2HFC} \).

### 4.6. Both retailers’ vertical fairness concern model (BVFC).

In reality, retailer 1 and retailer 2 are likely to have vertical fairness concern at the same time.

Next, we consider the scenario where both retailer 1 and retailer 2 have vertical fairness concern (i.e., BVFC). In BVFC scenario, the step of game is as follows:

First of all, retailer 1 and retailer 2 determine the response functions of retail price respectively, according to the utility maximization principle. Setting \( \frac{\partial u_2}{\partial p_2} = 0 \) and \( \frac{\partial u_2}{\partial w_2} = 0 \), the response functions are as follows:

\[
p_1^{BVFC} = \frac{(F_1 \lambda_2 + F_2) \sigma + \lambda_2 (\lambda_1 + 1) (c_1 - w_1) + 2Q (\lambda_1 + 1) (\lambda_2 + 1) \sigma^2}{(4\sigma - 1) (\lambda_2 + 1) (\lambda_1 + 1)}
\]

(43)

\[
p_2^{BVFC} = \frac{(F_3 + F_4) \lambda_1 + (F_5) \lambda_2 + (Q + 2w_2) \sigma - Q + w_1}{(4\sigma - 1) (\lambda_2 + 1) (\lambda_1 + 1)}
\]

(44)

Where \( F_1, F_2, \ldots, F_5 \) are shown in appendix F.

Since \( \sigma > 1, 0 < \lambda_1, \lambda_2 < 1, \frac{\partial^2 u_2}{\partial p_2^2} = -\frac{2\sigma(1+\lambda_2)}{\sigma - 1} < 0, \frac{\partial^2 u_2}{\partial w_2^2} = -\frac{2\sigma(1+\lambda_2)}{\sigma - 1} < 0, \) the second-order derivative of the utility function of retailer 1 and retailer 2 are less zero, which indicate they can get the optimal solutions. \( p_1^{BVFC} \) and \( p_2^{BVFC} \) are the global optimal solutions of retailer 1 and retailer 2, respectively.

Secondly, taking (43)(44) into (3), the manufacturer’s profit function \( \pi_m \) can be acquired. Setting \( \frac{\partial \pi_m}{\partial w_1} = 0 \) and \( \frac{\partial \pi_m}{\partial w_2} = 0 \), the manufacturer’s optimal wholesale
prices are as follows:

$$w_1^{\text{BVFC}} = \frac{F_0Q\sigma^3 + (F_7Q + F_{68}c_1 + F_{69} c_2) \sigma^2 + F_{10}Q + F_{11} c_1 + F_{12} c_2 \sigma + F_{13} c_1}{F_{14} \sigma^2 + F_{15} \sigma + 4\lambda^2 \lambda_1^2 + 4\lambda^2 \lambda_1 + 4\lambda_2 \lambda_1^2 + \lambda_2^2 + 2\lambda_2 \lambda_1 + \lambda_1^2}$$

$$w_2^{\text{BVFC}} = \frac{(F_{12}Q + F_{17}c_2) \sigma^2 + (F_{18}Q + F_{19} c_1 + F_{20} c_2) \sigma + F_{16} c_1 + F_{13} c_2}{F_{14} \sigma^2 + F_{15} \sigma + 4\lambda^2 \lambda_1^2 + 4\lambda^2 \lambda_1 + 4\lambda_2 \lambda_1^2 + \lambda_2^2 + 2\lambda_2 \lambda_1 + \lambda_1^2}$$

(45)

(46)

Where $F_6, F_7, \ldots, F_{20}$ are shown in appendix F.

The Hessian matrix of the manufacturer’s profit function is

$$H = \begin{pmatrix}
\frac{(8\lambda^2 \lambda_1 + 4\lambda \lambda_1 + 8\lambda_1 + 4\sigma^2 - 2\lambda_2 \lambda_1 - 4\lambda_1 - 2)}{-(\sigma - 1)(\lambda_1 + 1)(4\sigma - 1)(\lambda_2 + 1)} & \frac{(8\lambda^2 + 5\lambda \lambda_1 + 5\lambda^2 + 2) \sigma + (4\lambda_2^2 - 1) \lambda_1 - \lambda_2}{(\sigma - 1)(\lambda_1 + 1)(4\sigma - 1)(\lambda_2 + 1)} \\
\frac{2\sigma(4\lambda_2 \lambda_1 - 2\lambda_2 \lambda_1 + 4\lambda_2 \sigma + 2\lambda_1 \sigma - 2\lambda_2^2 - 2\sigma - 1)}{-(\sigma - 1)(\lambda_1 + 1)(4\sigma - 1)(\lambda_2 + 1)} & \frac{(8\lambda^2 \lambda_1 + 4\lambda \lambda_1 + 8\lambda_1 + 4\sigma^2 - 2\lambda_2 \lambda_1 - 4\lambda_1 - 2)}{-(\sigma - 1)(\lambda_1 + 1)(4\sigma - 1)(\lambda_2 + 1)}
\end{pmatrix}$$

$$H_{11} = -\frac{(8\lambda_2 \lambda_1 + 4\lambda_2 + 8\lambda_1 + 4) \sigma - 2\lambda_2 \lambda_1 - 4\lambda_1 - 2}{(\sigma - 1)(\lambda_1 + 1)(4\sigma - 1)(\lambda_2 + 1)} < 0$$

$$\det(H) = \frac{F_2 \sigma^2 + F_22 \sigma + 4\lambda_2 \lambda_1 \lambda_1^2 + 4\lambda^2 \lambda_1^2 + 4\lambda_2 \lambda_1^2 + \lambda_2^2 + 2\lambda_2 \lambda_1 + \lambda_1^2}{((\lambda_1 + 1)(4\sigma - 1)(\lambda_2 + 1))^2 (\sigma - 1)} > 0$$

Where $F_21, F_22$ are shown in appendix F.

Since $\sigma > 1, 0 < \lambda_1, \lambda_2 < 1, H_{11} < 0, \det(H) > 0$, the Hessian matrix is negative definite, which indicate $w_1^{\text{BVFC}}, w_2^{\text{BVFC}}$ are the global optimal solutions of the manufacturer. Lastly, taking (45)(46) into (43)(44) meanwhile, the optimal retail prices are as follows:

$$p_1^{\text{BVFC}} = \frac{F_{23}Q \sigma^3 + (F_{24}Q + F_{25} c_1 + F_{26} c_2) \sigma^2 + (F_{27}Q + F_{28} c_1 + F_{29} c_2) \sigma}{F_{14} \sigma^2 + F_{15} \sigma + 4\lambda^2 \lambda_1^2 + 4\lambda^2 \lambda_1 + 4\lambda_2 \lambda_1^2 + \lambda_2^2 + 2\lambda_2 \lambda_1 + \lambda_1^2}$$

$$p_2^{\text{BVFC}} = \frac{(F_{30}Q + F_{31} c_2) \sigma^2 + (F_{32}Q + F_{33} c_1 + F_{44} c_2) \sigma + F_{35}Q + F_{36} c_1}{F_{14} \sigma^2 + F_{15} \sigma + 4\lambda^2 \lambda_1^2 + 4\lambda^2 \lambda_1 + 4\lambda_2 \lambda_1^2 + \lambda_2^2 + 2\lambda_2 \lambda_1 + \lambda_1^2}$$

(47)

(48)

Where $F_{23}, F_{24}, \ldots, F_{30}$ are shown in appendix F.

**Theorem 4.6.** In BVFC scenario, the optimal retail prices of retailer 1 and retailer 2 are $p_1^{\text{BVFC}}$ and $p_2^{\text{BVFC}}$ respectively, and the manufacturer’s optimal wholesale prices are $w_1^{\text{BVFC}}$ and $w_2^{\text{BVFC}}$.

