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Decision and Coordination of Fresh Produce Three-layer E-commerce Supply Chain: A New Framework

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ABSTRACT This paper considers a fresh agricultural products' three-layer e-commerce supply chain consisting of a producer, a third-party logistics service provider and a fresh produce e-commerce enterprise in a new framework. The market demand for fresh agricultural products is affected by the safety traceability system availability, freshness level, and unit online selling price. We develop the game models and compare the equilibrium solutions under different supply chain decision scenarios. Two different types of contracts namely cost-sharing and revenue-sharing contract; consolidated rebate and revenue-sharing contract are proposed to facilitate coordination of the supply chain. The impact of changes of market preferences on supply chain decisions, supply chain performance, and contract policies implementation is examined. The research shows that (i) centralized decision scenario is superior to decentralized decision scenario, (ii) the supply chain can be coordinated by the two contracts, (iii) safety traceability system availability and freshness level of fresh agricultural products can be enhanced, (iv) the more sensitive the consumer is to safety traceability system availability and freshness level, the more profitable the supply chain will be, (v) when consumers are more sensitive to safety traceability system availability and freshness level, the supply chain is easier to coordinate; whereas, when consumers are more sensitive to online selling price, the supply chain is not easy to coordinate. This paper fills the research gap of, and provides a practical guideline to managers in fresh produce sector to better understand the collaboration strategy in achieving higher supply chain performance and efficiency.

INDEX TERMS Fresh produce, fresh produce e-commerce enterprise; coordination contract; supply chain management; safety traceability system availability.

I. INTRODUCTION

With the development of e-commerce, individuals in growing numbers gradually have the habit of online shopping, and the fresh agricultural products (FAPs) e-commerce has been developing rapidly. According to a recent report of China Electronic Commerce Research Center, the total volume of the FAPs e-commerce in China is about CNY 140.28 billion in 2017, and it is expected to reach a higher level in 2018 [1]. But at present, the corresponding market penetration rate is still lower, not more than 5%. Behind it is a huge market, with great potential for development.

In the rapidly evolving FAPs e-commerce environment, consumers have put forward higher requirements for the quality of FAPs. The produce quality is considered to be a direct factor influencing consumers' purchasing decisions [2]. In this case, it is extremely important to produce fresh, safe, green and organic FAPs in the source of the FAPs' supply chain. Due to the special perishable characteristics of FAPs [3-6], it is also particularly necessary to control it properly during the supply chain process. Appropriate production and operation management in the whole FAPs supply chain is of great significance not only to the development of supply chain enterprises, but also to the healthy consumption by people.

However, in actual supply chain production, there are a series of consumption security incidents such as the hand-dyed oranges, the poisonous strawberries, the vegetables with carcinogenic pesticides, which have greatly affected the consumers' consumption safety and confidence. The past few years have witnessed several fresh produce safety events reports, such as microbiological hazards [7], pesticide residues

[8] and heavy metals [9]. This also indicates from the side that in the source of current FAPs' supply chain, the concept of green and safe production is insufficient. Besides, in actual supply chain operation, the lower FAPs preservation level and lower distribution efficiency reduce the quality of FAPs and undermine the benefits of supply chain to a certain extent. The loss rate of perishable products is as high as 15/100 in developed countries and as high as 30/100 in developing countries, which have brought great losses to the supply chain, society and even the countries [10-13]. All of these reflect the reality from the side that there are many problems in the production and operation of the real FAPs' supply chain.

