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Decision and Coordination in a Dual-Channel Three-Layered Green Supply Chain

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Abstract: This paper investigated, for the first time, the game and coordination of a dual-channel, three-layered, green fresh produce supply chain, with regard to its economic, social, and environmental performance. Considering that the market demand is dual-channel priced and sensitive to the degree of greenness and the freshness-level, four game models, under different scenarios have been established. These included a centralized scenario, a decentralized scenario, and two contractual scenarios. The equilibrium solutions under the four scenarios were characterized. From the perspective of a sustainable development, the economic, social, and environmental performance of the supply chain was analyzed. To enhance the supply chain performance, two contract mechanisms were designed and the conditions for a multi-win outcome were obtained. Accordingly, many propositions and management implications were provided. The results showed that, (1) compared to the centralized supply chain case, the performance of the decentralized supply chain case is inferior; (2) in addition to increasing the concentration of the supply chain decisions, the two contracts proposed can effectively coordinate the green supply chain and improve its sustainable performance; and (3) the performance of the supply chain is positively driven by the consumers' sensitivity to greenness degree and the freshness level of fresh produce. This paper fills a research gap and helps the participants of the channel recognize the operational decision principle of a complex green supply chain, in order to achieve a higher and a long-term sustainable-development performance.

Keywords: green supply chain; contract theory; dual-channel three-layered; sustainability performance improvement

1. Introduction

In the pursuit of economic benefits, some supply chain channel members often fail to balance its environmental and social performance, which is not conducive to the long-term stable and sustainable development of the supply chain [1]. The sustainable development of a supply chain is essential because it is of great significance to the consumers, the supply chain, the region, and even to the whole world, in terms of the economy, environment, and society [2]. With the evolution of the market competition pattern, the competition between one enterprise and another has gradually evolved into the competition between one supply chain and another [3]. However, the competition of a supply chain is more embodied by the comprehensive competition of a sustainable development [4,5]. Therefore, in order to better promote the development of the supply chain, the supply chain participants should take the economic, environmental, and the societal performance into consideration, in an integrated manner [6]. Sustainable development requires joint efforts from supply chain members, in order to achieve their sustainability goals [7]. Given that the rational and effective management of green supply chains plays a pivotal part in the sustainable development of supply chains, there has been a wide interest in research on green supply chains [8]. In the exploration and practice of green supply chains, many related research issues have been gradually launched from different levels, including institutional pressure, total quality management, green policies, supplier relationship management, lean manufacturing, strategic management, and green technology. Given that research on the decision and coordination of green supply chains, with regard to their economic, societal, and environmental performance is still rare, this study further extends the scope of the research issues of green supply chains to the decision and coordination level.

With the rapid development of e-commerce, in recent decades, the marketing modes of fresh produce supply chains have been changing, and the retail enterprises are increasingly adopting the sales mode of a dual-channel supply chain, in order to promote the sales of their products [9]. At the same time, the change of the consumer shopping mode also makes it possible for the coexistence of an online sales channel, alongside the traditional offline sales channel. Fresh produce dual-channel supply chains are playing an increasingly prominent role in people's daily lives. In the operation and management of a dual-channel, three-layered supply chain, fresh produce is sold through online and offline channels and delivered through third-party logistics. The method by which to make a greenness degree decision, a freshness-keeping effort level decision, and a dual-channel price decision, is related to various aspects of economic, environmental, and social performance.

During the expansion of the supply chain, environmental problems, such as climate variability, the greenhouse effect, the hole in the ozone layer, sea-level rise, soil composition change, and acid rain have aroused attention from people from all walks of life. Environmental problems seriously affect the regional and even global ecosystem and the long-term healthy habitat lives of people. If effective measures are not taken, environmental degradation will increase further. According to Seuring and Shashi et al., in the operation and management of supply chains, it is very meaningful to consider the environmental benefits which are conveyed by the main climate change agreements, such as the United Nations Framework Convention on Climate Change, the Kyoto Protocol, the Copenhagen Accord, the Doha Amendment, and the Paris Agreement [10,11].

Having been socially influenced by the development of society, growing numbers of customers have gradually begun to have high expectations for produce safety and a strong awareness of sustainably produced food [12]. Since green products have relatively little negative impact on human health and the environment [13], and since the freshness level is crucial to people's healthy living consumption [14,15], the degree of greenness and the freshness level have become fundamental factors that affect consumer demand, pricing strategy, and supply chain performance. Products with eco labels, greenness labels, and freshness labels are more likely to be favored by consumers. Food products with fresh, toxic-free, and highly eco-friendly characteristics are more likely to win the market [16]. Therefore, green production and green supply are imperative to the operation of product supply chains [17]. It is particularly necessary to carry out certain freshness-keeping actions in the logistical processes, in order to ensure the freshness level of produce [18,19].

Economic benefits are often the goals that are pursued by enterprises. After all, the economic benefits of enterprises exert a subtle influence on the survival and development of enterprises. In dual-channel, three-layered fresh produce supply chains, the method by which the decisions of online and offline channels can achieve optimal economic profit is related to the self-interest of each supply chain member, which is also what they care about. Most companies have been striving to improve their economic interests.

Therefore, from the different aspects of the environment, society, and economy, one can see that, in dual-channel, three-layered green supply chains, it is of great significance to improve the degree of greenness and the freshness level of products, while improving the economic profits, in order to improve environmental and social performance, make the supply chain healthy, and reach goals of sustainable development. However, as supply chain participants, the members of the supply chain usually tend to maximize their own economic profits when making decisions; this not only makes the economic profit of the supply chain non-optimal, but also brings certain losses to the environment and society. When the social utility and environmental utility are low, they will, in turn, affect the size of the consumer market. As a result, both the nodal enterprises of the supply chain and the overall supply chain performance will suffer losses. In this case, the method of coordinating the decisions of the supply chain members and the method to best mitigate any channel conflicts, in order to maximize the sustainable performance of the supply chain, are particularly important.

The aim of this study is to explore the trade-off and coordination of economic, social, and environmental performance of a fresh-produce, dual-channel, three-layered green supply chain, so as to achieve the goal of maximizing the sustainability performance. This paper mainly answers the following questions:

(1) Should the green supply chain members cooperate to make their decisions? Can the sustainable performance of the green supply chain be improved?
(2) If the centralized mode is difficult to achieve, is there any other means by which to improve the performance of the supply chain?
(3) If so, can this approach improve the centralized supply chain scenario? What are the conditions and constraints imposed on the implementation?
(4) What is the impact of consumers' sensitivity to greenness degree and freshness level, on the sustainable performance of a green supply chain? What should the members of the supply chain do?

To solve these problems, a fresh-produce, dual-channel, three-layered green supply chain is considered, and four mathematical models are set up. The first model is under the decentralized supply chain scenario, where the three dual-channel members make individual decisions, separately, to maximize their profits. The second model is under the centralized supply chain scenario, where all members of the supply chain make their decisions, together, to maximize the overall performance of the green supply chain. The third model is under the joint revenue-sharing and cost-sharing contract scenario, where the three participants improve the economic, social, and the environmental performance of the supply chain, through a protocol contract formulation. Finally, the fourth model is under the cross cost-sharing and revenue-sharing contract scenario, where the three partners facilitate the sustainable performance of the supply chain through another proposed contract mechanism.

The main contributions of this paper are embodied in the following aspects.

(i) Our work is the first attempt to study this problem, i.e., the game and coordination of a fresh-produce, dual-channel, three-layered green supply chain. As dual-channel, green supply chains are relatively complex, as compared to single-channel green supply chains, research on the former is relatively scarce. For the first time, we further extend the research on green supply chains to a dual-channel, three-layered green supply chain. This study can help to make a contribution to filling this research gap.
(ii) The market demand function, when taken into account, is sensitive to greenness degree, freshness level, and unit dual-channel price, and provides a better description of the real green supply chain, making it closer to reality. It is considered and characterized in the four supply chain decision models.
(iii) Four game models are established, i.e., the decentralized decision model, the centralized decision model, and two contract coordination models. The equilibrium solutions of various decision-making models are obtained, relevant theorems, and propositions are derived, and corresponding management implications are provided, which can help the supply chain participants recognize the operational decision principles to achieve a higher and a long-term sustainable-development performance.

(iv) Two contract mechanisms are designed. The contract implementation conditions for improving the sustainable performance of the green supply chain and achieving a multi-win situation are derived, and the effect of the consumers' sensitivity to greenness degree and freshness level on the decisions and profits is analyzed. The findings and insights can provide reference for enterprises to make optimal strategic decisions in a complex supply chain decision-making, according to their own conditions.

The rest of this paper is organized as follows: Section 2 synoptically and concisely reviews the relevant literature; Section 3 presents the model description and assumptions; in Section 4, game models without contract, under the decentralized and centralized supply chain scenarios, are established and related theorems, corollaries, and propositions are derived and analyzed; in Section 5, coordination models with two contract mechanisms are developed to improve the economic, social, and environmental performance of the supply chain; numerical analysis is shown in Section 6; and conclusions and further research directions are given in Section 7.

2. Literature Review

The existing literature gives different definitions of a green supply chain management [20]. Green supply chain management is taken to involve integrating environmental awareness into all aspects of the supply chain, reducing environmental risks, optimizing supply chain resources, and enhancing economic and social benefits [21]. If environmental factors are not taken into account in a supply chain performance, the operational risk of the supply chain enterprises will increase. Green operation can not only improve the environmental performance of enterprises, but can also improve their economic efficiency [22].

At present, most of the literature relating to green supply chains mainly focuses on green procurement [23], green manufacturing [24], green logistics [25], green recycling [26], green supplier selection [27], and other aspects related to the green supply chain research. Additionally, since energy efficiency is a key resource for economic and social development [28], there is one research stream in the literature that pays attention to the energy efficiency of the supply chain solutions [29,30]. In this paper, we concentrate on the green production supply, freshness-keeping logistics, and green marketing of green supply chain.

The research methods for green supply chains mainly involve case studies [31] and empirical survey studies [32]. Most of this research is mainly qualitative [33]. Among the research methodologies employed, only a few articles apply quantitative models [34]. There are a few studies that focus on the framework method of prediction and measurement [35], and the evaluation method [36]. Additionally, some scholars perform literature surveys and review research methodologies [10]. After studying a questionnaire, Luthra et al. [37] indicated that through the practice of green supply chain management, the competitiveness of a critical success factor is the most indispensable critical success factor to realize the sustainability of the Indian automotive industry. In our work, considering that the greenness degree, freshness-keeping effort, and the dual-channel price are the important parameters for green supply chains and that there is a game relationship among the decisions of many supply chain members, quantitative analysis methods, such as game theory, contract theory, and system optimization theory are employed to investigate the effects of green produce supply at the supply chain source, freshness-keeping in logistical processes, and consumers with awareness of greenness and freshness, at the end market, on the different perspectives of the economic, social, and environmental performance of the supply chain.

As far as game theory is concerned, although a few scholars have applied it to study the competitive and cooperative relationship of green supply chains [38,39], it has not been combined with contract theory to improve the economic, social, and environmental performance of supply chains. Zhang et al. [40] studied the cooperative game and non-cooperative game in a supply chain, where green and non-green products coexist, and found that the Pareto optimization of supply chain profits can be achieved by Rubinstein bargaining. In this paper, we will use game theory to analyze the greenness degree decision, freshness-keeping decision, and the unit dual-channel selling price decision in both the centralized and decentralized scenarios of the green supply chain. We will then combine the contract theory to coordinate the supply chain decision and improve its performance and efficiency.

Revenue-sharing contract theory was initially explored in the leasing industry [41], and then gradually employed in the field of supply chains [42–44]. Qin and Yang [45] investigated the revenue-sharing contract in a two-echelon supply chain, composed of suppliers and retailers, and found that revenue-sharing contract can make it more profitable. Furthermore, Yao et al. [46] explored the effect of a revenue-sharing contract in a competitive supply chain, and found that, compared to the price-only contract, the revenue-sharing contract can obtain a better supply chain performance. However, there is scant literature investigating the effect of revenue-sharing contracts for the improvement of the sustainability performance of green supply chains. This paper will propose two improved revenue-sharing contracts to enhance the sustainability performance of green supply chains.