4.7. **Both retailers—horizontal fairness concern model (BHFC).** Similarly, retailer 1 and retailer 2 may also have horizontal fairness concern at the same time. Lastly, we consider the scenario where both retailer 1 and retailer 2 have horizontal fairness concern (i.e., BHFC). In BHFC scenario, the step of game is as follows:

First of all, retailer 1 and retailer 2 determine the response functions of retail price respectively, according to the utility maximization principle. Setting $\frac{\partial u_1 (r_1)}{\partial p_1} = 0$ and $\frac{\partial u_2 (r_2)}{\partial p_2} = 0$, the response functions are as follows:

$$p_1^{\text{BHFC}} = \frac{2Q (\lambda_3 + 1) (\lambda_4 + 1) \sigma^2 - 2 (\lambda_4 + 1) G_1 \sigma + \lambda_4 w_1}{4 (\lambda_3 + 1) (\lambda_4 + 1) \sigma - 1}$$

$$p_2^{\text{BHFC}} = \frac{(\lambda_3 + 1) (2\lambda_4 w_2 + Q + 2w_2) \sigma + G_2 \lambda_3 + 2\lambda_4 w_1 - Q + w_1}{4 (\lambda_3 + 1) (\lambda_4 + 1) \sigma - 1}$$

(49)

(50)

Where $G_1, G_2$ are shown in appendix G.
Since $\sigma > 1$, $0 < \lambda_1, \lambda_2 < 1$, \( \frac{\partial^2 u_1(\tau_r)}{\partial p_1^2} = -\frac{2(1+\lambda_3)}{\sigma-1} < 0 \), \( \frac{\partial^2 u_2(\tau_1)}{\partial p_2^2} = -\frac{2\sigma(1+\lambda_4)}{\sigma-1} < 0 \), the second-order derivative of the utility function of retailer 1 and retailer 2 are less zero, which indicate they can get the optimal solutions. $p_1^{BHFC}$ and $p_2^{BHFC}$ are the global optimal solutions of retailer 1 and retailer 2, respectively.

Secondly, taking (49)(50) into (3), the manufacturer’s profit function $\pi$ can be acquired. Setting $\pi_m = 0$ and $\pi_m = 0$, the manufacturer’s optimal wholesale prices are as follows:

\[ w_1^{BHFC} = \frac{G_3Q\sigma^3 + (G_4Q + G_5c_1 + G_6c_2)\sigma^2 + (G_7Q + G_8c_1 + G_9c_2)\sigma + G_{10}}{G_{11}\sigma^2 + G_{12}\sigma + (\lambda_3 + \lambda_4)^2} \]  
\[ w_2^{BHFC} = \frac{(G_{13}Q + G_{14}c_2)\sigma^2 + (G_{15}Q + G_{16}c_1 + G_{17}c_2)\sigma + G_{18}c_1 + G_{19}}{G_{13}\sigma^2 + G_{14}\sigma + (\lambda_3 + \lambda_4)^2} \]  
\[ H = \left( \begin{array}{cc} 4\lambda_3\lambda_4 + 2(\lambda_3 + \lambda_4 + 1) - 4\sigma(\lambda_3 + 1)(\lambda_4 + 1) & -(-\lambda_3 - \lambda_4 - 2)\sigma - \lambda_3 - \lambda_4 \\ -(-\lambda_3 + \lambda_4 + 2) - \lambda_3 - \lambda_4 & 4\sigma^2(\lambda_3\lambda_4 + \lambda_3 + \lambda_4 + 1) - 2\lambda_3\lambda_4 + 2\lambda_3 + 2\lambda_4 + 1 \end{array} \right) \]
\[ H_{11} = \frac{4\lambda_3\lambda_4 + 4\lambda_3 + 4\lambda_4 + 4\sigma - 4\lambda_3\lambda_4 - 2\lambda_3 - 2\lambda_4 \sigma - 2}{(4\sigma(\lambda_3 + 1)(\lambda_4 + 1) - 1)^2 (\sigma - 1)} < 0 \]
\[ \det(H) = \frac{G_{20}\sigma^2 - G_{21}\sigma + (\lambda_3 + \lambda_4)^2}{(4\sigma(\lambda_3 + 1)(\lambda_4 + 1) - 1)^2 (\sigma - 1)} > 0 \]

Where $G_{13}, G_{14}, \ldots, G_{19}$ are shown in appendix G.

Lastly, taking (51)(52) into (49)(50) meanwhile, the optimal retail prices are as follows:

\[ p_1^{BHFC} = \frac{G_{22}Q\sigma^3 + (G_{23}Q + G_{24}c_1 + G_{25}c_2)\sigma^2 + (G_{26} + G_{27}c_1)\sigma + G_{28}}{G_{22}\sigma^2 + G_{13}\sigma + (\lambda_3 + \lambda_4)^2} \]  
\[ p_2^{BHFC} = \frac{(G_{29}Q + G_{30}c_2)\sigma^2 + (G_{31}Q + G_{32}c_1 + G_{33}c_2)\sigma + G_{34} + G_{35}}{G_{11}\sigma^2 + G_{12}\sigma + (\lambda_3 + \lambda_4)^2} \]  
\[ G_{22}, G_{23}, \ldots, G_{45} \text{ are shown in appendix G.} \]

**Theorem 4.7.** In BVFC scenario, the optimal retail prices of retailer 1 and retailer 2 are $p_1^{BHFC}$ and $p_2^{BHFC}$ respectively, and the manufacturer’s optimal wholesale prices are $w_1^{BHFC}$ and $w_2^{BHFC}$.

5. **Numerical simulation.** In this section, numerical simulation is adopted to illustrate the combined impacts of fairness concern $\lambda$ and CGP $\sigma$ on the profits of the supply chain. Based on the previous research [8, 9] and the model assumption in this study, we set various parameter values and analyze our models under different scenarios. Assume that $Q = 1000$, $c_1 = 600$, $c_2 = 400$, $\sigma = 1.3$ and $\sigma = 1.9$. The low level of CGP is indicated when $\sigma = 1.3$, and the high level of CGP is indicated when $\sigma = 1.9$. According to those parameter values, numerical simulations are carried out in the above-mentioned scenarios by using Maple and Matlab mathematical software.
5.1. Numerical simulation in R1VFC scenario. The following simulation results in R1VFC scenario can be obtained by using Maple mathematical software to calculate as shown in Table 3 and Table 4. Besides, Figure 3 generated by the Matlab mathematical software shows the combined impacts of CGP and R1VFC on profits, so that the simulation results in Table 3 and Table 4 more intuitive.

Table 3. Simulation results in R1VFC scenario (σ=1.3)

| λ   | 0     | 0.2   | 0.4   | 0.6   | 0.8   | 1     |
|-----|-------|-------|-------|-------|-------|-------|
| πₘ  | 87460.32 | 86524.90 | 86036.24 | 85740.94 | 85545.31 | 85407.17 |
| π₁   | 5461.07  | 6860.16  | 7658.16  | 8173.59  | 8533.38  | 8798.38  |
| u₁(m) | 5461.07  | -9072.79  | -23693.07 | -38366.83 | -53076.16 | -67810.41 |
| π₂   | 4151.55  | 3743.56  | 3474.70  | 3283.23  | 3139.67  | 3027.98  |
| π₃   | 97072.94 | 97128.61 | 97169.10 | 97197.76 | 97218.36 | 97233.53 |
| w₁   | 950.00   | 940.76   | 935.74   | 932.61   | 930.47   | 928.93   |
| w₂   | 700.00   | 702.32   | 703.72   | 704.67   | 705.36   | 705.89   |
| p₁   | 990.48   | 989.44   | 988.47   | 987.64   | 986.96   | 986.39   |
| p₂   | 730.95   | 731.71   | 732.04   | 732.20   | 732.28   | 732.32   |
| q₁   | 134.92   | 140.92   | 145.25   | 148.52   | 151.08   | 153.13   |
| q₂   | 134.13   | 127.37   | 122.71   | 119.28   | 119.28   | 114.55   |

Table 4. Simulation results in R1VFC scenario (σ=1.9)

| λ   | 0     | 0.2   | 0.4   | 0.6   | 0.8   | 1     |
|-----|-------|-------|-------|-------|-------|-------|
| πₘ  | 155016.84 | 144556.70 | 138807.59 | 135177.66 | 132679.87 | 130857.09 |
| π₁   | 39855.63  | 51731.18  | 58474.09  | 62842.05  | 65909.71  | 68185.73  |
| u₁(m) | 39855.63  | 33166.07  | 26340.69  | 19440.69  | 12493.58  | 5514.37   |
| π₂   | 1749.57   | 1341.72   | 1111.64   | 963.61    | 860.41    | 784.43    |
| π₃   | 196622.03 | 197629.60 | 198393.33 | 198983.32 | 199449.99 | 199827.24 |
| w₁   | 1250.00   | 1198.20   | 1169.67   | 1151.63   | 1139.20   | 1130.12   |
| w₂   | 700.00    | 707.25    | 711.43    | 714.17    | 716.11    | 717.56    |
| p₁   | 1439.39   | 1439.58   | 1438.92   | 1438.11   | 1437.33   | 1436.62   |
| p₂   | 728.79    | 732.46    | 734.38    | 735.53    | 736.30    | 736.84    |
| q₁   | 210.44    | 214.32    | 217.18    | 219.36    | 221.08    | 222.47    |
| q₂   | 60.77     | 53.22     | 48.44     | 45.10     | 42.62     | 40.69     |

The following conclusion can be obtained from Figure (3-a) and Figure (3-c).
(1) In R1VFC scenario, the profits of retailer 1 increase as λ₁ increases, while the manufacture’s profits decrease.