Therefore, it requires the close collaboration of supply chain members to increase FAPs quality and safety, and reduce FAPs loss. In FAPs' supply chain, the safety traceability system availability investment of the producer can help improve his safety traceability system availability, which not only makes it convenient and timely for consumers to understand the information of all stages of agricultural products in the whole process of the supply chain, but also enables supply chain operators to quickly find relevant links in food safety incidents so as to reduce risks brought by the quality of agricultural products, and improve FAPs' quality and safety. [14]. Increasing investment in safety traceability systems can also provide companies with competitive advantages by improving the visibility of the processes performed and the corresponding control over product quality [15]. And the freshness-keeping effort of third-party logistics service provider (TPLSP) in the process of logistics distribution can help keep FAPs' high freshness level. All these measures of the producer and the TPLSP can indirectly affect the market scale and benefits of fresh produce e-commerce enterprise by affecting the satisfaction and the second-time online shopping intention of the consumers. However, this will impose a considerable cost on the producer and the TPLSP respectively. Determining the best trade-off between the revenues and costs so as to improve the supply chain performance, maximize total profit and provide higher quality FAPs to the target market is therefore a key issue faced by the three supply chain members. This is not only related to the interests of the FAPs' supply chain channel participants, but also related to the consumption safety and consumption quality of the market consumers.

The purpose of this paper is to study the decision and coordination issue of FAPs' three-layer e-commerce supply chain considering producer's safety traceability system availability and TPLSP's freshness-keeping in a new framework. We are going to address the following research questions:

(1) Should the three supply chain members, i.e., producer, TPLSP and fresh produce e-commerce enterprise, independently make decisions on safety traceability system availability investment, freshness-keeping effort and unit online selling price in the production, operation and sale of the FAPs?

(2) If no, how do they coordinate their decision-making under the different scenarios so as to achieve higher supply chain performance and efficiency?

(3) Can safety traceability system availability and freshness level of FAPs be improved?

(4) What is the impact of the market changes, such as the changes in consumers' preferences for safety traceability system availability, freshness, and online selling price, on the supply chain decisions and profits?

(5) How do the changes of market preferences affect the implementation of contract policies?

In order to answer these questions, we will develop and establish mathematical models for centralized, decentralized and contractual FAPs' supply chain, respectively. We will explore and characterize optimal decisions of the three supply chain parties in different FAPs' supply chain structures, and analyze the impact of consumers' sensitivities to safety traceability system availability, freshness level and other factors on the supply chain decisions and profits. We will design and investigate different types of contract coordination mechanisms to coordinate this particular supply chain for different situations. And we will investigate the impact of consumers' sensitivities to safety traceability system availability, FAPs freshness, and online selling price on the implementation of proposed contracts. These will not only help achieve the optimal decisions and profits of the supply chain and improve the supply chain performance, but also help provide the fresh and safe FAPs to target market under e-commerce environment.

The remainder of the paper is organized as follows. Section 2 reviews the related literature. In Section 3, the decision models under different scenarios are presented, and the optimal decisions of the three FAPs' supply chain members are characterized. In Section 4, we design two different types of contracts to coordinate the supply chain. And numerical analysis is conducted in Section 5. Section 6 summarizes our research, where the direction of future study is provided.

II. LITERATURE REVIEW

Channel coordination is an important and leading issue in supply chain management [16], which is imperative for improving the supply chain performance [17]. How to make the individual goal and system goal of each node in the supply chain tend to be consistent is the problem to be solved in the channel coordination. There is one stream of the relevant studies that have been well reported in the literature [19-26]. In these studies, the supply chain contracts such as wholesale contract [27], quantity discount contract [28], revenue sharing contract [29], buy back contract [30], sales rebate [31], quantity flexibility contract [32], and two-part pricing contract [33], option contract [34] are often taken as incentives by scholars to facilitate the coordination of supply chain. By eliminating certain channel conflicts, the corresponding supply chain performance has been better improved. However, these studies have only focused on the supply chain coordination of non-perishable products and haven't considered the characteristics and particularity of FAPs.