Research on green supply chains mostly pays attention to single-channel supply chains [47] and two-layer supply chains [48]. Basiri and Heydari [49] studied the coordination problem of a two-layer green supply chain and showed that the proposed cooperative mathematical programming model can improve the profit of the supply chain, making it close to the concentrated supply chain. Xu et al. [50] analyzed the production and the emission abatement decisions in a supply chain, consisting of one retailer and one manufacturer, and found that there is an interval of Pareto improvement, under the contract proposed, in which the retailer pays a lump sum to the manufacturer. However, to the best of our knowledge there is scarce literature considering the dual-channel, three-layered scenario, even though this complex situation is closer to reality. Therefore, in this paper, we first contemplate the fresh produce dual-channel, three-layered green supply chain. For the first time, we study the problem of game and coordination of the fresh produce dual-channel, three-layered green supply chain, with regard to improving its economic, social, and environmental performance. This can help to fill research gaps in the existing literature to a certain extent. This work can also provide some new perspectives for theoretical extension, development, and application, and provide insightful inspiration for improving the sustainable-development performance of supply chains. A comparison of the current work with some previous studies is presented in Table 1.

Table 1. Comparison of the current work with some previous studies.

Studies	Research Methods	Demand Pattern	Dual-Channel Three-Layered	Economic, Environmental, and Social Performance	Channel Coordination
[31]	Case studies	/	/	/	/
[32]	Empirical studies	/	/	/	/
[35]	Framework method of prediction and measurement	/	/	/	/
[36]	Evaluation method	/	/	/	/
[10]	Literature survey and review	/	/	/	/
[47]	Game theory, two-part tariff contract theory	Greening effort, single channel price	/	/	√
[48]	Game theory, Cost-sharing contract theory	Greenness degree, sale price	/	/	√
[49]	Game theory, mathematical programming model	Retail price, environmental quality, green sales effort level	/	/	√
[50]	Game theory, lump fee contract theory	Eco-friendly level, retail price	/	/	√
This work	Game theory, revenue-sharing contract theory, system theory	Greenness degree, freshness level, dual-channel price	√	√	√

3. Model Descriptions and Assumptions

3.1. Model Framework

In this paper we consider a fresh-produce, dual-channel three-layered green supply chain, consisting of a fresh-produce e-commerce enterprise, an offline supermarket, and a third-party logistics service provider (TPLSP). As is shown in Figure 1, the circulation channels of fresh-produce include online and offline channels. The fresh produce e-commerce enterprise supplies fresh produce to the offline supermarket at a wholesale price, P^w, which sells fresh produce to customers at an offline selling price, P^o. At the same time, the fresh produce e-commerce enterprise sells fresh produce to customers through its online shopping platform at an online selling price, P^f. Fresh produce from the two channels are distributed by the TPLSP to the end consumers, and the unit distribution price of fresh produce is P^t. A continuous variable, ζ, is used to characterize the greenness degree of the fresh produce of the fresh-produce e-commerce enterprise, and another continuous variable, e, is used to describe the freshness-keeping effort of the TPLSP, in the distribution process. The demand faced by the dual channel is sensitive to the unit channel price, greenness degree, and the freshness. Based on this model framework, in the following sections, game models in different situations are built, the decision-making of each member of the supply chain is derived, the economic, social, and environmental performance of the green supply chain is analyzed, and improvement strategies for the channel performance are designed.

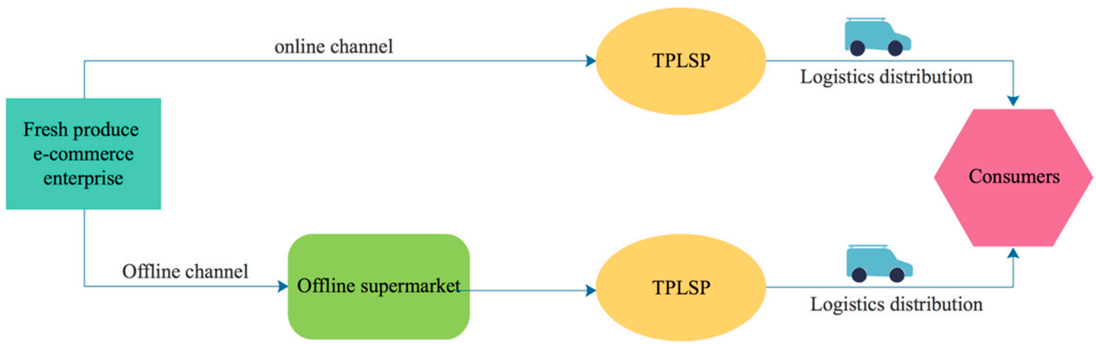

Figure 1. The green supply chain under consideration.

3.2. Notations

Table 2 shows the notations of the model symbols.

Table 2. Nomenclature.

Symbol	Descriptions	Symbol	Descriptions
P^f	Unit online selling price of fresh produce	λ_1	Green investment cost coefficient
c_1	Unit cost of fresh produce	λ_2	Freshness-keeping cost coefficient
P^w	Unit wholesale price of fresh produce	σ	Consumers' sensitivity to greenness degree of fresh produce
P^o	Unit offline selling price of fresh produce	δ	Consumers' sensitivity to freshness level of fresh produce
P^t	Unit distribution price of fresh produce	θ	Freshness level of fresh produce
b_1	Online-channel price elasticity	$C(\zeta)$	Green investment cost function
b_2	Offline-channel price elasticity	$C(e)$	Freshness-keeping cost function
μ_1	Cross-price price elasticity of online channel	a	Total potential market size
μ_2	Cross-price price elasticity of offline channel	θ_0	Sensitivity coefficient affecting freshness level of fresh produce
ζ^i	$(i = dc, c, jr, cc)$ greenness degree of fresh produce under the decentralized, centralized, JR&CS (joint revenue-sharing and cost-sharing) contract, and CC&RS (joint, cross, cost-sharing and revenue-sharing contract) contract scenarios, respectively	$\widetilde{P}^i$	$(i = dc, c, jr, cc)$ unit dual-channel price under the decentralized, centralized, JR&CS contract, and CC&RS contract scenarios, respectively
e^i	$(i = dc, c, jr, cc)$ freshness-keeping effort of TPLSP under the decentralized, centralized, JR&CS contract, and CC&RS contract scenarios, respectively	Q^i_{on}	$(i = dc, c, jr, cc)$ online ordering quantity of consumers under the decentralized, centralized, JR&CS contract, and CC&RS contract scenarios, respectively
Q^i_{off}	$(i = dc, c, jr, cc)$ offline ordering quantity of consumers under the decentralized, centralized, JR&CS contract, and CC&RS contract scenarios, respectively	Π^i_f	$(i = dc, jr, cc)$ expected profit of fresh produce e-commerce enterprise under the decentralized, JR&CS contract, and CC&RS contract scenarios, respectively
Π^i_o	$(i = dc, jr, cc)$ expected profit of offline supermarket under the decentralized, JR&CS contract, and CC&RS contract scenarios, respectively	Π^i_t	$(i = dc, jr, cc)$ expected profit TPLSP under the decentralized, JR&CS contract, and CC&RS contract scenarios, respectively
Π^i	$(i = dc, c, jr, cc)$ total supply chain expected profit under the decentralized, centralized, JR&CS contract, and CC&RS contract scenarios, respectively	$*$	Optimal value

3.3. Assumptions

Before developing the game models, we made the following assumptions.

(1) Without loss of generality, the parameters meet the following conditions: $P^f > c_1 + P^t$, $P^o > P^w + P^t$, and $P^w > c_1$. This assumption ensures that the profits of the supply chain members are positive.

(2) The relationship between freshness level and freshness-keeping effort is assumed to be $\theta = e\theta_0$. This type of assumption has been widely used [13,51,52]. This means that the enhancement of freshness-keeping will further improve the freshness of the fresh produce. Assume that the function between the freshness-keeping cost and the freshness-keeping effort, and that between the green investment cost and the greenness degree, are respectively expressed as $C(\zeta) = \frac{\lambda_1 \zeta^2}{2}$ and $C(e) = \frac{\lambda_2 e^2}{2}$, which have been considered by many scholars [53,54]. This assumption indicates that both of the cost functions are concave.

(3) There are no shortages in the two circulation channels of the green supply chain. The three supply chain members are rational and risk-neutral. During the games, the information is complete.

(4) On the basis of [55], we further assume that the ordering quantities of the consumers in the online and offline channels are linear functions and have the following forms, respectively:

$$Q_{on} = a - b_1 P^f + \mu_1 P^o + \delta e\theta_0 + \sigma\zeta \tag{1}$$

$$Q_{off} = a - b_2 P^o + \mu_2 P^f + \delta e\theta_0 + \sigma\zeta \tag{2}$$

where $b_1 > \mu_1$, $b_2 > \mu_2$. This means that the price elasticity of the self-channel is greater than the price elasticity of the cross-channel. To maintain an analytical tractability, on the basis of the works of Xu et al. [56], we assume that $b_1 = b_2 = b$ and $\mu_1 = \mu_2 = \mu$. This means that consumers have the same sensitivity to price in different channels, and the price of one channel has the same effect on the market as another channel. Similar to references [17,57], in order to reduce channel conflict, we assume the unit online selling price and the unit offline selling price remain the same, i.e., $P^f = P^o = \widetilde{P}$. Then $Q_{on} = Q_{off} = a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta$, where $\varpi = b - \mu$.

4. Game Models without Contract

In this section, game models in decentralized and centralized supply chain are developed. Optimal decisions and profits, under the different scenarios are derived and compared, and the corresponding sustainable performance is analyzed. Note that all proofs of theorems, corollaries, and propositions are provided in Appendix A.

4.1. Decentralized Supply Chain Scenario

In the centralized situation, the three supply chain members make decisions separately. When making decisions, they take the principle of maximizing their profits. Firstly, according to the market situation of a fresh-produce dual-channel and the reaction of the offline supermarket and the TPLSP, the fresh-produce e-commerce enterprise determines the unit wholesale price and greenness degree, so as to maximize its own profit. Additionally, the TPLSP determines the unit distribution price and the freshness-keeping effort by taking into account the current market condition. Finally, based on the decisions of the fresh produce e-commerce enterprise and the TPLSP, the offline supermarket determines the unit dual-channel selling price. According to the above game process the model is established as follows:

$$\begin{aligned}\textstyle\prod_f^{dc} &= (\widetilde{P} - c_1 - P^t)Q_{on} + (P^w - c_1)Q_{off} - C(\zeta)\\ &= (\widetilde{P} - c_1 - P^t)(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) + (P^w - c_1)(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) - \tfrac{\lambda_1\zeta^2}{2}\end{aligned} \tag{3}$$

$$\begin{aligned}\textstyle\prod_o^{dc} &= (\widetilde{P} - P^w - P^t)Q_{off}\\ &= (\widetilde{P} - P^w - P^t)(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta)\end{aligned} \tag{4}$$

$$\begin{aligned}\textstyle\prod_t^{dc} &= P^t(Q_{on} + Q_{off}) - C(e)\\ &= 2P^t(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) - \tfrac{\lambda_2 e^2}{2}\end{aligned} \tag{5}$$

Theorem 1. *In the decentralized supply chain scenario, the optimal unit dual-channel price, unit wholesale price, greenness degree, unit distribution price, and the freshness-keeping effort are as follows:*

$$\widetilde{P}^{dc^*} = \frac{4\lambda_1\lambda_2 a + c_1(\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{6}$$

$$P^{w^*} = \frac{\lambda_1\lambda_2 a + 2c_1(2\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2)}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{7}$$

$$\zeta^{dc^*} = \frac{2\sigma\lambda_2(a - \varpi c_1)}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{8}$$

$$P^{t^*} = \frac{2\lambda_1\lambda_2(a - \varpi c_1)}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{9}$$

$$e^{dc^*} = \frac{2\delta\theta_0\lambda_1(a - \varpi c_1)}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{10}$$

Theorem 1 shows the equilibrium solution of the optimal decisions of the three dual-channel members, under the decentralized scenario. Based on Theorem 1 we obtain the following corollary:

Corollary 1. *The optimal expected profits of the three supply chain participants, the optimal ordering quantity of the online and offline channels, and the total expected profit of the whole system, under the decentralized scenario are, respectively:*

$$\prod_f^{dc^*} = \frac{\lambda_1\lambda_2(a-\varpi c_1)^2(3\varpi\lambda_1\lambda_2 - 2\sigma^2\lambda_2)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} \tag{11}$$

$$\prod_o^{dc^*} = \frac{\lambda_1^2\lambda_2^2\varpi(a-\varpi c_1)^2}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} \tag{12}$$

$$\prod_t^{dc^*} = \frac{2\lambda_1\lambda_2(a-\varpi c_1)^2(2\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} \tag{13}$$

$$Q_{on}^{dc^*} = \frac{\varpi\lambda_1\lambda_2(a-\varpi c_1)}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{14}$$

$$Q_{off}^{dc^*} = \frac{\varpi\lambda_1\lambda_2(a-\varpi c_1)}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{15}$$

$$\prod^{dc^*} = \frac{2\lambda_1\lambda_2(a-\varpi c_1)^2(4\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} \tag{16}$$