The profits of retailer 1 and the manufacture under the high level of CGP (shown in the primary axis) are higher than those under the low level of CGP (shown in the secondary axis). In addition, R1VFC affects its profits and the manufacture’s profits. From simulation results in Table 3 and Table 4, w₁ and p₁ become lower as λ₁ increases, which means retailer 1 has a powerful competition ability in the market and bargaining power with the manufacturer. Therefore, R1VFC increases its profits but reduces the manufacture’s profits.

The following conclusion can be obtained from Figure (3-b) and Figure (3-d).
(2) In R1VFC scenario, the profits of retailer 2 decrease as λ₁ increases, while the whole supply chain’s profits increase.
The profits of retailer 2 under the high level of CGP are lower than those under the low level of CGP, while the whole supply chain’s profits under the high level of CGP are higher. R1VFC also affects the profits of retailer 2 and the whole supply chain. What’s more, \( w_2 \) and \( p_2 \) gets higher as the \( \lambda_1 \) increases, which means retailer 2 has a weak competition ability in the market. As a result, R1VFC reduces the profits of retailer 2.

As for the whole supply chain’s profits, the conclusion we obtained is different from the previous research [36] which pointed out that the retailer’s fairness concern would reduce the profits of the supply chain system. On the contrary, our research finds that retailers’ fairness concern may also increase the whole supply chain’s profits under three-party supply chain. How to explain this phenomenon? From \( \pi_m, \pi_{r1}, \pi_{r2} \) in Table 3 and Table 4, we can find that the higher level of R1VFC, the greater profits of retailer 1. Importantly, the profit rise of retailer 1 is more than the sum of profit loss of both the manufacturer and retailer 2, so the whole supply chain’s profits increase rather than decrease. We call this phenomenon “prominent effect”. What’s more, the “prominent effect” of retailer 1 is stronger with the level of CGP increases.

5.2. Numerical simulation in R2VFC scenario. Similarly, the following simulation results in R2VFC scenario can be obtained as shown in Table 5 and Table 6, and the combined impacts of CGP and R2VFC on profits are shown in Figure 4.

The following conclusion can be obtained from Figure (4-b) and Figure (4-c).
Table 5. Simulation results in R2VFC scenario (σ=1.3)

| λ  | 0       | 0.2     | 0.4    | 0.6    | 0.8    | 1       |
|----|---------|---------|--------|--------|--------|---------|
| πₘ | 87460.32| 86899.17| 86618.75| 86456.23| 86352.69| 86282.19|
| πᵣ₁| 546.07  | 4999.86 | 4691.87 | 4470.61 | 4303.71 | 4173.24 |
| πᵣ₂| 4151.55 | 5123.74 | 5674.90 | 6027.98 | 6272.30 | 6450.71 |
| uᵣ₂(ₘ) | 4151.55 | -11231.34| -26702.65| -42228.97| -57792.01| -73380.78|
| πₛ  | 97072.94| 97022.77| 96985.52| 96954.82| 96928.70| 96906.13|
| w₁  | 950.00  | 952.33  | 953.75  | 954.72  | 955.43  | 955.97  |
| w₂  | 700.00  | 693.48  | 689.96  | 687.77  | 686.28  | 685.21  |
| p₁  | 990.48  | 991.06  | 991.27  | 991.34  | 991.36  | 991.36  |
| p₂  | 730.95  | 729.78  | 728.78  | 727.96  | 727.29  | 726.74  |
| q₁  | 134.92  | 129.10  | 125.06  | 122.07  | 119.77  | 117.94  |
| q₂  | 134.13  | 141.12  | 146.16  | 149.96  | 152.93  | 155.32  |

Table 6. Simulation results in R2VFC scenario (σ=1.9)

| λ  | 0       | 0.2     | 0.4    | 0.6    | 0.8    | 1       |
|----|---------|---------|--------|--------|--------|---------|
| πₘ | 155016.8| 155448.8| 155762.9| 156000.9| 156187.4| 156337.3|
| πᵣ₁| 39855.6 | 38438.3 | 37444.8 | 36708.8 | 36141.3 | 35690.3 |
| πᵣ₂| 1749.5  | 1746.2  | 1684.0  | 1604.9  | 1524.0  | 1447.2  |
| uᵣ₂(ₘ) | 1749.5 | -28994.2 | -59947.4 | -91032.7 | -122206.6 | -153442.8 |
| πₛ  | 196622.0| 195633.3| 194891.8| 194314.7| 193852.8| 193474.8|
| w₁  | 1250.0  | 1252.3  | 1253.9  | 1255.1  | 1256.0  | 1256.7  |
| w₂  | 700.0   | 699.0   | 698.6   | 698.4   | 698.3   | 698.3   |
| p₁  | 1439.3  | 1438.3  | 1437.5  | 1436.8  | 1436.3  | 1435.9  |
| p₂  | 728.7   | 724.3   | 721.1   | 718.6   | 716.7   | 715.2   |
| q₁  | 210.4   | 206.6   | 203.9   | 201.9   | 200.3   | 199.1   |
| q₂  | 60.7    | 69.01   | 74.9    | 79.3    | 82.8    | 85.6    |

(3) In R2VFC scenario, when the level of CGP is low, the profits of retailer 2 increase as λ₂ increases, while the manufacturer’s profits decrease. In contrast, when the level of CGP is high, the profits of retailer 2 decrease as λ₂ increases, while the manufacturer’s profits increase.

The profits of retailer 2 and the manufacturer are influenced by CGP and R2VFC simultaneously. From simulation results in Table 5 and Table 6, w₂ and p₂ gets lower as λ₂ increases when the level of CGP is low, which means retailer 2 has a powerful competition ability in the market. Therefore, R2VFC increases its profits while reduces the manufacturer’s profits. However, R2VFC decreases its profits while increases the manufacturer’s profits when the level of CGP is high. Although retailer 2 can gain certain advantages in the wholesale price and the retail price by R2VFC in this situation, retailer 1 adopts price reduction strategy to compete with retailer 2. Besides, influenced by the high level of CGP, the product sales of retailer 2 do not improve as expected. On the contrary, the manufacturer gains more profits due to the price competition between the retailers, so the profits of retailer 2 decreases but the manufacturer’s profits increase when the level of CGP is high.

The following conclusion can be obtained from Figure (4-a) and Figure (4-d).
In R2VFC scenario, the profits of retailer 1 and the whole supply chain decrease as the $\lambda_2$ increases.

From simulation results in Table 5 and Table 6, $w_1$ and $p_1$ gets higher as $\lambda_2$ increases when the level of CGP is low, which means retailer 1 has a weak competition ability in the market. Therefore, R2VFC reduces the profits of retailer 1. Although retailer 2 can improve certain profits by R2VFC, it also reduces the profits of retailer 1 and the manufacturer. As for the whole supply chain, the sum of profit reduction is greater than the sum of profit increase of retailer 2, so the whole supply chain’s profits decrease as $\lambda_2$ increases. When the level of CGP is high, retailer 1 and retailer 2 will compete with each other, which reduces their profits. In particular, the sum of profit reduction of both retailer 1 and retailer 2 is greater than the sum of the manufacturer’s profit rise, so the whole supply chain’s profits still decrease as $\lambda_2$ increases.

5.3. **Comparative analysis between R1VFC and R2VFC.** Comparing Figure (3-a) and Figure (4-a), we can see that the profits of retailer 1 can be benefited by R1VFC, but will be damaged by R2VFC. Therefore, while the green retailer concerns about the manufacturer’s profits, it should also consider losses caused by the traditional retailer’s VFC.

Comparing Figure (3-b) and Figure (4-b), the profits of retailer 2 are always damaged by R1VFC, while influenced by CGP and fairness concern simultaneously in R2VFC scenario. When the level of CGP is low, R2VFC is beneficial to its profits.
In contrast, R2VFC is bad for its profits when the level of CGP is high. Therefore, the traditional retailer should understand the level of consumers’ preference for green products through careful market research (e.g., delivering questionnaires) and then carry out strategies.