With the development of the FAPs' supply chain and its increasingly important role in the lives of residents, some scholars have begun to pay attention to the coordination of the FAPs' supply chain. However, compared with the literature about supply chain coordination of non-perishable products, the studies about coordination of FAPs' supply chain is still fewer. And the majority of existing studies have dealt with only a two-layer supply chain consisting of a supplier and a retailer, or a producer and a distributor. Cai *et al.* [10] considered a supply chain consisting of a producer and a distributor and found the price-discount sharing and compensation schemes can achieve the optimization of the whole system. Xiao and Chen [4] presented a fixed inventory-plus factor strategy and demonstrated it is a Pareto improvement in a fresh products supply chain consisting of a producer and a distributor. Sun [35] developed a dynamic FAPs' supply chain model with supply disruptions and discovered that a lump-sum fee can motivate supplier and the retailer to accept two-part tariff contract. Wang and Chen [36] proposed the wholesale price and call option portfolio contracts to coordinate a one-supplier-one-retailer fresh produce supply chain, and showed that there was no correlation between the optimal option pricing policy of supplier and the demand risk and wholesale price. Zheng *et al.* [12] explored a two-layer FAPs' supply chain consisting of a supplier and a retailer, and designed a combination contract to achieve a win-win outcome. Yang *et al.* [37] focused on a two-layer FAP chain and proved the buy-back contract and the quantity discount contract are equivalent to the revenue sharing contract under certain conditions.

The above literature mainly studied the coordination of the upstream and downstream channel members; however, the FAPs' supply chain coordination with TPLSP' participation in decision is rarely considered. Since all decisions of TPLSP will have certain influence on the decisions of other channel members, it will be interesting to consider the participation of TPLSP in decision-making. At present, although some literature has considered the participation of TPLSP, these studies are mainly based on the principal-agent theory to study how to improve enterprise benefits or reduce enterprise cost [38-39]. In addition, the literature does not take into account the supply chain of FAPs and lack of research on contractual mechanism. And for the studies of FAPs' supply chain coordination with TPLSP' participation in decision, the existing studies only focused on a two-layer supply chain. Wu *et al.* [40] studied a FAPs' supply chain consisting of a distributor and a TPLSP, and the results indicate that the power structures have an important influence on channel performance and contract designs.

When reviewing the literature on the coordination of multi-layer FAPs' supply chain, we find that research on coordination of FAPs' supply chain among multiple members is relatively scarce, partly due to the difficulties related to the possible contracts. To the best of our knowledge, there are only a few scholars who have taken into consideration the coordination contracts among more than two FAPs' supply chain participants. Cai *et al.* [41] presented a supply chain consisting of a producer, a third-party logistics provider and a distributor and found that the wholesale-market clearance and wholesale-price-discount sharing contract can play down the risks involved in the process of transportation and selling. Feng *et al.* [42] considered a three-layer supply chain and developed a supplier-led game model. Then a compound contract was designed to realize the coordination of the supply chain. However, their studies only considered one contract coordination mechanism and did not consider the e-commerce online shopping environment. And they did not take into account the safety traceability system availability, freshness and online selling price sensitive demand while the logistics transportation price in their research is an exogenous variable, not an endogenous variable. Our model will deal with the scenario where all prices are endogenous variables and we will study the effect of different types of contracts for coordinating the presented FAPs e-commerce supply chain under safety traceability system availability, freshness and online selling price sensitive demand.

In addition to being influenced by the retail price, the market demand for FAPs is also affected by other factors, such as freshness [41], price promotion [43], sales effort [44], safety traceability system availability, or other factors; however, fewer scholars have explored the impact of multiple factors on market demand. By combing the literature, we found that the literature on FAPs' supply chain coordination considering producer's safety traceability system availability, TPLSP' freshness-keeping and fresh produce e-commerce enterprise's online selling price is also very sparse. And the existing literature has mainly studied the impact of retail price and freshness on market demand. Wang and Dan [45] examined the coordination of FAPs' supply chain considering retailer's preservation, and demonstrated that preservation cost and revenue sharing contract can achieve supply chain coordination and enhance the overall utility of consumers. Wang and Dan [46] investigated the FAP supply chain coordination with supplier's preservation, and found that when the retailer was in a strong position, the purchase price based on product freshness contract could make the supply chain more profitable. These studies only focused on the two-level supply chain composed of a supplier and a retailer, and didn't consider the producer's safety traceability system availability, TPLSP's freshness-keeping, and fresh produce e-commerce enterprise's online selling price simultaneously. How do these multiple factors affect the decisions and profits of the three channel members? How to design the contract coordination mechanism in this case? Few scholars have studied it. This is also one of the aspects that we are going to study.