4.2. Centralized Supply Chain Scenario

In the centralized situation all the members of the green supply chain are considered, as a whole system, to make the optimal decisions, i.e., optimal unit dual-channel selling price, green degree, and the freshness-keeping effort, to maximize the overall profit of the system. The profit model is as follows:

$$\begin{aligned} \prod^c &= (\widetilde{P} - c_1)Q_{on} + (\widetilde{P} - c_1)Q_{off} - C(\zeta) - C(e) \\ &= (\widetilde{P} - c_1)(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) + (\widetilde{P} - c_1)(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) - \tfrac{\lambda_1\zeta^2}{2} - \tfrac{\lambda_2 e^2}{2} \end{aligned} \tag{17}$$

Theorem 2. *In the centralized supply chain scenario, the optimal unit dual-channel selling price, greenness degree, and the freshness-keeping effort are as follows:*

$$\widetilde{P}^{c*} = \frac{\lambda_1\lambda_2 a + c_1(\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{18}$$

$$\zeta^{c^*} = \frac{2\sigma\lambda_2(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{19}$$

$$e^{c^*} = \frac{2\delta\theta_0\lambda_1(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{20}$$

Theorem 2 shows the optimal decision of the green supply chain system, under the centralized scenario. Based on Theorem 2, we obtain the following corollary:

Corollary 2. *The optimal ordering quantity of the online and offline channels and the total expected profit of the whole system are, respectively:*

$$Q_{on}^{c\ *} = \frac{\varpi\lambda_1\lambda_2(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{21}$$

$$Q^{c}_{off}{}^{*} = \frac{\varpi\lambda_1\lambda_2(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} \tag{22}$$

$$\prod^{c*} = \frac{2\lambda_1\lambda_2(a-\varpi c_1)^2(\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} \tag{23}$$

4.3. Comparison and Analysis of Different Scenarios

Based on the above theorems and corollaries, under the decentralized and centralized supply chain decision scenarios, we obtain the following propositions:

Proposition 1. *(1)* $\widetilde{P}^{dc*} > \widetilde{P}^{c*}$.
(2) $\zeta^{dc^*} < \zeta^{c^*}$; $e^{dc^*} < e^{c^*}$.

Proposition 1 shows that, under the decentralized dual-channel scenario, the unit dual-channel selling price is higher than that under the centralized dual-channel scenario, however, the greenness degree and the freshness-keeping effort are lower than that of the centralized decision-making. This indicates that when the dual channel is in a decentralized situation, consumers in the online and offline channels will obtain a lower freshness level and greenness degree. At the same time channel consumers will face a higher product price. Then, the supply chain scenario of the decentralized decision-making will reduce the purchasing and consumption enthusiasm of the consumers to a certain extent.

Proposition 2. *(1)* $Q^{dc*}_{on} < Q^{c}_{on}{}^{*}$; $Q^{dc^*}_{off} < Q^{c}_{off}{}^{*}$.
(2) $\prod^{dc*} < \prod^{c^*}$.

Proposition 2 shows that, for the decentralized supply chain system, its fresh-produce ordering quantities and total profits are less than that of the centralized supply chain system. This reveals that the decentralized dual-channel supply chain has led to a significant decline in the sales of fresh produce, in both the online and offline channels, and that the economic performance has also suffered losses. Therefore, the decentralized supply chain decision-making, without any improvement measures, is detrimental to the supply chain.

Proposition 3. *(1)* $\frac{\partial \widetilde{P}^{dc}}{\partial c_1} > 0$; $\frac{\partial \zeta^{dc}}{\partial c_1} < 0$; $\frac{\partial e^{dc}}{\partial c_1} < 0$; $\frac{\partial Q^{dc}_{on}}{\partial c_1} < 0$; $\frac{\partial Q^{dc}_{off}}{\partial c_1} < 0$; $\frac{\partial \prod^{dc}}{\partial c_1} < 0$.
(2) $\frac{\partial \widetilde{P}^{c}}{\partial c_1} > 0$; $\frac{\partial \zeta^{c}}{\partial c_1} < 0$; $\frac{\partial e^{c}}{\partial c_1} < 0$; $\frac{\partial Q^{c}_{on}}{\partial c_1} < 0$; $\frac{\partial Q^{c}_{off}}{\partial c_1} < 0$; $\frac{\partial \prod^{c}}{\partial c_1} < 0$.

Proposition 3 indicates that, in both the centralized and decentralized green supply chains, when the unit cost of fresh produce rises the dual-channel price increases, while the greenness degree, the freshness-keeping effort, the ordering quantities of the online and offline channels, and the supply chain profits decrease. This shows that the cost of fresh produce has a certain negative impact on supply chain decisions and profits. Therefore, the three channel members should work together to develop a cost-saving technology, optimize the cost structure of green products, and achieve a low-cost, high-quality production, so as to improve the expected profit of the dual-channel, three-layered green supply chain.

Proposition 4. *(1)* $\frac{\partial \widetilde{P}^{dc}}{\partial \delta} > 0$; $\frac{\partial \zeta^{dc}}{\partial \delta} > 0$; $\frac{\partial e^{dc}}{\partial \delta} > 0$; $\frac{\partial Q^{dc}_{on}}{\partial \delta} > 0$; $\frac{\partial Q^{dc}_{off}}{\partial \delta} > 0$; $\frac{\partial \prod^{dc}}{\partial \delta} > 0$.
(2) $\frac{\partial \widetilde{P}^{c}}{\partial \delta} > 0$; $\frac{\partial \zeta^{c}}{\partial \delta} > 0$; $\frac{\partial e^{c}}{\partial \delta} > 0$; $\frac{\partial Q^{c}_{on}}{\partial \delta} > 0$; $\frac{\partial Q^{c}_{off}}{\partial \delta} > 0$; $\frac{\partial \prod^{c}}{\partial \delta} > 0$.

Proposition 4 indicates that, in both the centralized and the decentralized decision-making situations, the freshness sensitivity coefficient has a positive effect on the unit dual-channel selling price, greenness degree, the freshness-keeping effort, the dual-channel ordering quantity, and the total expected profit. As the freshness sensitivity coefficient increases, the channels have to make a more freshness-keeping effort to improve the freshness level. Although the price has been raised to a certain extent, the increase in greenness degree and freshness level has, nevertheless, won customer orders for the channels. As a result, the profits of the dual-channel supply chain are enhanced. Therefore, the greater the sensitivity coefficient, the better the improvement of a supply chain performance. The three channel members should gradually cultivate fresh and safe consumption concepts so that consumers, in both channels, develop higher, fresh, and safe consumption awareness, thus, improving the supply chain performance.

Proposition 5. *(1)* $\frac{\partial \widetilde{P}^{dc}}{\partial \sigma} > 0$; $\frac{\partial \zeta^{dc}}{\partial \sigma} > 0$; $\frac{\partial e^{dc}}{\partial \sigma} > 0$; $\frac{\partial Q_{on}^{dc}}{\partial \sigma} > 0$; $\frac{\partial Q_{off}^{dc}}{\partial \sigma} > 0$; $\frac{\partial \prod^{dc}}{\partial \sigma} > 0$.
(2) $\frac{\partial \widetilde{P}^{c}}{\partial \sigma} > 0$; $\frac{\partial \zeta^{c}}{\partial \sigma} > 0$; $\frac{\partial e^{c}}{\partial \sigma} > 0$; $\frac{\partial Q_{on}^{c}}{\partial \sigma} > 0$; $\frac{\partial Q_{off}^{c}}{\partial \sigma} > 0$; $\frac{\partial \prod^{c}}{\partial \sigma} > 0$.

Proposition 5 indicates that the unit dual-channel selling price, greenness degree, the freshness-keeping effort, the dual-channel ordering quantity, and the total expected profit under the two supply chain scenarios are proportional to the greenness degree sensitivity coefficient. This means that when the green sensitivity coefficient increases, the supply chain will increase the greenness degree. Due to the increase in greenness and freshness, which brings about considerable market demand, the profit of the supply chain system is enhanced. Therefore, in order to improve the long-term performance of the supply chain, the participants of the green supply chain should make joint efforts to improve the public green awareness and greenness degree. Since these efforts contributes to the green development of residents, regions, and even the world, local governments are also supposed to give policy support. In this way, the development of green supply chains will be healthier, faster, and more sustainable.

It can be seen from Propositions 1 and 2 that the economic, social, and environmental performance of the decentralized, fresh-produce, dual-channel three-layered green supply chain is inferior to that of the centralized scenario. Therefore, the dual-channel members can enhance the greenness degree and the freshness level of products and the profit of the supply chain, by improving the concentration of supply chain decisions. However, it is usually difficult to realize the centralized supply chain decision mode in reality. This raises the question of how we can improve the economic, social, and environmental performance of the decentralized supply chain, in this case. Next, the economic, social, and environmental performance indicators of the centralized scenario will be taken as the benchmark of coordination. Two contract mechanisms will be proposed to improve this highly important issue.

5. Coordination Model with Contract

In this section, we design two contract coordination mechanisms to improve the sustainable performance of the decentralized green supply chain, i.e., a joint revenue-sharing and cost-sharing contract, and a joint, cross, cost-sharing and revenue-sharing contract, which are respectively named as *JR&CS* contract and *CC&RS* contract. The corresponding contract coordination models are developed in the following sub-sections.

5.1. JR&CS Contract Coordination Model

In this sub-section, a *JR&CS* contract mechanism is proposed. The fresh produce e-commerce enterprise sells fresh products to the offline supermarket at a low unit wholesale price P^w. The offline supermarket shares a certain proportion of the green investment cost of the fresh produce e-commerce enterprise and the freshness-keeping cost of the TPLSP, with cost sharing ratios of $1-\varphi$ and $1-\phi$, respectively. The fresh produce e-commerce enterprise and offline supermarket, jointly, share their profits with the TPLSP, and the proportion of revenue sharing ratios are μ_1 and μ_2, respectively. Under the *JR&CS* contract, the game model is established as follows:

$$\begin{aligned}&\prod_f^{jr}=\left[(1-\mu_1)\widetilde{P}-c_1-P^t\right]Q_{on}+(P^w-c_1)Q_{off}-\varphi C(\zeta)\\&=\left[(1-\mu_1)\widetilde{P}-c_1-P^t\right](a-\varpi\widetilde{P}+\delta e\theta_0+\sigma\zeta)+(P^w-c_1)(a-\varpi\widetilde{P}+\delta e\theta_0\\&+\sigma\zeta)-\frac{\varphi\lambda_1\zeta^2}{2}\end{aligned} \tag{24}$$

$$\begin{aligned}&\prod_o^{jr}=\left[(1-\mu_2)\widetilde{P}-P^w-P^t\right]Q_{off}-(1-\varphi)C(\zeta)-(1-\phi)C(e)\\&=\left[(1-\mu_2)\widetilde{P}-P^w-P^t\right](a-\varpi\widetilde{P}+\delta e\theta_0+\sigma\zeta)-(1-\varphi)\frac{\lambda_1\zeta^2}{2}-(1-\phi)\frac{\lambda_2e^2}{2}\end{aligned} \tag{25}$$

$$\begin{aligned}&\prod_t^{jr}=P^t(Q_{on}+Q_{off})-\phi C(e)+\mu_1\widetilde{P}Q_{on}+\mu_2\widetilde{P}Q_{off}\\&=2P^t(a-\varpi\widetilde{P}+\delta e\theta_0+\sigma\zeta)-\frac{\phi\lambda_2e^2}{2}+\mu_1\widetilde{P}(a-\varpi\widetilde{P}+\delta e\theta_0+\sigma\zeta)+\mu_2\widetilde{P}(a\\&-\varpi\widetilde{P}+\delta e\theta_0+\sigma\zeta)\end{aligned} \tag{26}$$

Theorem 3. *Under the JR&CS contract, the optimal unit dual-channel selling price, greenness degree, and unit and freshness-keeping effort are respectively:*

$$\widetilde{P}^{jr^*}=\frac{(1-\mu_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\mu_2)} \tag{27}$$

$$\zeta^{jr^*}=\frac{\sigma\left[(1-\mu_1)a+\varpi(P^w-P^t-2c_1)\right]\left[2\varpi\phi\lambda_2-(\mu_1+\mu_2)\delta^2\theta_0^2\right]+\sigma\delta^2\theta_0^2(1-\mu_1)\left[(\mu_1+\mu_2)a+2\varpi P^t\right]}{\left[2\varpi\varphi\lambda_1-(1-\mu_1)\sigma^2\right]\left[2\varpi\phi\lambda_2-(\mu_1+\mu_2)\delta^2\theta_0^2\right]-\sigma^2\delta^2\theta_0^2(1-\mu_1)(\mu_1+\mu_2)} \tag{28}$$

$$e^{jr^*}=\frac{\delta\theta_0\left[(\mu_1+\mu_2)a+2\varpi P^t\right]\left[2\varpi\varphi\lambda_1-(1-\mu_1)\sigma^2\right]+\sigma^2\delta\theta_0(\mu_1+\mu_2)\left[(1-\mu_1)a+\varpi(P^w-P^t-2c_1)\right]}{\left[2\varpi\varphi\lambda_1-(1-\mu_1)\sigma^2\right]\left[2\varpi\phi\lambda_2-(\mu_1+\mu_2)\delta^2\theta_0^2\right]-\sigma^2\delta^2\theta_0^2(1-\mu_1)(\mu_1+\mu_2)} \tag{29}$$