Comparing Figure (3-c) and Figure (4-c), R1VFC and R2VFC have negative impact on the manufacturer when the level of CGP is low, while R2VFC has positive impact on the manufacturer when the level of CGP is high. Therefore, the manufacturer should deal with the fairness of benefit distribution with two retailers when the level of CGP is low, while should pay more attention to the fairness of benefit distribution between itself and the green retailer when the level of CGP is high. This is because the traditional retailer’s VFC will cause price competition between retailers when the level of CGP is high, and the manufacturer can benefit from it.

Comparing Figure (3-d) and Figure (4-d), R1VFC and R2VFC have different effects on the whole supply chain. R1VFC has positive effect on the whole supply chain, while R2VFC has negative effect on the whole supply chain. However, the negative effect of the traditional retailer’s VFC can be relieved through some measures such as profit redistribution to improve the benefit of the whole supply chain.

5.4. **Numerical simulation in R1HFC scenario.** Similarly, the following simulation results in R1HFC scenario can be obtained as shown in Table 7 and Table 8, and the combined impacts of CGP and R1HFC on profits are shown in Figure 5.

| Table 7. Simulation results in R1HFC scenario ($\sigma=1.3$) |
|-------------|------------|------------|------------|------------|------------|------------|
| $\lambda$  | 0          | 0.2        | 0.4        | 0.6        | 0.8        | 1          |
| $\pi_m$    | 87400.32   | 88162.13   | 88670.59   | 89055.92   | 89358.01   | 89601.20   |
| $\pi_{r1}$ | 5461.07    | 4804.17    | 4323.18    | 3955.74    | 3665.87    | 3431.35    |
| $ur_1(r_2)$| 5461.07    | 4914.64    | 4323.11    | 3702.96    | 3063.48    | 2410.34    |
| $\pi_{r2}$ | 4151.55    | 4251.80    | 4323.35    | 4377.05    | 4418.87    | 4452.37    |
| $\pi_s$    | 97072.94   | 97218.10   | 97317.12   | 97388.71   | 97442.75   | 97484.92   |
| $w_1$      | 950.00     | 952.61     | 954.51     | 955.96     | 957.10     | 958.01     |
| $w_2$      | 700.00     | 697.39     | 695.52     | 694.10     | 692.99     | 692.10     |
| $p_1$      | 990.48     | 988.05     | 986.29     | 984.96     | 983.91     | 983.07     |
| $p_2$      | 730.95     | 728.72     | 727.10     | 725.88     | 724.92     | 724.15     |
| $q_1$      | 134.92     | 135.55     | 136.02     | 136.40     | 136.70     | 136.94     |
| $q_2$      | 134.13     | 135.74     | 136.87     | 137.72     | 138.38     | 138.90     |

The following conclusion can be obtained from Figure (5-a), Figure (5-b) and Figure (5-c).

(5) In R1HFC scenario, the profits of retailer 1 decrease as $\lambda_3$ increases, while the profits of retailer 2 and the manufacturer decrease.

We can see that the impact of R1HFC is different from R1VFC. Specifically, R1VFC is good for retailer 1 but bad for retailer 2 and the manufacturer, while R1HFC is bad for itself but good for retailer 2 and the manufacturer. This shows that retailer 1 should reduce the perception of horizontal unfairness, which is unfavorable to itself.

The following conclusion can be obtained from Figure (5-d).
Table 8. Simulation results in R1HFC scenario ($\sigma=1.9$)

| $\lambda$ | 0   | 0.2 | 0.4 | 0.6 | 0.8 | 1     |
|-----------|-----|-----|-----|-----|-----|-------|
| $\pi_m$   | 155016.84 | 156077.52 | 156896.16 | 157542.60 | 158064.30 | 158493.43 |
| $\pi_r$   | 39855.63 | 38221.01 | 36996.40 | 36046.73 | 35289.49 | 34671.87 |
| $u_r_1(r_2)$ | 39855.63 | 45435.93 | 50817.12 | 56069.28 | 61233.10 | 66333.79 |
| $\pi_{r_2}$ | 1749.57 | 2146.42 | 2444.61 | 2675.82 | 2859.98 | 3009.96 |
| $\pi_s$   | 196622.03 | 196444.95 | 196337.17 | 196265.15 | 196213.77 | 196175.26 |
| $w_1$     | 700.00 | 691.75 | 685.91 | 681.55 | 678.18 | 675.48 |
| $w_2$     | 1439.39 | 1435.49 | 1432.54 | 1430.24 | 1428.40 | 1426.90 |
| $p_1$     | 728.79 | 723.63 | 719.94 | 717.16 | 714.98 | 713.24 |
| $p_2$     | 210.44 | 209.05 | 208.22 | 207.68 | 207.31 | 207.04 |
| $q_1$     | 134.13 | 127.37 | 122.71 | 119.28 | 119.28 | 114.55 |
| $q_2$     | 196622.03 | 196444.95 | 196337.17 | 196265.15 | 196213.77 | 196175.26 |

Figure 5. Combined impacts of CGP and R1HFC on profits

(6) In R1HFC scenario, the whole supply chain’s profits increase as $\lambda_3$ increases when the level of CGP is low, while decrease when the level of CGP is high. The whole supply chain’s profits under the high level of CGP is still higher than those under the low level of CGP. In addition, the whole supply chain’s profits are influenced by CGP and R1HFC simultaneously. Specifically, R1HFC has positive impact on the whole supply chain when the level of CGP is low, while has negative
impact on it when the level of CGP is high. This shows that the profits loss of retailer 1 caused by its HFC will greatly increase with the improve of CGP.

5.5. Numerical simulation in R2HFC scenario. Similarly, the following simulation results in R2HFC scenario can be obtained as shown in Table 9 and Table 10, and the combined impacts of CGP and R2HFC on profits are shown in Figure 6.

![Graphs showing combined impacts of CGP and R2HFC on profits](attachment:graphs.png)

**Figure 6.** Combined impacts of CGP and R2HFC on profits

The following conclusion can be obtained from Figure (6-b) and Figure (6-c).

(7) In R2HFC scenario, the profits of retailer 2 decrease as $\lambda_4$ increases, while the manufacturer’s profits increase.

R2HFC is bad for retailer 2, but beneficial to the manufacturer. This shows that retailer 2 should reduce the perception of horizontal unfairness, which has negative effect on its profits, while the manufacturer can benefit from it.

The following conclusion can be obtained from Figure (6-a) and Figure (6-d).

(8) In R2HFC scenario, the profits of retailer 1 and the whole supply chain increase as $\lambda_4$ increases when the level of CGP is low, while decrease when the level of CGP is high.

The profits of retailer 1 and the whole supply chain are influenced by R2HFC and CGP simultaneously. R2HFC is beneficial to retailer 1 and the whole supply chain when the level of CGP is low, while bad for them when the level of CGP is high. As for retailer 1, although its profits will be improved with the level of CGP
increases, the HFC of retailer 2 should be considered at the same time in order to reduce the loss of profits.

5.6. Comparative analysis between R1HFC and R2HFC. Comparing Figure (5-a) and Figure (6-a), Figure (5-b) and Figure (6-b), the impacts of R1HFC and R2HFC are not completely symmetrical. Specifically, the profits of retailer 1 decrease as $\lambda_3$ increases in R1HFC scenario, while influenced by CGP in R2HFC scenario. R2HFC is beneficial to retailer 1 when the level of CGP is low, while bad for it when the level of CGP is high. Therefore, on the one hand, the green retailer should reduce the perception of horizontal unfairness. On the other hand, the HFC of the traditional retailer should also be considered to reduce the loss of profits when the level of CGP is high.