Literature presented above has given us a certain degree of inspiration from different perspectives. From the above literature review, it can be found that coordination of FAPs' supply chain is a relative less studied area. No one has explored the coordination of the complex FAPs' three-layer e-commerce supply chain presented in this paper by taking into account all these scenarios simultaneously, such as the FAPs characteristics, the multi-layer supply chain, the endogenous prices, the TPLSP's participation and the e-commerce environment, especially considering the market demand for FAPs is affected by the safety traceability system availability, the freshness and the unit online selling price concurrently. In addition, although some scholars have used the contract as a tool to explore the supply chain coordination of FAPs, as far as our understanding, the literature of concurrently examining different types of coordination contracts is still a few. To be precise, the existing literature has not yet simultaneously examined the cost-sharing and revenue-sharing contract (CS&RS) and consolidated rebate and revenue-sharing contract (CR&RS) in the study of the FAPs' supply chain coordination issue. These, to a certain extent, also motives our research in considering the coordination of such a FAPs' supply chain.

In view of the realistic background and theoretical background, we carry out the research presented in this paper. We integrate all the above cases into a new supply chain framework and make the first attempt to study the channel coordination of the complex FAPs' three-layer e-commerce supply chain. That are, we will take into consideration that the demand for FAPs is affected by the safety traceability system availability, the freshness and the unit online selling price simultaneously for the first time. And we will take into account TPLSP's participation in decisions and fresh produce e-commerce enterprise's home delivery mode, and consider that all prices and other decision variables of the supply chain are endogenous, simultaneously. Then on the basis of these, we will describe and characterize the decisions of the different supply chain scenario, and develop different types of channel coordination strategies so as to improve the supply chain performance for the first such endeavor. Our study can help fill the research gap and complement the existing literature by coordinating such a supply chain. It will help provide a better understanding of the optimal decisions of such a particular FAPs' supply chain in different scenarios and the coordination effects of different types of contract mechanisms in improving the supply chain performance. Therefore, this will be an interesting topic no matter in the realistic background or the theoretical background.

III. DECISION MODELS

A. NOTATIONS AND ASSUMPTIONS

Table 1 shows the notations used to develop our models.

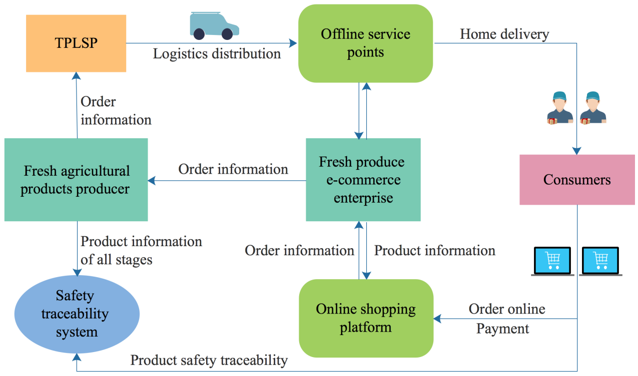

FIGURE 1. FAPs' supply chain under consideration.

TABLE 1. Notations.