Proposition 6. *When the contract parameters meet the conditions,* $(1-\mu_2)c_1=P^w+P^t$, $4\varpi\varphi\phi=1$, $2\varpi\varphi(\mu_1+\mu_2)=1$, $2\varpi\phi(1-\mu_1)=1$, $(\mu_1+\mu_2)c_1+2P^t=0$, *and* $P^w-P^t-2c_1+(1-\mu_1)c_1=0$, *the sustainable performance of the green supply chain system will be improved to achieve the optimal level of the centralized system.*

Proposition 6 indicates that, under the above conditions of contract parameters, the unit, dual-channel selling price, the greenness degree, and the freshness-keeping effort of the dual-channel, three-layered green supply chain are coordinated and the profit has reached the maximum. This reveals that, although the centralized supply chain mode is difficult to realize, the decentralized decision-making supply chain can achieve the performance and efficiency of the centralized scenario, through the *JR&CS* contract. From the *JR&CS* contract, we can find that if the fresh-produce e-commerce enterprise and the offline supermarket jointly share more revenue with the TPLSP, then the third party is willing to bear more freshness-keeping cost. At this point, because the fresh produce e-commerce enterprise shares more revenue with the TPLSP, its share of the green investment cost will be reduced. As the green investment cost shared by the fresh produce e-commerce enterprise decreases, the green investment cost shared by the offline supermarket will rise accordingly. However, as its profit shared with the TPLSP increases, its share of the freshness-keeping cost will decrease accordingly.

Proposition 7. *When the contract parameters simultaneously satisfy the following conditions,* $(1-\mu_2)\varpi\lambda_1\lambda_2-(\mu_1+1)\sigma^2\lambda_2+(\mu_2+\mu_1-2)\delta^2\theta_0^2\lambda_1>\frac{4\varpi\lambda_1\lambda_2(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$, $\mu_1+\mu_2>\frac{8(2\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1)}$, *and* $1-\mu_1>\frac{4(3\varpi\lambda_1\lambda_2-2\sigma^2\lambda_2)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2(\varpi\lambda_1\lambda_2-\sigma^2\lambda_2)}$, *the supply chain sustainable performance reaches the optimal system, while the profits of all parties reach the Pareto improvement.*

Proposition 7 shows the contract parameter conditions that achieve the Pareto improvement. Only when all three members of the dual-channel, three-layered green supply chain have additional profits to obtain, can the members of the supply chain be motivated to accept the above contract and ensure its implementation, accordingly. Under the *JR&CS* contract, the offline supermarket shares the green investment cost and the freshness-keeping cost, and the offline supermarket and the fresh produce e-commerce enterprise jointly share their revenues with the TPLSP, promoting the improvement of the greenness degree and the freshness level of the fresh produce. The overall performance of the green supply chain is improved, while ensuring that the profits of all supply chain members are greater than that of the decentralized supply chain, without the contract. This indicates that when the supply chain decision makers draw up contracts they must take the above contract parameters as the premise, which will not only enable them to share the extra profits generated by the contract but will also effectively improve the overall economic, social, and environmental performance. It also helps to make the supply chain develop continuously, quickly, healthily, steadily, and forwardly. This will be beneficial to the supply chain members as well as the whole society and environment.

5.2. CC&RS Contract Coordination Model

Another *CC&RS* contract mechanism has been designed in this section. The offline supermarket and the fresh produce e-commerce enterprise jointly share the freshness-keeping cost of the TPLSP. Their proportions of cost sharing are all $\frac{1-\Omega}{2}$. The offline supermarket and the TPLSP jointly share the green investment cost of the fresh produce e-commerce enterprise, and their cost sharing ratios are all $\frac{1-\mathcal{F}}{2}$. The offline supermarket shares its revenue of η_1 (revenue sharing parameter) ratio, with the fresh produce e-commerce enterprise and shares its revenue of η_2 (revenue sharing parameter) ratio, with the TPLSP. Accordingly, the contract coordination model is built as follows:

$$\begin{aligned}\prod\nolimits_f^{cc} &= (\widetilde{P} - c_1 - P^t)Q_{on} + (P^w - c_1)Q_{off} - \mathcal{F}C(\zeta) - \tfrac{1-\Omega}{2}C(e) + \eta_1 \widetilde{P} Q_{off} \\ &= (\widetilde{P} - c_1 - P^t)(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) + (P^w - c_1)(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) \\ &- \tfrac{\mathcal{F}\lambda_1\zeta^2}{2} - \tfrac{(1-\Omega)\lambda_2 e^2}{4} + \eta_1\widetilde{P}(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta)\end{aligned} \tag{30}$$

$$\begin{aligned}&\prod\nolimits_o^{cc} = \left[(1-\eta_1-\eta_2)\widetilde{P} - P^w - P^t\right]Q_{off} - \tfrac{1-\mathcal{F}}{2}C(\zeta) - \tfrac{1-\Omega}{2}C(e) \\ &= \left[(1-\eta_1-\eta_2)\widetilde{P} - P^w - P^t\right](a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) - \tfrac{(1-\mathcal{F})\lambda_1\zeta^2}{4} - \tfrac{(1-\Omega)\lambda_2 e^2}{4}\end{aligned} \tag{31}$$

$$\begin{aligned}&\prod\nolimits_t^{cc} = P^t(Q_{on} + Q_{off}) - \tfrac{1-\mathcal{F}}{2}C(\zeta) - \Omega C(e) + \eta_2\widetilde{P}Q_{off} \\ &= 2P^t(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta) - \tfrac{(1-\mathcal{F})\lambda_1\zeta^2}{4} - \tfrac{\Omega\lambda_2 e^2}{2} + \eta_2\widetilde{P}(a - \varpi\widetilde{P} + \delta e\theta_0 + \sigma\zeta)\end{aligned} \tag{32}$$

Theorem 4. *Under the CC&RS contract, the optimal dual-channel selling price, the greenness degree, and the freshness-keeping effort are as follows:*

$$\widetilde{P}^{cc*} = \frac{(1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta) + \varpi(P^w+P^t)}{2\varpi(1-\eta_1-\eta_2)} \tag{33}$$

$$\zeta^{cc^*} = \frac{\sigma\left[(1+\eta_1)a + \varpi(P^w - P^t - 2c_1)\right]\left[2\varpi\Omega\lambda_2 - \eta_2\delta^2\theta_0^2\right] + \sigma\delta^2\theta_0^2(1+\eta_1)\left[\eta_2 a + 2\varpi P^t\right]}{\left[2\varpi\mathcal{F}\lambda_1 - (1+\eta_1)\sigma^2\right]\left[2\varpi\Omega\lambda_2 - \eta_2\delta^2\theta_0^2\right] - \sigma^2\delta^2\theta_0^2\eta_2(1+\eta_1)} \tag{34}$$

$$e^{cc^*} = \frac{\delta\theta_0\left[\eta_2 a + 2\varpi P^t\right]\left[2\varpi\mathcal{F}\lambda_1 - (1+\eta_1)\sigma^2\right] + \sigma^2\delta\theta_0\eta_2\left[(1+\eta_1)a + \varpi(P^w - P^t - 2c_1)\right]}{\left[2\varpi\mathcal{F}\lambda_1 - (1+\eta_1)\sigma^2\right]\left[2\varpi\Omega\lambda_2 - \eta_2\delta^2\theta_0^2\right] - \sigma^2\delta^2\theta_0^2\eta_2(1+\eta_1)} \tag{35}$$

Proposition 8. *The green supply chain can be coordinated when the contract parameters meet the following conditions:* $(1-\eta_1-\eta_2)c_1 = P^w + P^t$, $4\varpi\Omega\mathcal{F} = 1$, $2\varpi\mathcal{F}\eta_2 = 1$, $2\varpi\Omega(1+\eta_1) = 1$, *and* $\eta_2 c_1 + 2P^t = 0$, $P^w - P^t + (\eta_1 - 1)c_1 = 0$.

Proposition 8 indicates that, under the *CC&RS* contract, the unit online and offline selling price, the greenness degree, the freshness-keeping effort, and the profit in the decentralized supply chain were optimized. Additionally, from the above contract parameters we can find that $P^t = -\eta_2 c_1/2$ and $P^w = (1 - \eta_1 - \eta_2/2)c_1$, which means that the unit distribution price of the TPLSP is negative and the unit wholesale price of the fresh produce e-commerce enterprise is less than the unit cost of the fresh produce. This indicates that the contract has changed the internal prices of the green supply chain system. With the increase of the profit sharing ratio, the wholesale price and the logistics price of fresh e-commerce enterprises will become lower. It can also be found that $\eta_2 = 2\Omega$ and $1 + \eta_1 = 2\mathcal{F}$, which indicates that, if the offline supermarket bears more of the green investment cost and the freshness-keeping cost, it should cut the share of the revenue to the fresh produce e-commerce enterprise and the TPLSP. Moreover, from the contract conditions $4\varpi\Omega\mathcal{F} = 1$, $2\varpi\mathcal{F}\eta_2 = 1$, and $2\varpi\Omega(1 + \eta_1) = 1$, one can observe that there is an inverse relationship between Ω and $\mathcal{F}$, the same as the relationship between $\mathcal{F}$ and η_2, and the relationship between Ω and $1 + \eta_1$. This indicates that if the fresh-produce e-commerce enterprise is willing to share more green investment cost, its share of the freshness-keeping cost will be increased, and then the revenue compensation it obtains from the offline supermarket will be improved. If the TPLSP takes on less of the freshness-keeping cost, the green investment cost it takes on will also be lower, and then the revenue compensation it receives from the offline supermarket will also be less.

Proposition 9. *The green supply chain can be coordinated and the Pareto improvement can be achieved with the contract parameters, simultaneously, satisfying the following conditions:* $2(1 - \eta_1 - \eta_2)\varpi\lambda_1\lambda_2 - 2(1 + \eta_1)\delta^2\theta_0^2\lambda_1 + (\eta_1 - 1)\sigma^2\lambda_2 > \frac{8\varpi\lambda_1\lambda_2(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$, $2\eta_2\varpi\lambda_1\lambda_2 - 2\eta_2\delta^2\theta_0^2\lambda_1 + (\eta_1 - 1)\sigma^2\lambda_2 > \frac{16(2\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$, *and* $2(1 + \eta_1)\varpi\lambda_1\lambda_2 + (\eta_2 - 2)\delta^2\theta_0^2\lambda_1 - 2(1 + \eta_1)\sigma^2\lambda_2 > \frac{8(3\varpi\lambda_1\lambda_2-2\sigma^2\lambda_2)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$.

Proposition 9 indicates that the *CC&RS* contract can coordinate the green supply chain and realize the Pareto improvement. This means that all the three channel participants gain more profit with the *CC&RS* contract than that without the *CC&RS* contract. Therefore, in order to benefit all supply chain members, the above conditions should be met in contract negotiation. Under the *CC&RS* contract, the fresh produce e-commerce enterprise undertakes a certain percentage of the freshness-keeping cost and the TPLSP bears a certain ratio of the green investment cost. The offline supermarket shares the green investment cost and the freshness-keeping cost and gives them (the fresh-produce e-commerce enterprise and TPLSP) the corresponding revenue sharing compensation. This would further stimulate the improvement of the greenness degree and the freshness level of the fresh produce, and increase the profits of the supply chain system. Finally, the profits of all three members of the green supply chain would be improved, realizing the Pareto improvement.

6. Numerical Analysis

This section describes a numerical experiment that was carried out to give an intuitive representation of the above theoretical deduction. While illustrating the results of the theoretical deduction, it also provides a better understanding of its mechanism. According to the assumptions, we set the following parameter values, considering the satisfying conditions of the feasible region: $a = 200$, $b = 22$, $\mu = 2$, $c_1 = 1$, $\lambda_1 = 2$, $\lambda_2 = 2$, $\delta = 1$, $\theta = 1$, and $\sigma = 0.5$.