Comparing Figure (5-c) and Figure (6-c), Figure (5-d) and Figure (6-d), we can find that it is same that the impacts of R1HFC and R2HFC on the profits of the manufacturer and the whole supply chain. Interestingly, $w_1^{R1HFC}, w_2^{R1HFC} \neq w_1^{R2HFC}, w_2^{R2HFC}$, but $p_1^{R1HFC}, p_2^{R1HFC} = p_1^{R2HFC}, p_2^{R2HFC}$. This indicates that although the manufacturer’s optimal wholesale price is affected by R1HFC and R2HFC, the optimal retail prices of two retailers are not affected. In real life, we are difficult to discover this conclusion. Even if the green retailer and the traditional

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**Table 9. Simulation results in R2HFC scenario ($\sigma=1.3$)**

| $\lambda$ | 0         | 0.2       | 0.4       | 0.6       | 0.8       | 1         |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\pi_m$  | 87400.32  | 88162.13  | 88670.59  | 89055.92  | 89358.01  | 89601.20  |
| $\pi_{r_1}$ | 5461.07   | 5511.81   | 5550.75   | 5581.37   | 5605.99   | 5626.19   |
| $u_{r_2}(r_1)$ | 4151.55   | 3544.17   | 3095.78   | 2751.42   | 2478.75   | 2257.54   |
| $\pi_{r_1}$ | 4115.55   | 3150.64   | 2113.79   | 1053.45   | -23.04    | -1111.10  |
| $\pi_s$  | 97072.94  | 97218.11  | 97317.12  | 97388.71  | 97442.75  | 97484.93  |
| $w_1$  | 950.00    | 947.39    | 945.49    | 944.04    | 942.90    | 941.99    |
| $w_2$  | 700.00    | 702.61    | 704.48    | 705.90    | 707.01    | 707.90    |
| $p_1$  | 990.48    | 988.05    | 986.29    | 984.96    | 983.91    | 983.07    |
| $p_2$  | 730.95    | 728.72    | 727.10    | 725.88    | 724.92    | 724.15    |
| $q_1$  | 134.92    | 135.55    | 136.02    | 136.40    | 136.70    | 136.94    |
| $q_2$  | 134.13    | 135.74    | 136.87    | 137.72    | 138.38    | 138.90    |

**Table 10. Simulation results in R2HFC scenario ($\sigma=1.9$)**

| $\lambda$ | 0         | 0.2       | 0.4       | 0.6       | 0.8       | 1         |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\pi_m$  | 155016.84 | 156077.52 | 156896.16 | 157542.60 | 158064.30 | 158493.43 |
| $\pi_{r_1}$ | 39855.63  | 39331.98  | 39020.85  | 38819.46  | 38680.82  | 38580.82  |
| $u_{r_2}(r_1)$ | 1749.57   | 1035.45   | 420.15    | -96.91    | -531.35   | -898.98   |
| $\pi_{r_1}$ | 1749.57   | -6623.86  | -15020.13 | -23446.73 | -31901.08 | -40378.78 |
| $\pi_s$  | 196622.04 | 196444.95 | 196337.16 | 196265.15 | 196213.77 | 196175.27 |
| $w_1$  | 1250.00   | 1247.34   | 1245.14   | 1243.32   | 1241.82   | 1240.56   |
| $w_2$  | 700.00    | 708.25    | 714.09    | 718.45    | 721.82    | 724.52    |
| $p_1$  | 1439.39   | 1435.49   | 1432.54   | 1430.24   | 1428.40   | 1426.90   |
| $p_2$  | 728.79    | 723.63    | 719.94    | 717.16    | 714.98    | 713.24    |
| $q_1$  | 210.44    | 209.05    | 208.22    | 207.68    | 207.31    | 207.04    |
| $q_2$  | 134.13    | 135.74    | 136.87    | 137.72    | 138.38    | 138.90    |
retailer are competitors, they are both concerned about the profits of each other, and the unilateral HFC will not change their optimal retail price.

5.7. **Numerical simulation in BVFC scenario.** In order to better study the combined impacts of CGP and BVFC on the profits, the following graphs generated by Matlab mathematical software are used to show the change in profits of the supply chain members in BVFC scenario.

![Figure 7](image1.png)  
**Figure 7.** Combined impacts of CGP and BVFC on profits ($\sigma = 1.3$)

![Figure 8](image2.png)  
**Figure 8.** Combined impacts of CGP and BVFC on profits ($\sigma = 1.9$)

The following conclusions can be obtained from Figure (7) and Figure (8).

(9) In BVFC scenario, the profits of retailer 1 and retailer 2 increase as the simultaneous increase of $\lambda_1$ and $\lambda_2$, while the manufacturer’s profits decrease.

The profits of retailer 1, the manufacture, and the whole supply chain under the high level of CGP are still higher than those under the low level of CGP. In addition, although the high level of BVFC is beneficial to the two retailers, the different levels of $\lambda_1$ and $\lambda_2$ will also affect their profits. In other words, BVFC is not absolutely good for their profits, which is influenced by the different VFC levels of two retailers. Therefore, it is very crucial for the two retailers to know the respective VFC levels clearly. As for the manufacturer, the high level of BVFC is bad for its profits. Specially, R1VFC will drastically reduce the manufacturer’s profits when the level of CGP is high, so the manufacturer should deal with the fairness of benefit distribution with retailer 1 in this case.

(10) In BVFC scenario, BVFC is beneficial to the whole supply chain if $\lambda_1 > \lambda_2$, while bad for the whole supply chain if $\lambda_1 < \lambda_2$.

The whole supply chain’s profits are affected by the different levels of $\lambda_1$ and $\lambda_2$. Specifically, BVFC is beneficial to the whole supply chain when the VFC level of retailer 1 is higher than that of retailer 2, whereas BVFC is bad for the whole supply chain when the VFC level of retailer 1 is less than that of retailer 2.

5.8. **Numerical simulation in BHFC scenario.** Similarly, the following graphs are used to show the change in profits of supply chain members in BHFC scenario.
(11) In BHFC scenario, the profits of retailer 1 and retailer 2 decrease as the simultaneous increase of $\lambda_3$ and $\lambda_4$, while the manufacturer’s profits increase. Similarly, the different levels of $\lambda_3$ and $\lambda_4$ will affect the two retailers’ profits, but the high level of BHFC is always bad for them. As for the manufacturer, BHFC is always beneficial to its profits and the manufacturer can benefit from it. Besides, the higher level of BHFC, the greater benefits for the manufacturer.

(12) In BHFC scenario, the whole supply chain’s profits increase as the simultaneous increase of $\lambda_3$ and $\lambda_4$ when the level of CGP is low, while decrease as the simultaneous increase of $\lambda_3$ and $\lambda_4$ when the level of CGP is high.

The whole supply chain’s profits are affected by the level of CGP. Specifically, when the level of CGP is low, the higher level of BHFC, the greater benefits for the whole supply chain. When the level of CGP is high, the higher level of BHFC, the less benefits for the whole supply chain.

5.9. Comparative analysis between BVFC and BHFC. Comparing Figure (7) and Figure (9), when the level of CGP is low, the high level of BVFC is beneficial to retailer 1 and retailer 2, while the high level of BHFC is bad for them. In addition, the high level of BVFC is bad for the manufacturer, while the high level of BHFC is beneficial to it. Therefore, the green retailer and the traditional retailer can simultaneously enhance VFC to increase their profits, and they should turn the attention of fairness concern to the manufacturer, not each other. For the manufacturer, it should alleviate the vertical unfairness perception of two retailers to reduce its profits loss. When the level of CGP is low, the different levels of BVFC will affect the whole supply chain’s profits, while BHFC is always beneficial to the whole supply chain.

Comparing Figure (8) and Figure (10), when the level of CGP is high, the different levels of BVFC will still affect the whole supply chain’s profits, while the high level of BHFC is bad for the whole supply chain. Specifically, when the level of CGP is high, the whole supply chain’s profits will increase if the VFC level of the
green retailer is higher than the VFC level of the traditional retailer, but the high level of BHFC will reduce the whole supply chain’s profits.

6. **Conclusion.** CGP and fairness concern are important research contents of supply chain. From two perspectives of consumers and supply chain members, this paper considers the combined impacts of CGP and fairness concern on the supply chain under the background of “one-to-many” supply chain. Moreover, the optimal decisions of supply chain members are solved by using the non-cooperative game method in seven scenarios. Finally, we conducted much analysis through numerical simulation. The results and some insights are as follows:

   (1) The green retailer can benefit from R1VFC, but will also be damaged by R2VFC. Similarly, when the level of CGP is low, the traditional retailer can benefit from R2VFC but will also be damaged by R1VFC. Nevertheless, if the green retailer and the traditional retailer both have vertical fairness concern (i.e., BVFC) and the level of BVFC is high, both their profits will be improved. Therefore, the green retailers and the traditional retailer may be able to cooperate with each other to improve their profits. If the green retailer and the traditional retailer both have horizontal fairness concern (i.e., BHFC), then the excessive fairness concern between them will intensify their competition with each other, which is disadvantageous to them, while the manufacturer can benefit from it. Thus, the green retailer and the traditional retailer should turn their attention of fairness concern to the manufacturer, not each other.

   (2) As for the manufacturer, BVFC is almost bad for it, but BHFC is always beneficial to it. What’s more, the manufacturer’s profits will be reduced drastically when the level of CGP is high in BVFC scenario. Therefore, when the green retailer and the traditional retailer both have vertical fairness concern, the manufacturer should adjust wholesale price to alleviate the vertical unfairness perception of two retailers to reduce its profits loss.