Symbol	Description
c_M	unit production cost of producer
c_T	unit logistics distribution cost of TPLSP
c_R	unit operating cost of fresh produce e-commerce enterprise
c_F	unit home delivery cost of fresh produce e-commerce enterprise
Q	online ordering quantity of consumers
θ_0	sensitivity coefficient affecting freshness level
a	market potential
b	price-elasticity of demand function
ε	random variable affecting market demand
k	sensitivity coefficient affecting safety traceability system availability
λ	freshness-keeping cost coefficient
ξ	consumers' sensitivity to safety traceability system availability
δ	consumers' sensitivity to FAPs freshness
$g(e_M)$	safety traceability system availability function
$\theta(e_T)$	freshness function
$C(e_T)$	freshness-keeping cost function
$\prod^c$	total expected profit in centralized system
$\prod^{dc}$	total expected profit in decentralized system
$\prod_R^{dc}$	expected profit of fresh produce e-commerce enterprise in decentralized system
$\prod_T^{dc}$	expected profit of TPLSP in decentralized system
$\prod_M^{dc}$	expected profit of producer in decentralized system
Decision Variable	**Description**
P_M	unit wholesale price of producer
e_M	safety traceability system availability investment of producer
P_T	unit logistics distribution price of TPLSP
e_T	freshness-keeping effort of TPLSP
P_R	unit online selling price of fresh produce e-commerce enterprise

We consider a three-layer e-commerce FAPs' supply chain that consists of a producer, a TPLSP and a fresh produce e-commerce enterprise. The supply chain is shown in Figure 1. The fresh produce e-commerce enterprise releases FAPs information and displays goods on the online shopping platform. The consumers browse online FAPs information, choose to purchase FAPs and pay for them. Order information and payment information is delivered to the fresh produce e-commerce enterprise. And the order information is transmitted by the fresh produce e-commerce enterprise to producer. Then, the producer deals with the orders, and distributes the FAPs to the offline service points of the fresh produce e-commerce enterprise through the TPLSP. Finally, the offline service points deliver the FAPs to the consumers' homes. Note that the unit wholesale price of producer is P_M and the unit production cost is c_M. A continuous variable e_M is introduced to measure producer's safety traceability system availability investment. We denote the unit logistics distribution price and unit logistics distribution cost of the TPLSP as P_T and c_T, respectively. And a continuous variable e_T is introduced to measure the cold-chain logistics service level of the TPLSP, which is called the freshness-keeping effort [10]. P_R is the unit online selling price of the fresh produce e-commerce enterprise, c_R is the unit operating cost, and c_F is the unit home delivery cost of the FAPs.

Assume that the demand of the FAPs is online retail price, freshness and safety traceability system availability sensitive. With reference to the additive type demand function, which is widely used in different studies [47-52], we assume that it is of the form $Q = a - bP_R + \xi g(e_M) + \delta\theta(e_T) + \varepsilon$. Where a is the market potential, b represents the price-elasticity of demand function, ξ measures the influence of producer's safety traceability system availability on demand, and δ denotes the consumers' sensitivity to FAPs' freshness. For non-negativity of the FAPs market demand function, we assume that $p_R \in (0, a/b)$. Safety traceability system availability is affected by the safety traceability system availability investment. On the basis of [53], we assume that the function is $g(e_M) = k\sqrt{e_M}$, where k is the sensitivity coefficient affecting safety traceability system availability. Freshness-keeping effort has a certain effect on the freshness of FAPs. Referring to the contract theory, there is a linear relationship between effort level and dependent variable, and the multiplicative function form has been made in some studies [9], [45], so we assume that it is of the form $\theta(e_T) = e_T\theta_0$, where θ_0 is the sensitivity coefficient affecting the freshness level. ε is a random variable that reflects the fluctuations of the market demand, $\varepsilon \sim N(0, \sigma^2)$. The functional relationship between freshness-keeping cost and freshness-keeping effort is $C(e_T) = \lambda {e_T}^2/2$, where λ is the freshness-keeping cost coefficient (which is considered in some literature, e.g., [54-56]. This assumption indicates that the freshness-keeping cost is a concave function with increasing marginal cost.

Assume that the producer, the TPLSP and the fresh produce e-commerce enterprise are risk-neutral and rational. They purse its own maximum profit. In any cycle, the shortages are not allowed. In the process of games, information is common knowledge.

Without loss of generality, we assume that the parameters satisfy the relations $P_R > c_R + c_F + P_M + P_T$. It means that there is a positive profit margin for the fresh produce e-commerce enterprise. To ensure that the decision variables are all positive, the parameters meet the following conditions $a - b(c_M + c_T + c_R + c_F) > 0$.