6.1. Comparison of Supply Chain Performance under Different Scenarios

Table 3 shows that the unit, dual-channel price in the centralized scenario is lower than that in the decentralized scenario, while the greenness degree, the freshness-keeping effort, the dual-channel ordering quantity, and the total expected profit in the centralized scenario are higher than that in the decentralized scenario. This indicates that, when the supply chain is in a decentralized decision-making situation, the greenness degree of fresh produce in the dual channels will be relatively lower, consumers will purchase fresh produce of lower freshness, and the order quantity in both online and offline channels will be reduced; at the same time, the profit of the supply chain will suffer a certain loss. This reveals that the economic, social, and environmental performance of the centralized scenario is superior, and also reveals the necessity of coordinating the decentralized green supply chain. Under the *JR&CS* contract and the *CC&RS* contract, all the decisions and total expected profit are coordinated to reach the optimal state of centralized decision-making. This indicates that the two proposed contracts can effectively coordinate the supply chain to achieve optimal performance.

Table 3. Comparison of different supply chain scenarios.

Symbol	Decentralized Scenario	Centralized Scenario	*JR&CS* Scenario	*CC&RS* Scenario
$\widetilde{P}$	6.616	5.645	5.645	5.645
ζ	0.911	2.323	2.323	2.323
e	1.823	4.645	4.645	4.645
Q_{on}	36.456	92.903	92.903	92.903
Q_{off}	36.456	92.903	92.903	92.903
$\prod$	527.454	836.129	836.129	836.129

6.2. Sensitivity Analysis of Contracts Parameters

(1) Contract parameter sensitivity analysis of *JR&CS*

According to the above contract parameter condition, we drew the following domain: $78\mu_2 - \mu_1 < 63.681$, $\mu_1 + \mu_2 > 0.624$, and $0 < \mu_1 < 0.537$. Next, we analyzed the sensitivity of contract parameters. Figure 2a shows the sensitivity analysis of μ_1 and Figure 2b shows the sensitivity analysis of μ_2, under the *JR&CS* contract. From Figure 2a, it can be easily observed that with the increase of μ_1 the profit of the TPLSP rose sharply, while that of the fresh-produce e-commerce enterprise dropped sharply. At the same time there was a slight increase in the profit of the offline supermarket. Figure 2b demonstrates clearly that remarkable increases in the TPLSP's profit took place with the change of μ_2. Meanwhile, the profit of the offline supermarket experienced a constant steady decline. Additionally, it could be noticed that the profit of the fresh-produce e-commerce enterprise climbed slowly and weakly. From Figure 2a,b, one could find that the profits of the offline supermarket, the TPLSP, and the fresh-produce e-commerce enterprise, under the contract scenario were higher than that under the decentralized scenario. This indicated that in the range of the above contract parameters, the profits of channel members achieved the Pareto improvement. This further revealed that, under the *JR&CS* contract, there were improvements in not only the overall economic, social, and environmental performance of the supply chain, but also to a certain extent, in the profits of all the three supply chain participants. This could help motivate the three members to reach an agreement so as to better improve the sustainable performance of the supply chain, in the long run.

(2) Contract parameter sensitivity analysis of *CC&RS*

In this sub-section, we describe the sensitivity analysis of the parameters of the *CC&RS* contract. The following intervals could be obtained by calculating the parameter range satisfied by the supply chain coordination: $163.5\eta_1 + 160\eta_2 < 130.863$ and $0.5\eta_1 + 156\eta_2 > 97.816$. Figure 2c,d respectively describe the sensitivity analysis of η_1 and η_2. It is clear from Figure 2c that the positive change in parameter η_1 led to a gradual increase in the profit of the fresh-produce e-commerce enterprise and a gradual decrease in the profit of the offline supermarket. In the meantime, the profit of the TPLSP experienced a steady but slight increase. Similarly, as is shown in Figure 2d, the profit of the TPLSP increased significantly as the contract parameter η_2 increased, while the profit of the offline supermarket decreased dramatically, as the contract parameter η_2 increased. In comparison, the profit of the fresh-produce e-commerce enterprise increased by a narrow margin; it remained almost constant. This showed that the contract parameter η_1 had more impact on the profits of the fresh-produce e-commerce enterprise and the offline supermarket, whereas, the contract parameter

η_2 had more impact on the profits of the TPLSP and the offline supermarket. However, it should be noted that, under the *CC&RS* contract, the profits of green dual-channel members achieved the Pareto improvement, which was better than in the case of decentralized decision-making. Therefore, the members of the supply chain should allocate the incremental income reasonably, according to the strategic environment, to better coordinate the development.

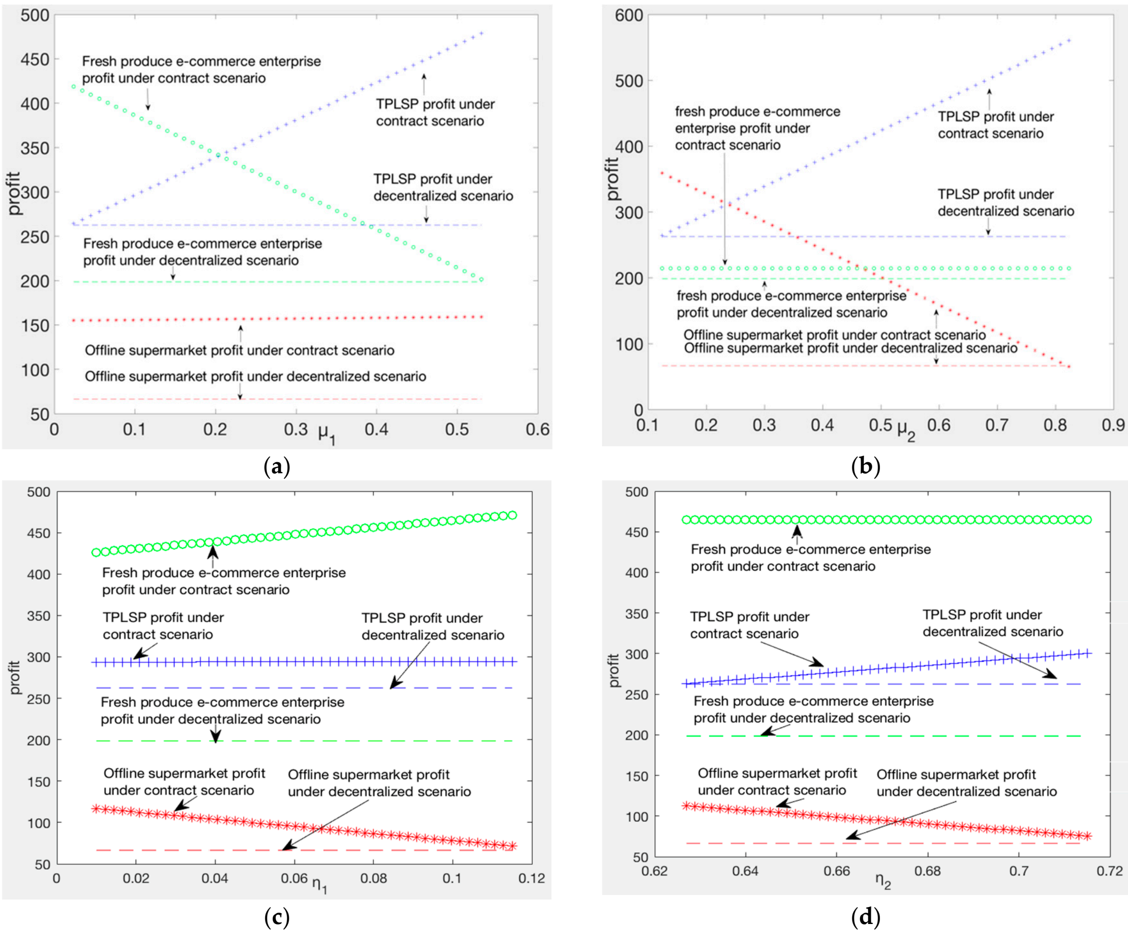

Figure 2. Sensitivity analysis of the contract parameters, under the *JR&CS* and *CC&RS* contracts. (**a**) The profit of each supply chain member vs. μ_1, under the *JR&CS* contract. (**b**) The profit of each supply chain member vs. μ_2, under *the JR&CS* contract. (**c**) The profit of each supply chain member vs. η_1, under the *CC&RS* contract. (**d**) The profit of each supply chain member vs. η_2, under the *CC&RS* contract.

6.3. Sensitivity Analysis of Greenness Degree and the Freshness Coefficients

Figure 3a–f shows the effect of greenness degree and the freshness coefficient on the unit, dual-channel selling price, the greenness degree, the freshness-keeping effort, the dual-channel ordering quantity, and the total expected profit. Figure 3a reveals that under both centralized and decentralized scenarios, the unit dual-channel selling price increased as the consumers' sensitivity to the fresh-produce greenness degree and the freshness level increased. The same is true for the greenness degree, the freshness-keeping effort, the dual-channel ordering quantity, and the total expected profit, as shown in Figure 3b–f. This revealed that the positive increase of consumers' sensitivity to greenness degree and the freshness level would increase the decision values of the unit dual-channel selling price, the greenness degree, and the freshness-keeping effort. As a result of the improvement of the greenness degree and the freshness level, consumers in both online and offline channels were more inclined to purchase the fresh produce, which in turn stimulated a relatively larger amount of the dual-channel ordering, thus, increasing the overall profit of the whole supply chain. Therefore, when consumers prefer the greenness degree and the freshness level of fresh produce, the sustainable performance of the dual-channel, three-layered green supply chain would be higher. Therefore, the three members of the green supply chain should strive to improve the consumers' health and safety consumption concept, intensify efforts to cultivate the consumers' green awareness, and then subtly improve the overall performance of the supply chain.

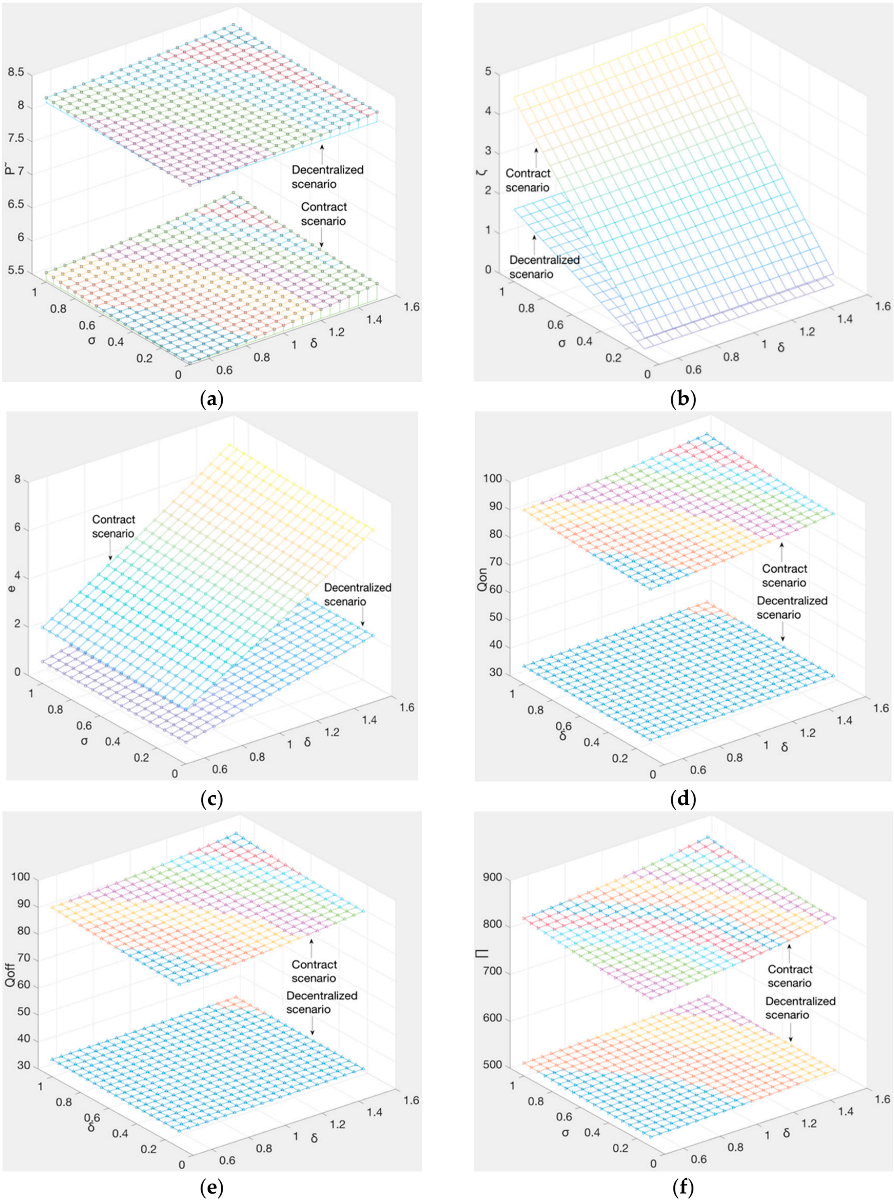

Figure 3. Sensitivity analysis of the greenness degree and the freshness coefficients. (**a**) The unit dual-channel selling price $\widetilde{P}$ vs. δ and σ. (**b**) The greenness degree ζ vs. δ and σ. (**c**) The freshness-keeping effort e vs. δ and σ. (**d**) The online channel ordering quantity Q_{on} vs. δ and σ. (**e**) The offline channel ordering quantity Q_{off} vs. δ and σ. (**f**) The total expected profit $\prod$ vs. δ and σ.