   (3) As for the whole supply chain, the profits of itself, the green retailer, and the manufacturer under the high level of CGP are higher than those under the low level of CGP. The manufacturer, as a leader in the market, should strengthen R&D of green products and produce more green and low-carbon products to meet consumers’ demand when the level of CGP is high. Although this is bad for the traditional retailer, the whole supply chain and other supply chain members can benefit from it.

7. **Limitations and future research directions.** This model has several limitations that can be researched in future. First, the manufacturer may also concern about the inequality between its profits and retailers’ profits, so this model can consider the manufacturer’s fairness concern in the future. Specifically, the manufacturer has vertical fairness concern with the green retailer and the traditional retailer respectively, and the manufacturer has vertical fairness concern with the two retailers simultaneously. Second, we assume that supply chain members are completed information symmetric. However, in reality, the fairness concern information of decision-maker is their private information. If the information is beneficial to the decision-maker, they will not disclose their fairness concern information. Thus, this model can consider the incomplete fairness concern information of two retailers in the future. Finally, this model can be extended into multiple manufacturers. What happens if multiple manufacturers compete with each other? These will be further explored in the future.
Data availability. The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of interest. The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Appendix A. The symbols involved in the above formula are as follows:

\[ A_1 = -Q^2 - 4Qc_1 - 2Qc_2 + 2c_2^2 \]
\[ A_2 = -Q^2 + 4Qc_1 + 2Qc_2 + 2c_1^2 - 2c_1c_2 - c_2^2 \]

Appendix B.

\[ B_1 = 8Q\sigma^3 + 5Q\sigma^2 + 24c_1\sigma^2 - 6c_2\sigma^2 - Q\sigma - 8c_1\sigma + 2c_2\sigma + c_1 \]
\[ B_2 = 16Q\sigma^3 + 3Q\sigma^2 + 32c_1\sigma^2 - 6c_2\sigma^2 - Q\sigma - 6c_1\sigma + c_2\sigma \]
\[ B_3 = 18Q\sigma^2 + 16c_2\sigma^2 - 6Q\sigma - 2c_1\sigma - 4c_2\sigma + c_1 + c_2 \]
\[ B_4 = 26Q\sigma^2 + 24c_2\sigma^2 - 8Q\sigma - 2c_1\sigma - 5c_2\sigma + c_1 \]
\[ B_5 = 24Q\sigma^2 - 14Q\sigma + 8c_1\sigma + 6c_2\sigma + 2Q - c_1 - c_2 \]
\[ B_6 = 36Q\sigma^2 - 18Q\sigma + 12c_1\sigma + 7c_2\sigma - c_1 \]
\[ B_7 = 21Q\sigma^2 + 8c_2\sigma^2 - 10Q\sigma + 3c_1\sigma + c_2\sigma + Q \]
\[ B_8 = 31Q\sigma^2 + 12c_2\sigma^2 - 13Q + 5c_1 + c_2 \]

Appendix C.

\[ C_1 = 16Q\sigma^3 - 3Q\sigma^2 + 16c_1\sigma^2 - 2c_2\sigma^2 - Q\sigma - 4c_1\sigma + c_2\sigma + c_1 \]
\[ C_2 = 24Q\sigma^3 - 5Q\sigma^2 + 24c_1\sigma^2 - 2c_2\sigma^2 - Q\sigma - 5c_1\sigma + c_2\sigma \]
\[ C_3 = 14Q\sigma^2 + 24c_2\sigma^2 - 2Q\sigma - 6c_1\sigma - 8c_2\sigma + c_1 + c_2 \]
\[ C_4 = 22Q\sigma^2 + 32c_2\sigma^2 - 4Q\sigma - 6c_1\sigma - 9c_2\sigma + c_1 \]
\[ C_5 = 24Q\sigma^2 - 13Q\sigma + 8c_1\sigma + 3c_2\sigma + Q + c_1 \]
\[ C_6 = 36Q\sigma^2 - 18Q\sigma + 12c_1\sigma + 5c_2\sigma + c_1 \]
\[ C_7 = 18Q\sigma^2 + 8c_2\sigma^2 - 7Q\sigma + 6c_1\sigma - c_2\sigma + Q - c_1 \]
\[ C_8 = 29Q\sigma^2 + 12c_2\sigma - 11Q + 7c_1 - c_2 \]

Appendix D.

\[ D_1 = 8Q\sigma^3 + Q\sigma^2 + 8c_1\sigma^2 - 2c_2\sigma^2 - Q\sigma + c_2\sigma + c_1 \]
\[ D_2 = 16Q\sigma^3 - Q\sigma^2 + 16c_1\sigma^2 - 2c_2\sigma^2 - Q\sigma - c_1\sigma + c_2\sigma \]
\[ D_3 = 6Q\sigma^2 + 8c_2\sigma^2 + Q\sigma + 2c_1\sigma - c_2\sigma + Q - c_1 \]
\[ D_4 = 14Q\sigma^2 + 16c_2\sigma^2 + 2c_1\sigma - 3c_2\sigma - c_1 \]
\[ D_5 = 12Q\sigma^2 - 5Q\sigma + 4c_1\sigma + 3c_2\sigma + Q + c_1 \]
\[ D_6 = 24Q\sigma^2 - 10Q\sigma + 8c_1\sigma + 5c_2\sigma + c_1 \]
\[ D_7 = 9Q\sigma^2 + 4c_2\sigma^2 - 2Q\sigma + 3c_1\sigma + c_2\sigma + Q \]
\[ D_8 = 19Q\sigma + 8c_2\sigma - 5Q + 5c_1 + c_2 \]
Appendix E.

\[ E_1 = 8Q\sigma^2 - 2Q\sigma + 8c_1\sigma + 2c_2\sigma + 2Q - c_2 - c_1 \]
\[ E_2 = 16Q\sigma^2 - 3Q\sigma + 16c_1\sigma + 2c_2\sigma + Q - 3c_1 - c_2 \]
\[ E_3 = 10Q\sigma^2 + 8c_2\sigma^2 - 2Q\sigma - 2c_1\sigma + c_2 + c_1 \]
\[ E_4 = 18Q\sigma^2 + 16c_2\sigma^2 - 4Q\sigma - 2c_1\sigma - c_2\sigma + c_1 \]
\[ E_5 = 12Q\sigma^2 - 5Q\sigma + 4c_1\sigma + 3c_2\sigma + Q + c_1 \]
\[ E_6 = 24Q\sigma^2 - 10Q\sigma + 8c_1\sigma + 5c_2\sigma + c_1 \]
\[ E_7 = 9Q\sigma^2 + 4c_2\sigma^2 - 2Q\sigma + 3c_1\sigma + c_2\sigma + Q \]
\[ E_8 = 19Q\sigma + 8c_2\sigma - 5Q + 5c_1 + c_2 \]

Appendix F.