B. CENTRALIZED DECISION

In centralized supply chain scenario, the producer, the TPLSP and the fresh produce e-commerce enterprise are treated as an entity. A single decision maker makes the optimal decisions to maximize the total profit of the whole system. Centralized decision making does not take into account the transfer payments among the three supply chain members. The total expected profit of the FAPs' supply chain is

$$\prod^c = (P_R - c_M - c_T - c_R - c_F)(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) - e_M - \frac{\lambda {e_T}^2}{2} \quad (1)$$

Theorem 1. *For any given parameters, the optimal unit online selling price, optimal safety traceability system availability investment, and optimal freshness-keeping effort are*

$$P_R^{c*} = \frac{2a\lambda + [2b\lambda - (\xi^2k^2\lambda + 2\delta^2\theta_0^2)](c_M + c_T + c_R + c_F)}{4b\lambda - (\xi^2k^2\lambda + 2\delta^2\theta_0^2)} \quad (2)$$

$$e_M^{c*} = \frac{\xi^2k^2\lambda^2[a - b(c_M + c_T + c_R + c_F)]^2}{[4b\lambda - (\xi^2k^2\lambda + 2\delta^2\theta_0^2)]^2} \quad (3)$$

$$e_T^{c*} = \frac{2\delta\theta_0[a - b(c_M + c_T + c_R + c_F)]}{4b\lambda - (\xi^2k^2\lambda + 2\delta^2\theta_0^2)} \quad (4)$$

Proof of Theorem 1 is provided in Appendix A. Theorem 1 means that in centralized FAPs' supply chain, there are unique optimal unit online selling price, optimal safety traceability system availability investment and optimal freshness-keeping effort.

According to theorem 1, we substitute P_R^{c*}, e_M^{c*} and e_T^{c*} into Q and Eq. (1), then the optimal online ordering quantity and total expected profit in the centralized system can be obtained as follows:

$$Q^{c*} = \frac{2b\lambda[a - b(c_M + c_T + c_R + c_F)]}{4b\lambda - (\xi^2k^2\lambda + 2\delta^2\theta_0^2)} \quad (5)$$

$$\prod^{c*} = \frac{[4b\lambda^2 - (\xi^2k^2\lambda^2 + 2\lambda\delta^2\theta_0^2)][a - b(c_M + c_T + c_R + c_F)]^2}{[4b\lambda - (\xi^2k^2\lambda + 2\delta^2\theta_0^2)]^2} \quad (6)$$

C. DECENTRALIZED DECISION

A decentralized supply chain is considered in which producer, TPLSP and fresh produce e-commerce enterprise make their decisions independently. This section aims to determine the optimal unit wholesale price P_M and safety traceability system availability investment e_M of the producer, the optimal unit logistics distribution price P_T and freshness-keeping effort e_T of the TPLSP, and the optimal unit online selling price P_R of the fresh produce e-commerce enterprise so as to maximize expected individual profit.

The game order is as follows: First of all, the producer makes the first move and determines unit wholesale price P_M and safety traceability system availability investment e_M using the response function of the fresh produce e-commerce enterprise. Meanwhile, the TPLSP determines unit logistics distribution price P_T and freshness-keeping effort e_T. Then, the fresh produce e-commerce enterprise reacts to determine the unit online selling price P_R to maximize its own profit.

1) OPTIMAL DECISIONS OF THE FRESH PRODUCE E-COMMERCE ENTERPRISE

The expected profit function of fresh produce e-commerce enterprise is

$$\prod_R^{dc} = (P_R - P_M - P_T - c_R - c_F)(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) \quad (7)$$

Lemma 1. *For any given producer's unit wholesale price P_M, safety traceability system availability investment e_M, TPLSP's unit logistics distribution price P_T and freshness-keeping effort e_T, the optimal unit online selling price is*

$$P_R^{dc^*}(P_M, e_M, P_T, e_T) = \frac{a+\xi k\sqrt{e_M}+\delta e_T\theta_0+b(P_M+P_T+c_R+c_F)}{2b} \quad (8)$$

Proof of Lemma 1 is provided in Appendix B. Lemma 1 describes the optimal online selling price decision for the fresh produce e-commerce enterprise, which can be employed to maximize its own profit in decentralized supply chain without a contract.