7. Conclusions

Sustainable green supply chains involving economic, social, and environmental aspects are enormously significant to the consumers' safe consumption and environmental protection, and the supply chain members' profits. Given that most of the research on green supply chains is focused on qualitative analysis, and that research on the dual-channel, three-layered green supply chains is exceedingly rare, here we make a first attempt to employ the game theory, the contract theory, and the system optimization theory, to study the coordination of the sustainable decisions of a dual-channel, three-layered green supply chain, by way of a quantitative model analysis. The main findings are as follows.

First, from the perspective of the supply chain decisions and profits, we found that a centralized scenario supply chain and two contract supply chain scenarios are superior to a decentralized scenario supply chain. This indicates that both the centralized scenario and the two contract scenarios can improve the sustainable performance of the whole supply chain. The channel conflict caused by decentralized decisions has a certain impact on the results of the supply chain performance. Since the centralized scenario is generally difficult to realize, the two proposed contract scenarios can effectively improve the supply chain sustainable performance and achieve the effect of the centralized scenario.

Second, in order to promote better sustainable performance of the green supply chain, it is essential to ensure that the two contracts are carried out without scarifying individual profit. In the Pareto improvement interval, the values of the contract parameters affect the profit distribution of the supply chain members, and the specific values of the contract parameters depend on the negotiation ability of channel members. When negotiating the contracts, channel members are supposed to guarantee that the contract parameters meet the range of the Pareto improvement, which is conducive to the better implementation of the contracts and the better maintenance of the cooperative supply chain.

Third, it is worth noting that the greenness degree, the freshness level, the dual-channel ordering quantity, and the profit of the supply chain are positively driven by the consumers' sensitivity to the greenness degree and the freshness level. Therefore, for the supply chain decision-makers, improving the consumers' concern about the greenness degree and the freshness level of products, and enhancing the consumers' awareness of greenness and safety by proper publicity means, will be a preferable supply chain operation strategy, which will be beneficial to the improvement of the economic, social, and environmental performance of the supply chain, thus, achieving its better sustainable development.

This paper provides more profound managerial implications. When all the links of the supply chain are individually optimized, rather than integrating its objectives and activities with the rest of the supply chain, the whole chain will show an unsatisfactory performance. Like the supply chain investigated in this paper, when channel members are only concerned with their own economic profits they often make the overall supply chain economic performance, even the environmental and social performance, suffer certain losses. Therefore, when making decisions, the supply chain members must take into account the overall supply-chain performance. However, in general, when making decisions based on the overall situation, the performance of one or more supply chain members will suffer certain losses, which in turn will remove their motivation to do so. Therefore, it is highly necessary to coordinate the members of a supply chain and formulate good coordination mechanisms, which could not only improve the enthusiasm of the channel participants but could also maximize the overall profit of the supply chain. At the strategic level, this can effectively improve the overall competitiveness of the supply chain. The optimal equilibrium decisions, in various supply chain situations obtained in this paper, will be helpful to the decision-making of supply chain members to optimize and maximize their performance. Through the proposed contract mechanism, the members of the supply chain can effectively eliminate the conflict of interests among themselves. While improving the economic performance of each member, the overall economic, environmental, and social performance of the supply chain can also be maximized. This will, furthermore, promote the rapid and sustainable development of the fresh-produce, dual-channel, three-layered green supply chain.

There are several future research directions that are worth taking into consideration. Our model only considers the scenario of a linear dual-channel demand. However, in reality there are many non-linear market demand scenarios. Therefore, one of the future research directions is to further study the non-linear market demand scenarios to explore how different demand functions affect the results.

Additionally, this paper merely investigated a dual-channel green supply chain system. Another less explored question is whether an integrated supply chain system has a very significant impact on another integrated supply chain system and, if so, what is that impact? Therefore, another future research direction is to consider the impact of the decision-making of other supply-chain systems on the decision-making and coordination of the supply-chain system discussed here.

Last, but not least, the supply chain explored in this paper is under a situation without shortage. Therefore, taking into account the disruption of the fresh-produce, dual-channel, three-layered green supply chain is also an interesting research topic. In this case, the questions include, what are the optimal decisions of the supply chain, whether there is a possibility of eliminating or improving the conflict of interest, how to design the contract-coordination mechanism, and what is the scope of the contract implementation? These are very interesting questions that remain to be studied.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Proof of Theorem 1.

According to Equation (4), we obtain $\frac{\partial \prod_o^{dc}}{\partial \widetilde{P}} = -2\varpi \widetilde{P} + a + \delta e\theta_0 + \sigma\zeta + \varpi(P^w + P^t)$ and $\frac{\partial^2 \prod_o^{dc}}{\partial \widetilde{P}^2} = -2\varpi < 0$. Therefore, $\prod_o^{dc}$ is concave to $\widetilde{P}$. Letting $\frac{\partial \prod_o^{dc}}{\partial \widetilde{P}} = 0$, we derive $\widetilde{P}^{dc^*} = \frac{a+\delta e\theta_0+\sigma\zeta+\varpi(P^w+P^t)}{2\varpi}$. Substituting $\widetilde{P}^{dc^*}$ into Equation (5), then $\prod_t^{dc} = P^t\left[a + \delta e\theta_0 + \sigma\zeta - \varpi(P^w + P^t)\right] - \frac{\lambda_2 e^2}{2}$. The Hessian matrix can be obtained:

$$H(\prod_t^{dc}) = \begin{bmatrix} -2\varpi & \delta\theta_0 \\ \delta\theta_0 & -\lambda_2 \end{bmatrix}$$

When $2\varpi\lambda_2 - \delta^2\theta_0^2 > 0$, the Hessian matrix is negative definite. By solving $\frac{\partial \prod_t^{dc}}{\partial P^t} = 0$ and $\frac{\partial \prod_t^{dc}}{\partial e} = 0$, we obtain $P^{t^*} = \frac{a+\delta e\theta_0+\sigma\zeta-\varpi P^w}{2\varpi}$, $e^{dc^*} = \frac{\delta\theta_0 P^t}{\lambda_2}$. Similarly, we derive $\prod_f^{dc} = \left[\frac{a+\delta e\theta_0+\sigma\zeta+\varpi(P^w+P^t)}{2\varpi} + P^w - 2c_1 + P^t\right]\frac{a+\delta e\theta_0+\sigma\zeta-\varpi(P^w+P^t)}{2} - \frac{\lambda_1\zeta^2}{2}$, and the Hessian matrix:

$$H(\prod_f^{dc}) = \begin{bmatrix} -\frac{3\varpi}{2} & \frac{\sigma}{2} \\ \frac{\sigma}{2} & \frac{\sigma^2}{2\varpi} - \lambda_1 \end{bmatrix}$$

When $3\varpi\lambda_1 - 2\sigma^2 > 0$, the Hessian matrix is negative definite. We set $\frac{\partial \prod_f^{dc}}{\partial P^w} = 0$ and $\frac{\partial \prod_f^{dc}}{\partial \zeta} = 0$, and we obtain $P^{w^*} = \frac{a+\delta e\theta_0+\sigma\zeta+\varpi(2c_1-P^t)}{3\varpi}$ and $\zeta^{dc^*} = \frac{\sigma\left[a+\delta e\theta_0+\sigma\zeta+\varpi(P^w-2c_1-P^t)\right]}{2\varpi\lambda_2-\sigma^2}$. We simplify the equations and put them into $\widetilde{P}^{dc*}$, then we obtain Equations (6)–(10). □

Proof of Corollary 1.

We substitute $\widetilde{P}^{dc^*}$, P^{t^*}, e^{dc^*}, P^{w^*}, and ζ^{dc^*} into Equations (1)–(5), and Equations (11)–(16) can be derived. □

Proof of Theorem 2.

According to Equation (17), we obtain the Hessian matrix of $\prod^c$ as follows:

$$H(\prod^c) = \begin{bmatrix} -2\varpi & 2\delta\theta_0 & 2\sigma^2 \\ 2\delta\theta_0 & -\lambda_2 & 0 \\ 2\sigma^2 & 0 & -\lambda_1 \end{bmatrix}$$

The Hessian matrix is negative definite if $\varpi\lambda_2 - 2\delta^2\theta_0^2 > 0$ and $\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2 > 0$. By solving $\frac{\partial\prod^c}{\partial\widetilde{P}} = 0$, $\frac{\partial\prod^c}{\partial\zeta} = 0$, and $\frac{\partial\prod^c}{\partial e}$, we obtain $\widetilde{P}^{c*} = \frac{\lambda_1\lambda_2 a + c_1(\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2}$, $\zeta^{c*} = \frac{2\sigma\lambda_2(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2}$, and $e^{c*} = \frac{2\delta\theta_0\lambda_1(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2}$. □

Proof of Corollary 2.
Putting $\widetilde{P}^{c*}$, e^{dc*}, and ζ^{dc*} into Equations (1), (2) and (17), and we obtain Equations (21)–(23). □

Proof of Proposition 1.
$\zeta^{c*} - \zeta^{dc*} = \frac{6\sigma\varpi\lambda_1\lambda_2{}^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)}$, $e^{c*} - e^{dc*} = \frac{6\delta\theta_0\varpi\lambda_1{}^2\lambda_2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)}$, $\widetilde{P}^{c*} - \widetilde{P}^{dc*} = \frac{-3\lambda_1\lambda_2(a-\varpi c_1)(\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)}$. Because $a - \varpi c_1 > 0$ and $\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2 > 0$, therefore, $\widetilde{P}^{dc} > \widetilde{P}^c$, $\zeta^{dc*} < \zeta^{c*}$; $e^{dc*} < e^{c*}$. □

Proof of Proposition 2.
$Q_{on}^c{}^* - Q_{on}^{dc*} = \frac{6\varpi^2\lambda_1{}^2\lambda_2{}^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2M)(5\varpi\lambda_1\lambda_2 - 2M)}$, $\prod^{c*} - \prod^{dc*} = \frac{\lambda_1\lambda_2(a-\varpi c_1)\left[19\varpi^2\lambda_1{}^2\lambda_2{}^2 - 12\varpi\lambda_1\lambda_2 M + M^2 + 4\delta^2\theta_0^2\lambda_1(\varpi\lambda_1\lambda_2 - M)\right]}{(2\varpi\lambda_1\lambda_2 - 2M)(5\varpi\lambda_1\lambda_2 - 2M)^2}$, where $M = \delta^2\theta_0^2\lambda_1 + \sigma^2\lambda_2$. Since $a - \varpi c_1 > 0$ and $\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2 > 0$, we obtain $19\varpi^2\lambda_1{}^2\lambda_2{}^2 - 12\varpi\lambda_1\lambda_2 M = \varpi\lambda_1\lambda_2(19\varpi\lambda_1\lambda_2 - 12M) > 0$ and $\varpi\lambda_1\lambda_2 - M > 0$, then $Q_{on}^c{}^* > Q_{on}^{dc*}$ and $\prod^{c*} > \prod^{dc*}$. □

Proof of Proposition 3.
$\frac{\partial\widetilde{P}^{dc}}{\partial c_1} = \frac{\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} > 0$; $\frac{\partial\zeta^{dc}}{\partial c_1} = \frac{-2\sigma\lambda_2\varpi}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial e^{dc}}{\partial c_1} = \frac{-2\delta\theta_0\lambda_1\varpi}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial Q_{on}^{dc}}{\partial c_1} = \frac{-\varpi\lambda_1\lambda_2\varpi}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial Q_{off}^{dc}}{\partial c_1} = \frac{-\varpi\lambda_1\lambda_2\varpi}{5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial\prod^{dc}}{\partial c_1} = \frac{-2\lambda_1\lambda_2\varpi(a-\varpi c_1)(4\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} < 0$. $\frac{\partial\widetilde{P}^c}{\partial c_1} = \frac{\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} > 0$; $\frac{\partial\zeta^c}{\partial c_1} = \frac{-2\sigma\lambda_2\varpi}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial e^c}{\partial c_1} = \frac{-\varpi\lambda_1\lambda_2\varpi}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial Q_{on}^c}{\partial c_1} = \frac{-\varpi\lambda_1\lambda_2\varpi}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial Q_{off}^c}{\partial c_1} = \frac{-\varpi\lambda_1\lambda_2\varpi}{2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2} < 0$; $\frac{\partial\prod^c}{\partial c_1} = \frac{-2\lambda_1\lambda_2\varpi(a-\varpi c_1)(\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} < 0$. □