\[ F_1 = (-2Q - 2c_1 + c_2 + 4w_1)\lambda_1 - 2Q - c_2 + 2w_1 + 2w_2 \]
\[ F_2 = (-2Q - 2c_1 + 2c_2 + 4w_1 - w_2)\lambda_1 - 2Q + 2w_1 + w_2 \]
\[ F_3 = ((Q - 2c_2 + 4w_2)\sigma - Q + c_1 + c_2 - w_2)\lambda_2 \]
\[ F_4 = (Q + 2w_2)\sigma - Q - c_1 + c_2 + 2w_1 - w_2 \]
\[ F_5 = (Q - 2c_2 + 4w_2)\sigma - Q + 2c_1 - w_1 \]
\[ F_6 = 16\lambda_2^2 + 32\lambda_2^2\lambda_1 + 24\lambda_2\lambda_1^2 + 16\lambda_2^2 + 48\lambda_2\lambda_1 + 8\lambda_1^2 + 24\lambda_2 + 16\lambda_1 + 8 \]
\[ F_7 = 4\lambda_2^2\lambda_1 + \lambda_2^2\lambda_1 + 9\lambda_2\lambda_1^2 - 3\lambda_2^2 + 4\lambda_2\lambda_1 + 5\lambda_1^2 - 5\lambda_2 + 3\lambda_1 - 2 \]
\[ F_8 = 48\lambda_2^2 + 64\lambda_2^2\lambda_1 + 72\lambda_2\lambda_1^2 + 16\lambda_2^2 + 96\lambda_2\lambda_1 + 24\lambda_2^2 + 24\lambda_2 + 32\lambda_1 + 8 \]
\[ F_9 = -8\lambda_2^2\lambda_1^2 - 10\lambda_2^2\lambda_1 - 14\lambda_2\lambda_1^2 - 2\lambda_2^2 - 16\lambda_2\lambda_1 - 6\lambda_1^2 - 2\lambda_2 - 6\lambda_1 \]
\[ F_{10} = -2\lambda_2^2\lambda_1^2 - 3\lambda_2^2\lambda_1 - 3\lambda_2\lambda_1^2 - \lambda_2^2 - 4\lambda_2\lambda_1 - \lambda_1^2 - \lambda_2 - \lambda_1 \]
\[ F_{11} = -28\lambda_2^2\lambda_1^2 - 31\lambda_2^2\lambda_1 - 35\lambda_2\lambda_1^2 - 4\lambda_2^2 - 38\lambda_2\lambda_1 - 8\lambda_1^2 - 5\lambda_2 - 9\lambda_1 - 2 \]
\[ F_{12} = 2\lambda_2^2\lambda_1^2 + 3\lambda_2^2\lambda_1 + 3\lambda_2\lambda_1^2 + \lambda_2^2 + 4\lambda_2\lambda_1 + \lambda_1^2 + \lambda_2 + \lambda_1 \]
\[ F_{13} = 4\lambda_2^2\lambda_1^2 + 4\lambda_2^2\lambda_1 + 4\lambda_2\lambda_1^2 + \lambda_2^2 + 2\lambda_2\lambda_1 + \lambda_1^2 \]
\[ F_{14} = \lambda_1\lambda_2(64\lambda_2\lambda_1 + 96\lambda_2 + 96\lambda_1 + 144) + 32\lambda_2^2 + 32\lambda_1^2 + 48\lambda_2 + 48\lambda_1 + 16 \]
\[ F_{15} = -32\lambda_2^2\lambda_1^2 - 40\lambda_2^2\lambda_1 - 40\lambda_2\lambda_1^2 - 9\lambda_2^2 - 50\lambda_2\lambda_1 - 9\lambda_1^2 - 12\lambda_2 - 12\lambda_1 - 4 \]
\[ F_{16} = 24\lambda_2^2\lambda_1^2 + 38\lambda_2^2\lambda_1 + 42\lambda_2\lambda_1^2 + 14\lambda_2^2 + 64\lambda_2\lambda_1 + 18\lambda_1^2 + 22\lambda_2 + 26\lambda_1 + 8 \]
\[ F_{17} = 48\lambda_2^2\lambda_1^2 + 72\lambda_2^2\lambda_1 + 64\lambda_2\lambda_1^2 + 24\lambda_2^2 + 96\lambda_2\lambda_1 + 16\lambda_1^2 + 32\lambda_2 + 24\lambda_1 + 8 \]
\[ F_{18} = -6\lambda_2^2\lambda_1^2 - 8\lambda_2^2\lambda_1 - 12\lambda_2\lambda_1^2 - 2\lambda_2^2 - 16\lambda_2\lambda_1 - 6\lambda_1^2 - 4\lambda_2 - 8\lambda_1 - 2 \]
\[ F_{19} = -8\lambda_2^2\lambda_1^2 - 14\lambda_2^2\lambda_1 - 10\lambda_2\lambda_1^2 - 6\lambda_2^2 - 16\lambda_2\lambda_1 - 2\lambda_1^2 - 6\lambda_2 - 2\lambda_1 \]
\[ F_{20} = -28\lambda_2^2\lambda_1^2 - 35\lambda_2^2\lambda_1 - 31\lambda_2\lambda_1^2 - 8\lambda_2^2 - 38\lambda_2\lambda_1 - 4\lambda_1^2 - 9\lambda_2 - 5\lambda_1 - 2 \]
\[ F_{21} = \lambda_1\lambda_2(64\lambda_2\lambda_1 + 96\lambda_2 + 96\lambda_1 + 144) + 32\lambda_2^2 + 32\lambda_1^2 + 48\lambda_2 + 48\lambda_1 + 16 \]
\[ F_{22} = -32\lambda_2^2\lambda_1^2 - 40\lambda_2^2\lambda_1 - 40\lambda_2\lambda_1^2 - 9\lambda_2^2 - 50\lambda_2\lambda_1 - 9\lambda_1^2 - 12\lambda_2 - 12\lambda_1 - 4 \]
\[ F_{23} = \lambda_2\lambda_1(48\lambda_2\lambda_1 + 72\lambda_2 + 72\lambda_1 + 108) + 24\lambda_1^2 + 24\lambda_2^2 + 36\lambda_2 + 36\lambda_1 + 12 \]
\[ F_{24} = -\lambda_2\lambda_1(36\lambda_2\lambda_1 + 47\lambda_2 + 49\lambda_1 + 63) - 14\lambda_1^2 - 13\lambda_2^2 - 18\lambda_2 - 18\lambda_1 - 6 \]
\[ F_{25} = 16\lambda_2^2\lambda_1^2 + 24\lambda_2^2\lambda_1 + 24\lambda_2\lambda_1^2 + 8\lambda_2^2 + 36\lambda_2\lambda_1 + 8\lambda_1^2 + 12\lambda_2 + 12\lambda_1 + 4 \]
\[ F_{26} = 8\lambda_2^2\lambda_1^2 + 10\lambda_2^2\lambda_1 + 14\lambda_2\lambda_1^2 + 3\lambda_2^2 + 17\lambda_2\lambda_1 + 6\lambda_1^2 + 5\lambda_2 + 7\lambda_1 + 2 \]
$F_{27} = 6\lambda_2^2 \lambda_1^2 + 5\lambda_3^2 \lambda_1 + 7\lambda_2 \lambda_1^2 + \lambda_2^2 + 3\lambda_2 \lambda_1 + 2\lambda_1^2$

$F_{28} = -4\lambda_2^2 \lambda_1^2 - 3\lambda_3^2 \lambda_1 - 5\lambda_2 \lambda_1^2 + \lambda_2^2 - 4\lambda_2 \lambda_1 - \lambda_1^2 + \lambda_2 - \lambda_1$

$F_{29} = -2\lambda_2^2 \lambda_1^2 - \lambda_2^2 \lambda_1 - 3\lambda_2 \lambda_1^2 - \lambda_2 \lambda_1 - \lambda_1^2$

$F_{30} = 8\lambda_2 \lambda_1 (40\lambda_2 + 58\lambda_1 + 91) + 21\lambda_2^2 + 18\lambda_2^2 + 29\lambda_2 + 31\lambda_1 + 10$

$F_{31} = 16\lambda_2^2 \lambda_1^2 + 24\lambda_2 \lambda_1^2 + 8\lambda_2^2 + 36\lambda_2 \lambda_1 + 8\lambda_1^2 + 12\lambda_2 + 12\lambda_1 + 4$

$F_{32} = -\lambda_3 \lambda_1 (26\lambda_2 + 32\lambda_2 + 36\lambda_1 + 45) - 10\lambda_1^2 - 7\lambda_2^2 - 11\lambda_2 - 13\lambda_1 - 4$

$F_{33} = 8\lambda_3^2 \lambda_4^2 + 14\lambda_3 \lambda_4^2 + 10\lambda_2 \lambda_1^2 + 6\lambda_2^2 + 17\lambda_2 \lambda_1 + 3\lambda_2^2 + 7\lambda_2 + 5\lambda_1 + 2$

$F_{34} = -4\lambda_2^2 \lambda_1^2 - 5\lambda_2 \lambda_1^2 - \lambda_2^2 - 4\lambda_2 \lambda_1 + \lambda_1^2 - \lambda_2 + \lambda_1$

$F_{35} = 4\lambda_2^2 \lambda_1^2 + 4\lambda_2 \lambda_1^2 + 4\lambda_2 \lambda_1^2 + \lambda_2^2 + 2\lambda_2 \lambda_1 + \lambda_1^2$

$F_{36} = -2\lambda_2^2 \lambda_1^2 - 3\lambda_2 \lambda_1^2 - \lambda_2^2 - \lambda_2 \lambda_1$

Appendix G.