Proof of Proposition 4.
$\frac{\partial\widetilde{P}^{dc}}{\partial\delta} = \frac{16\lambda_2\delta\theta_0^2\lambda_1^2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial\zeta^{dc}}{\partial\delta} = \frac{4\lambda_2\sigma\delta\theta_0^2\lambda_1^2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial e^{dc}}{\partial\delta} = \frac{8\delta^2\theta_0^3\lambda_1^2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{on}^{dc}}{\partial\delta} = \frac{4\varpi\delta\theta_0^2\lambda_1^2\lambda_2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{off}^{dc}}{\partial\delta} = \frac{4\varpi\delta\theta_0^2\lambda_1^2\lambda_2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial\prod^{dc}}{\partial\delta} = \frac{4\lambda_2\delta\theta_0^2\lambda_1^2(a-\varpi c_1)^2(11\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)}{(5\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^3} > 0$. $\frac{\partial\widetilde{P}^c}{\partial\delta} = \frac{4\lambda_2\delta\theta_0^2\lambda_1^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial\zeta^c}{\partial\delta} = \frac{4\lambda_2\sigma\delta\theta_0^2\lambda_1^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial e^c}{\partial\delta} = \frac{8\delta^2\theta_0^3\lambda_1^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{on}^c}{\partial\delta} = \frac{4\varpi\delta\theta_0^2\lambda_1^2\lambda_2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{off}^c}{\partial\delta} = \frac{4\varpi\delta\theta_0^2\lambda_1^2\lambda_2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2 - 2\delta^2\theta_0^2\lambda_1 - 2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial\prod^c}{\partial\delta} = \frac{\delta\theta_0^2\lambda_1^2\lambda_2(a-\varpi c_1)^2}{(\varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2)^2} > 0$. □

Proof of Proposition 5.
$\frac{\partial \widetilde{P}^{dc}}{\partial \sigma} = \frac{16\sigma\lambda_1\lambda_2^2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial \zeta^{dc}}{\partial \sigma} = \frac{8\sigma^2\lambda_2^2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial e^{dc}}{\partial \sigma} = \frac{8\delta\sigma\lambda_1\lambda_2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{on}^{dc}}{\partial \sigma} = \frac{4\sigma\varpi\lambda_1\lambda_2^2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{off}^{dc}}{\partial \sigma} = \frac{4\sigma\varpi\lambda_1\lambda_2^2(a-\varpi c_1)}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial \prod^{dc}}{\partial \sigma} = \frac{4\lambda_1\sigma\lambda_2^2(a-\varpi c_1)^2(11\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$. $\frac{\partial \widetilde{P}^{c}}{\partial \sigma} = \frac{4\sigma\lambda_1\lambda_2^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial \zeta^{c}}{\partial \sigma} = \frac{8\sigma^2\lambda_2^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial e^{c}}{\partial \sigma} = \frac{8\delta\sigma\lambda_1\lambda_2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{on}^{c}}{\partial \sigma} = \frac{4\sigma\varpi\lambda_1\lambda_2^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial Q_{off}^{c}}{\partial \sigma} = \frac{4\sigma\varpi\lambda_1\lambda_2^2(a-\varpi c_1)}{(2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2} > 0$; $\frac{\partial \prod^{c}}{\partial \sigma} = \frac{\sigma\lambda_1\lambda_2^2(a-\varpi c_1)^2}{(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2} > 0$. □

Proof of Theorem 3.
We deduce the differential of $\prod_o^{jr}$ with respect to $\widetilde{P}$. $\frac{\partial \prod_o^{jr}}{\partial \widetilde{P}} = -2\varpi(1-\mu_2)\widetilde{P} + (1-\mu_2)(a+\delta e\theta_0+\sigma\zeta) + \varpi(P^w+P^t)$ and $\frac{\partial^2 \prod_o^{jr}}{\partial \widetilde{P}^2} = -2\varpi(1-\mu_2) < 0$. By solving $\frac{\partial \prod_o^{jr}}{\partial \widetilde{P}} = 0$, we obtain $\widetilde{P}^{jr^*} = \frac{(1-\mu_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\mu_2)}$. Substituting $\widetilde{P}^{jr^*}$ into Equation (24), we obtain $\prod_f^{jr} = \left[(1-\mu_1)\frac{(1-\mu_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\mu_2)} - 2c_1 + P^w - P^t\right]\left[(1-\mu_1)\frac{(1-\mu_2)(a+\delta e\theta_0+\sigma\zeta)-\varpi(P^w+P^t)}{2(1-\mu_2)}\right] - \frac{\varphi\lambda_1\zeta^2}{2}$. $\frac{\partial \prod_f^{jr}}{\partial \zeta} = \frac{(1-\mu_1)\sigma(a+\delta e\theta_0+\sigma\zeta)}{2\varpi} + \frac{\sigma(-2c_1+P^w-P^t)}{2} - \varphi\lambda_1\zeta$, then $\zeta^{jr^*} = \frac{\sigma\left[(1-\mu_1)(a+\delta e\theta_0)+\varpi(-2c_1+P^w-P^t)\right]}{2\varpi\varphi\lambda_1-\sigma^2(1-\mu_1)}$. Similarly, putting $\widetilde{P}^{jr^*}$ into Equation (26), we have $\prod_t^{jr} = \left[(\mu_1+\mu_2)\frac{(1-\mu_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\mu_2)} + 2P^t\right]\left[\frac{(1-\mu_2)(a+\delta e\theta_0+\sigma\zeta)-\varpi(P^w+P^t)}{2(1-\mu_2)}\right] - \frac{\phi\lambda_2 e^2}{2}$. $\frac{\partial \prod_t^{jr}}{\partial e} = \frac{(\mu_1+\mu_2)\delta\theta_0(a+\delta e\theta_0+\sigma\zeta)}{2\varpi} + \frac{2P^t\delta\theta_0}{2} - \phi\lambda_2 e$, then $e^{jr^*} = \frac{\delta\theta_0\left[(\mu_1+\mu_2)(a+\sigma\zeta)+2P^t\varpi\right]}{2\varpi\phi\lambda_2-\delta^2\theta_0^2(\mu_1+\mu_2)}$. By solving the equations, Equations (27)–(29) are obtained. □

Proof of Proposition 6.
Let $\widetilde{P}^{jr^*} = \widetilde{P}^{c^*}$ and $\zeta^{jr^*} = \zeta^{c^*}$, $e^{jr^*} = e^{c^*}$, that is $\frac{(1-\mu_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\mu_2)} = \frac{a+\delta e\theta_0+\sigma\zeta+\varpi c_1}{2\varpi}$, $\frac{\sigma\left[(1-\mu_1)a+\varpi(P^w-P^t-2c_1)\right]\left[2\varpi\phi\lambda_2-(\mu_1+\mu_2)\delta^2\theta_0^2\right]+\sigma\delta^2\theta_0^2(1-\mu_1)\left[(\mu_1+\mu_2)a+2\varpi P^t\right]}{\left[2\varpi\varphi\lambda_1-(1-\mu_1)\sigma^2\right]\left[2\varpi\phi\lambda_2-(\mu_1+\mu_2)\delta^2\theta_0^2\right]-\sigma^2\delta^2\theta_0^2(1-\mu_1)(\mu_1+\mu_2)} = \frac{2\sigma\lambda_2(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2}$, and $\frac{\delta\theta_0\left[(\mu_1+\mu_2)a+2\varpi P^t\right]\left[2\varpi\varphi\lambda_1-(1-\mu_1)\sigma^2\right]+\sigma^2\delta\theta_0(\mu_1+\mu_2)\left[(1-\mu_1)a+\varpi(P^w-P^t-2c_1)\right]}{\left[2\varpi\varphi\lambda_1-(1-\mu_1)\sigma^2\right]\left[2\varpi\phi\lambda_2-(\mu_1+\mu_2)\delta^2\theta_0^2\right]-\sigma^2\delta^2\theta_0^2(1-\mu_1)(\mu_1+\mu_2)} = \frac{2\delta\theta_0\lambda_1(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2}$. We derive that $(1-\mu_2)c_1 = P^w + P^t$, $4\varpi^2\varphi\phi\lambda_1\lambda_2 - 2\varpi\varphi\delta^2\theta_0^2(\mu_1+\mu_2)\lambda_1 - 2\varpi\phi\sigma^2\lambda_2(1-\mu_1) = \varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2$, $2\varpi\phi\lambda_2\left[(1-\mu_1)a+\varpi(-2c_1+P^w-P^t)\right] + \delta^2\theta_0^2\left[-(\mu_1+\mu_2)\varpi(P^w-P^t-2c_1)+(1-\mu_1)2\varpi P^t\right] = \lambda_2(a-\varpi c_1)$, and $2\varpi\varphi\left[(\mu_1+\mu_2)a+2\varpi P^t\right] + \sigma^2\left[-(1-\mu_1)2\varpi P^t+(\mu_1+\mu_2)\varpi(P^w-P^t-2c_1)\right] = \lambda_1(a-\varpi c_1)$. Further deriving from the equations, we obtain $4\varpi\varphi\phi = 1$, $2\varpi\varphi(\mu_1+\mu_2) = 1$, $2\varpi\phi(1-\mu_1) = 1$, $2\varpi\varphi\left[(\mu_1+\mu_2)a+2\varpi P^t\right] = a-\varpi c_1$, $2\varpi\phi\left[(1-\mu_1)a+\varpi(-2c_1+P^w-P^t)\right] = a-\varpi c_1$, and $2\varpi P^t(1-\mu_1) = (\mu_1+\mu_2)(-2c_1+P^w-P^t)$. Substituting $2\varpi\varphi = \frac{1}{\mu_1+\mu_2}$ and $2\varpi\phi = \frac{1}{1-\mu_1}$ into $2\varpi\varphi\left[(\mu_1+\mu_2)a+2\varpi P^t\right] = a-\varpi c_1$, $2\varpi\phi\left[(1-\mu_1)a+\varpi(-2c_1+P^w-P^t)\right] = a-\varpi c_1$, we obtain $(\mu_1+\mu_2)c_1 = -2P^t$, $P^w - P^t - 2c_1 = -(1-\mu_1)c_1$, Substituting $(\mu_1+\mu_2)c_1 = -2P^t$ into $2\varpi P^t(1-\mu_1) = (\mu_1+\mu_2)(-2c_1+P^w-P^t)$, it can be derived that $P^w-P^t-2c_1 = -(1-\mu_1)c_1$. From the above derivation, we obtain $(1-\mu_2)c_1 = P^w+P^t$, $4\varpi\varphi\phi = 1$, $2\varpi\varphi(\mu_1+\mu_2) = 1$, $2\varpi\phi(1-\mu_1) = 1$, $(\mu_1+\mu_2)c_1+2P^t = 0$, and $P^w-P^t-2c_1+(1-\mu_1)c_1 = 0$. □

Proof of Proposition 7.
When the profits of the three supply chain members are not less than the decentralized scenario, Pareto improvement can be achieved. Taking the above parameters into the equation, we obtain $\prod_o^{jr^*} = \frac{(1-\mu_2)}{2}\prod^{c^*} + \left[\frac{(1-\mu_2)}{2}-(1-\varphi)\right]C(\zeta) + \left[\frac{(1-\mu_2)}{2}-(1-\phi)\right]C(e)$, $\prod_t^{jr^*} = \frac{(\mu_1+\mu_2)}{2}\prod^{c^*} + \left[\frac{(\mu_1+\mu_2)}{2}-\phi\right]C(e) + \frac{(\mu_1+\mu_2)}{2}C(\zeta)$, and $\prod_f^{jr^*} = \frac{(1-\mu_1)}{2}\prod^{c^*} + \left[\frac{(1-\mu_1)}{2}-\varphi\right]C(\zeta) +$

$\frac{(1-\mu_1)}{2}C(e)$. Based on $4\varpi\varphi\phi = 1, 2\varpi\varphi(\mu_1+\mu_2) = 1, 2\varpi\phi(1-\mu_1) = 1$, we obtain $\phi = \frac{\mu_1+\mu_2}{2}$, $\varphi = \frac{1-\mu_1}{2}$, thus we have $\prod_o^{jr^*} = \frac{(1-\mu_2)}{2}\prod^{c^*} - \frac{(\mu_1+\mu_2)}{2}C(\zeta) - \frac{(1-\mu_1)}{2}C(e)$, $\prod_t^{jr^*} = \frac{(\mu_1+\mu_2)}{2}\prod^{c^*} + \frac{(\mu_1+\mu_2)}{2}C(\zeta)$, and $\prod_f^{jr^*} = \frac{(1-\mu_1)}{2}\prod^{c^*} + \frac{(1-\mu_1)}{2}C(e)$. By simplifying a set of inequalities, i.e., $\prod_f^{jr^*} > \prod_f^{dc^*}$, $\prod_o^{jr^*} > \prod_o^{dc^*}$, $\prod_t^{jr^*} > \prod_t^{dc^*}$, we obtain $2(1-\mu_2)\varpi\lambda_1\lambda_2 + (\mu_2-\mu_1-2)\sigma^2\lambda_2 + (2\mu_2+\mu_1-3)\delta^2\theta_0^2\lambda_1 > \frac{4\varpi\lambda_1\lambda_2(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$, $\mu_1+\mu_2 > \frac{8(2\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2(2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)}$, and $1-\mu_1 > \frac{4(3\varpi\lambda_1\lambda_2-2\sigma^2\lambda_2)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2(2\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)}$. □

Proof of Theorem 4.

Calculating the differential of $\prod_o^{cc}$ with respect to $\widetilde{P}$, we have $\frac{\partial\prod_o^{cc}}{\partial\widetilde{P}} = -2\varpi(1-\eta_1-\eta_2)\widetilde{P} + (1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta) + \varpi(P^w+P^t)$, $\frac{\partial^2\prod_o^{cc}}{\partial\widetilde{P}^2} = -2\varpi(1-\eta_1-\eta_2) < 0$. By solving $\frac{\partial\prod_o^{cc}}{\partial\widetilde{P}} = 0$, we obtain $\widetilde{P}^{cc^*} = \frac{(1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\eta_1-\eta_2)}$. Substituting $\widetilde{P}^{cc^*}$ into Equation (30), we obtain $\prod_f^{cc} = \left[(1+\eta_1)\frac{(1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\eta_1-\eta_2)} + P^w - P^t - 2c_1\right]\left[\frac{(1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta)-\varpi(P^w+P^t)}{2(1-\eta_1-\eta_2)}\right] - \frac{\mathcal{F}\lambda_1\zeta^2}{2} - \frac{(1-\Omega)\lambda_2e^2}{4}$. $\frac{\partial\prod_f^{cc}}{\partial\zeta} = \frac{(1+\eta_1)\sigma(a+\delta e\theta_0+\sigma\zeta)}{2\varpi} + \frac{\sigma(-2c_1+P^w-P^t)}{2} - \mathcal{F}\lambda_1\zeta$, then $\zeta^{cc^*} = \frac{\sigma\left[(1+\eta_1)(a+\delta e\theta_0)+\varpi(P^w-P^t-2c_1)\right]}{2\varpi\mathcal{F}\lambda_1-\sigma^2(1+\eta_1)}$. Similarly, putting $\widetilde{P}^{cc^*}$ into Equation (32), we obtain $\prod_t^{cc} = \left[\eta_2\frac{(1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\eta_1-\eta_2)} + 2P^t\right]\left[\frac{(1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta)-\varpi(P^w+P^t)}{2(1-\eta_1-\eta_2)}\right] - \frac{(1-\mathcal{F})\lambda_1\zeta^2}{4} - \frac{\Omega\lambda_2e^2}{2}$. $\frac{\partial\prod_t^{cc}}{\partial e} = \frac{\eta_2\delta\theta_0(a+\delta e\theta_0+\sigma\zeta)}{2\varpi} + \frac{2P^t\delta\theta_0}{2} - \Omega\lambda_2 e$, then $e^{cc^*} = \frac{\delta\theta_0\left[\eta_2(a+\sigma\zeta)+2P^t\varpi\right]}{2\varpi\Omega\lambda_2-\eta_2\delta^2\theta_0^2}$. By solving the equations consisting of $\widetilde{P}^{cc^*}$, ζ^{cc^*}, and e^{cc^*}, the specific values of $\widetilde{P}^{cc^*}$, ζ^{cc^*}, and e^{cc^*} are obtained, i.e., Equations (33)–(35). □

Proof of Proposition 8.

Let $\widetilde{P}^{cc^*} = \widetilde{P}^{c^*}$, $\zeta^{cc^*} = \zeta^{c^*}$, and $e^{cc^*} = e^{c^*}$, that is $\frac{(1-\eta_1-\eta_2)(a+\delta e\theta_0+\sigma\zeta)+\varpi(P^w+P^t)}{2\varpi(1-\eta_1-\eta_2)} = \frac{a+\delta e\theta_0+\sigma\zeta+\varpi c_1}{2\varpi}$, $\frac{\sigma\left[(1+\eta_1)a+\varpi(P^w-P^t-2c_1)\right]\left[2\varpi\Omega\lambda_2-\eta_2\delta^2\theta_0^2\right]+\sigma\delta^2\theta_0^2(1+\eta_1)\left[\eta_2a+2\varpi P^t\right]}{\left[2\varpi\mathcal{F}\lambda_1-(1+\eta_1)\sigma^2\right]\left[2\varpi\Omega\lambda_2-\eta_2\delta^2\theta_0^2\right]-\sigma^2\delta^2\theta_0^2\eta_2(1+\eta_1)} = \frac{2\delta\lambda_2(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2}$, and $\frac{\delta\theta_0\left[\eta_2a+2\varpi P^t\right]\left[2\varpi\mathcal{F}\lambda_1-(1+\eta_1)\sigma^2\right]+\sigma^2\delta\theta_0\eta_2\left[(1+\eta_1)a+\varpi(P^w-P^t-2c_1)\right]}{\left[2\varpi\mathcal{F}\lambda_1-(1+\eta_1)\sigma^2\right]\left[2\varpi\Omega\lambda_2-\eta_2\delta^2\theta_0^2\right]-\sigma^2\delta^2\theta_0^2\eta_2(1+\eta_1)} = \frac{2\delta\theta_0\lambda_1(a-\varpi c_1)}{2\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2}$. We derive that $(1-\eta_1-\eta_2)c_1 = P^w+P^t$, $4\varpi^2\Omega\mathcal{F}\lambda_1\lambda_2 - 2\varpi\eta_2\mathcal{F}\delta^2\theta_0^2\lambda_1 - 2\varpi(1+\eta_1)\Omega\sigma^2\lambda_2 = \varpi\lambda_1\lambda_2 - \delta^2\theta_0^2\lambda_1 - \sigma^2\lambda_2$, $\left[(1+\eta_1)a+\varpi(P^w-P^t-2c_1)\right]\left[2\varpi\Omega\lambda_2-\eta_2\delta^2\theta_0^2\right] + \sigma\delta^2\theta_0^2(1+\eta_1)\left[\eta_2a+2\varpi P^t\right] = \lambda_2(a-\varpi c_1)$, and $\left[\eta_2a+2\varpi P^t\right]\left[2\varpi\mathcal{F}\lambda_1-(1+\eta_1)\sigma^2\right] + \sigma^2\delta\theta_0\eta_2\left[(1+\eta_1)a+\varpi(P^w-P^t-2c_1)\right] = \lambda_1(a-\varpi c_1)$. Further deriving the equations, we obtain $4\varpi\Omega\mathcal{F} = 1$, $2\varpi\mathcal{F}\eta_2 = 1$, $2\varpi\Omega(1+\eta_1) = 1$, $2\varpi\Omega\left[(1+\eta_1)a+\varpi(P^w-P^t-2c_1)\right] = a-\varpi c_1$, $2\varpi\mathcal{F}\left[\eta_2a+\varpi P^t\right] = a-\varpi c_1$, and $2\varpi P^t(1+\eta_1) = \eta_2(P^w-P^t-2c_1)$. Substituting $2\varpi\mathcal{F} = \frac{1}{\eta_2}$ and $2\varpi\Omega = \frac{1}{1+\eta_1}$ into $2\varpi\Omega(1+\eta_1) = 1$, $2\varpi\Omega\left[(1+\eta_1)a+\varpi(P^w-P^t-2c_1)\right] = a-\varpi c_1$, and $2\varpi\mathcal{F}\left[\eta_2a+\varpi P^t\right] = a-\varpi c_1$, we obtain $\eta_2c_1 = -2P^t$, $P^w-P^t-2c_1 = -(1+\eta_1)c_1$, substituting $\eta_2c_1 = -2P^t$ into $2\varpi P^t(1+\eta_1) = \eta_2(P^w-P^t-2c_1)$, it can be derived that $P^w-P^t-2c_1 = -(1+\eta_1)c_1$. From the above derivation, we obtain $(1-\eta_1-\eta_2)c_1 = P^w+P^t$, $4\varpi\Omega\mathcal{F} = 1$, $2\varpi\mathcal{F}\eta_2 = 1$, $2\varpi\phi(1+\eta_1) = 1$, $\eta_2c_1+2P^t = 0$, and $P^w-P^t-2c_1+(1+\eta_1)c_1 = 0$. □

Proof of Proposition 9.

The Pareto improvement can be realized if the profits of the dual-channel members are greater than in the decentralized scenario. By substituting the above contract conditions into the model, we derive $\prod_o^{cc^*} = \frac{(1-\eta_1-\eta_2)}{2}\prod^{c^*} + \frac{(1-\eta_1-\eta_2)-(1-\mathcal{F})}{4}\lambda_1\zeta^2 + \frac{(1-\eta_1-\eta_2)-(1-\Omega)}{4}\lambda_1e^2$, $\prod_t^{cc^*} = \frac{\eta_2}{2}\prod^{c^*} + \frac{\eta_2-(1-\mathcal{F})}{4}\lambda_1\zeta^2 + \frac{\eta_2-2\Omega}{4}\lambda_1e^2$, and $\prod_f^{cc^*} = \frac{(1+\eta_1)}{2}\prod^{c^*} + \frac{1+\eta_1-2\mathcal{F}}{4}\lambda_1\zeta^2 + \frac{(1+\eta_1)-(1-\Omega)}{8}\lambda_1e^2$. Because $4\varpi\Omega\mathcal{F} = 1$, $2\varpi\mathcal{F}\eta_2 = 1$, and $2\varpi\Omega(1+\eta_1) = 1$, we obtain $\Omega = \frac{\eta_2}{2}$, $\varphi = \frac{1+\eta_1}{2}$, then $\prod_o^{cc^*} = \frac{(1-\eta_1-\eta_2)}{2}\prod^{c^*} + \frac{1-\eta_1-2\eta_2}{8}\lambda_1\zeta^2 + \frac{-2\eta_1-\eta_2}{8}\lambda_1e^2$, $\prod_t^{cc^*} = \frac{\eta_2}{2}\prod^{c^*} + \frac{2\eta_2-\eta_1-1}{8}\lambda_1\zeta^2$, and $\prod_f^{cc^*} = \frac{(1+\eta_1)}{2}\prod^{c^*} + \frac{2\eta_1+\eta_2}{8}\lambda_1e^2$. By simplifying a set of inequalities, i.e., $\prod_f^{ccc^*} > \prod_f^{dc^*}$, $\prod_o^{cc^*} > \prod_o^{dc^*}$, $\prod_t^{cc^*} > \prod_t^{dc^*}$, we derive that $2(1-\eta_1-\eta_2)\varpi\lambda_1\lambda_2 - 2(1+\eta_1)\delta^2\theta_0^2\lambda_1 + (\eta_1-1)\sigma^2\lambda_2 > \frac{8\varpi\lambda_1\lambda_2(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$, $2\eta_2\varpi\lambda_1\lambda_2 - 2\eta_2\delta^2\theta_0^2\lambda_1 + (\eta_1-1)\sigma^2\lambda_2 > \frac{16(2\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$, and $2(1+\eta_1)\varpi\lambda_1\lambda_2 + (\eta_2-2)\delta^2\theta_0^2\lambda_1 - 2(1+\eta_1)\sigma^2\lambda_2 > \frac{8(3\varpi\lambda_1\lambda_2-2\sigma^2\lambda_2)(\varpi\lambda_1\lambda_2-\delta^2\theta_0^2\lambda_1-\sigma^2\lambda_2)^2}{(5\varpi\lambda_1\lambda_2-2\delta^2\theta_0^2\lambda_1-2\sigma^2\lambda_2)^2}$. □

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