$G_1 = (Q - w_1 - w_2) \lambda_3 + Q - w_1 - \frac{w_2}{2}$

$G_2 = 2\lambda_4 w_1 - Q + w_1 + w_2$

$G_3 = 8\lambda_3^2 \lambda_4^2 + 16\lambda_3^2 \lambda_4 + 16\lambda_3 \lambda_4^2 + 8\lambda_3^2 + 32\lambda_3 \lambda_4 + 8\lambda_4^2 + 16\lambda_3 + 16\lambda_4 + 8$

$G_4 = -8\lambda_3^2 \lambda_4^2 - 6\lambda_4^2 \lambda_4 - 10\lambda_3 \lambda_4^2 + \lambda_4^2 - 9\lambda_4^2 - 2\lambda_3^2 - \lambda_3 - 3\lambda_4 - 2$

$G_5 = 8\lambda_3^2 \lambda_4^2 + 16\lambda_3^2 \lambda_4 + 16\lambda_3 \lambda_4^2 + 8\lambda_3^2 + 32\lambda_3 \lambda_4 + 8\lambda_4^2 + 16\lambda_3 + 16\lambda_4 + 8$

$G_6 = -2\lambda_3^2 \lambda_4^2 + 2\lambda_3 \lambda_4^2 - 2\lambda_3^2 + 2\lambda_4^2 - 2\lambda_3 + 2\lambda_4$

$G_7 = -2\lambda_3^2 \lambda_4^2 + 2\lambda_3 \lambda_4^2 - \lambda_3^2 + \lambda_3 \lambda_4 + 2\lambda_4^2 - \lambda_3 + \lambda_4$

$G_8 = -8\lambda_3^2 \lambda_4^2 - 8\lambda_3 \lambda_4^2 - 8\lambda_3 \lambda_4^2 - 9\lambda_3 \lambda_4^2 - \lambda_3^2 - 3\lambda_4 - 2$

$G_9 = 2\lambda_3^2 \lambda_4^2 - 2\lambda_3 \lambda_4^2 + \lambda_3^2 - \lambda_4^2 + \lambda_3 - \lambda_4$

$G_{10} = (\lambda_3^2 + \lambda_3 \lambda_4) Q + (\lambda_3 \lambda_4 + \lambda_4^2) c_2$

$G_{11} = \lambda_3 \lambda_4 (16\lambda_3 \lambda_4 + 32\lambda_3 + 32\lambda_4 + 64) + 16\lambda_4^2 + 16\lambda_3^2 + 32\lambda_3 + 32\lambda_4 + 16$

$G_{12} = -16\lambda_3^2 \lambda_4^2 - 16\lambda_3^2 \lambda_4 - 16\lambda_3 \lambda_4^2 - \lambda_3^2 - 18\lambda_3 \lambda_4 - \lambda_4^2 - 4\lambda_3 - 4\lambda_4 - 4$

$G_{13} = 8\lambda_3^2 \lambda_4^2 + 14\lambda_3^2 \lambda_4 + 18\lambda_3 \lambda_4^2 + 6\lambda_3^2 + 32\lambda_3 \lambda_4 + 10\lambda_4^2 + 14\lambda_3 + 18\lambda_4 + 8$

$G_{14} = 8\lambda_3^2 \lambda_4^2 + 16\lambda_3^2 \lambda_4 + 16\lambda_3 \lambda_4^2 + 8\lambda_3^2 + 32\lambda_3 \lambda_4 + 8\lambda_4^2 + 16\lambda_3 + 16\lambda_4 + 8$

$G_{15} = -8\lambda_3^2 \lambda_4^2 - 6\lambda_3^2 \lambda_4 - 10\lambda_3 \lambda_4^2 + \lambda_3^2 - 9\lambda_3 \lambda_4 - 2\lambda_4^2 - 4\lambda_4 - 2$

$G_{16} = 2\lambda_3^2 \lambda_4 - 2\lambda_3 \lambda_4^2 + 2\lambda_3^2 - 2\lambda_4^2 + 2\lambda_3 - 2\lambda_4$

$G_{17} = -8\lambda_3^2 \lambda_4^2 - 8\lambda_3 \lambda_4^2 - 8\lambda_3 \lambda_4^2 - \lambda_3^2 - 9\lambda_3 \lambda_4 - 3\lambda_3 - \lambda_4 - 2$

$G_{18} = -2\lambda_3^2 \lambda_4^2 + 2\lambda_3 \lambda_4^2 - \lambda_3^2 + \lambda_4^2 - \lambda_3 + \lambda_4$

$G_{19} = (\lambda_3^2 + \lambda_3 \lambda_4) c_1$

$G_{20} = \lambda_3 \lambda_4 (16\lambda_3 \lambda_4 + 32\lambda_3 + 32\lambda_4 + 64) + 16\lambda_4^2 + 16\lambda_3^2 + 32\lambda_3 + 32\lambda_4 + 16$

$G_{21} = 16\lambda_3^2 \lambda_4^2 + 16\lambda_3^2 \lambda_4 + 16\lambda_3 \lambda_4^2 + \lambda_3^2 + 18\lambda_3 \lambda_4 + \lambda_4^2 + 4\lambda_3 + 4\lambda_4 + 4$

$G_{22} = \lambda_3 \lambda_4 (12\lambda_3 \lambda_4 + 24\lambda_3 + 24\lambda_4 + 48) + 12\lambda_3^2 + 12\lambda_4^2 + 24\lambda_3 + 24\lambda_4 + 12$

$G_{23} = -16\lambda_3^2 \lambda_4^2 - 20\lambda_3 \lambda_4^2 - 20\lambda_3 \lambda_4^2 - 5\lambda_3^2 - 28\lambda_3 \lambda_4 - 5\lambda_4^2 - 10\lambda_3 - 10\lambda_4 - 6$
\[ G_{24} = 4\lambda_3^2\lambda_4^2 + 8\lambda_3^2\lambda_4 + 8\lambda_3\lambda_4^2 + 4\lambda_3^2 + 16\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_3 + 8\lambda_4 + 4 \]
\[ G_{25} = 4\lambda_3^2\lambda_4^2 + 7\lambda_3^2\lambda_4 + 7\lambda_3\lambda_4^2 + 3\lambda_3^2 + 12\lambda_3\lambda_4 + 3\lambda_4^2 + 5\lambda_3 + 5\lambda_4 + 2 \]
\[ G_{26} = [4\lambda_3\lambda_4(\lambda_3\lambda_4 + \lambda_3 + \lambda_4) + \lambda_3^2 + \lambda_4^2]Q - \lambda_3\lambda_4(4\lambda_3\lambda_4 + 3\lambda_3 + 3\lambda_4 + 2) \]
\[ G_{27} = -4\lambda_3^2\lambda_4^2 - 3\lambda_3^2\lambda_4 - 3\lambda_3\lambda_4^2 + \lambda_3^2 - 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_3 + \lambda_4 \]
\[ G_{28} = (-\lambda_3^2\lambda_4 - \lambda_3\lambda_4^2) c_1 \]
\[ G_{29} = 8\lambda_3^2\lambda_4^2 + 17\lambda_3^2\lambda_4 + 17\lambda_3\lambda_4^2 + 9\lambda_3^2 + 36\lambda_3\lambda_4 + 9\lambda_4^2 + 19\lambda_3 + 19\lambda_4 + 10 \]
\[ G_{30} = 4\lambda_3^2\lambda_4^2 + 8\lambda_3^2\lambda_4 + 8\lambda_3\lambda_4^2 + 4\lambda_3^2 + 16\lambda_3\lambda_4 + 4\lambda_4^2 + 8\lambda_3 + 8\lambda_4 + 4 \]
\[ G_{31} = -8\lambda_3^2\lambda_4^2 - 10\lambda_3^2\lambda_4 - 10\lambda_3\lambda_4^2 - 2\lambda_3^2 - 14\lambda_3\lambda_4 - 2\lambda_4^2 - 5\lambda_3 - 5\lambda_4 - 4 \]
\[ G_{32} = 4\lambda_3^2\lambda_4^2 + 7\lambda_3^2\lambda_4 + 7\lambda_3\lambda_4^2 + 3\lambda_3^2 + 12\lambda_3\lambda_4 + 3\lambda_4^2 + 5\lambda_3 + 5\lambda_4 + 2 \]
\[ G_{33} = -4\lambda_3^2\lambda_4^2 - 3\lambda_3^2\lambda_4 - 3\lambda_3\lambda_4^2 + \lambda_3^2 - 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_3 + \lambda_4 \]
\[ G_{34} = [\lambda_3\lambda_4(\lambda_3 + \lambda_4 + 2) + \lambda_3^2 + \lambda_4^2]Q - \lambda_3\lambda_4(4\lambda_3\lambda_4 + 3\lambda_3 + 3\lambda_4 + 2) c_1 \]
\[ G_{35} = (-\lambda_3^2\lambda_4 - \lambda_3\lambda_4^2) c_2 \]

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