2) OPTIMAL DECISIONS OF TPLSP

The expected profit function of TPLSP is

$$\prod_T^{dc} = (P_T - c_T)(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) - \frac{\lambda e_T{}^2}{2} \quad (9)$$

Substituting Eq. (8) into Eq. (9), we have

$$\prod_T^{dc} = \frac{(P_T-c_T)[a+\xi k\sqrt{e_M}+\delta e_T\theta_0-b(P_M+P_T+c_R+c_F)]}{2} - \frac{\lambda e_T{}^2}{2} \quad (10)$$

Lemma 2. *The optimal unit logistics distribution price and optimal freshness-keeping effort are*

$$P_T^{dc^*}(P_M, e_M, e_T) = \frac{a+\xi k\sqrt{e_M}+\delta e_T\theta_0-b(P_M+c_R+c_F-c_T)}{2b} \quad (11)$$

$$e_T^{dc^*}(P_T) = \frac{(P_T-c_T)\delta\theta_0}{2\lambda} \quad (12)$$

Proof of Lemma 2 is provided in Appendix C. Lemma 2 portrays the optimal decisions of the TPLSP.

3) OPTIMAL DECISIONS OF PRODUCER

The expected profit function of producer is

$$\prod_M^{dc} = (P_M - c_M)(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) - e_M \quad (13)$$

Substituting Eq. (8) into Eq. (13), we have

$$\prod_M^{dc} = \frac{(P_M-c_M)[a+\xi k\sqrt{e_M}+\delta e_T\theta_0-b(P_M+P_T+c_R+c_F)]}{2} - e_M \quad (14)$$

Lemma 3. *The optimal unit wholesale price and the safety traceability system availability investment are*

$$P_M^{dc^*}(P_T, e_T, e_M) = \frac{a+\xi k\sqrt{e_M}+\delta e_T\theta_0-b(P_T+c_R+c_F-c_M)}{2b} \quad (15)$$

$$e_M^{dc^*}(P_M) = \frac{(P_M-c_M)^2\xi^2k^2}{16} \quad (16)$$

Proof of Lemma 3 is provided in Appendix D. Lemma 3 presents the optimal decisions of the producer.

From Lemma 1, Lemma 2 and Lemma 3, we can find that the decisions of each decentralized supply chain member are directly or indirectly influenced by the decisions of other supply chain members. The optimal unit online selling price is positively influenced by the decisions of TPLSP' unit logistics distribution price and freshness-keeping effort and the decisions of producer' unit wholesale price and safety traceability system availability investment. TPLSP' unit logistics distribution price decision is not only positively influenced by its own freshness-keeping effort, but also positively influenced by producer' safety traceability system availability investment decision and negatively influenced by the unit wholesale price decision. The freshness-keeping effort decision the TPLSP is influenced by the unit logistics distribution price decision while the safety traceability system availability investment of the producer is influenced by the unit wholesale price. In addition to being positively influenced by its safety traceability system availability investment decision, unit wholesale price decision for producer is also subject to the positive impact of the freshness-keeping effort and the negative impact of unit logistics distribution price decision from TPLSP. Then what is the optimal equilibrium solution? By Lemma 1, Lemma 2 and Lemma 3, we have the following observations.

Theorem 2. *The equilibrium solution of optimal unit wholesale price, safety traceability system availability investment, unit logistics distribution price, freshness-keeping effort and unit online selling price are*

$$P_M^{dc^*} = \frac{4\lambda[a+b(2c_M-c_T-c_R-c_F)]-(\xi^2k^2\lambda+2\delta^2\theta_0^2)c_M}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)} \quad (17)$$

$$e_M^{dc^*} = \frac{\xi^2k^2\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} \quad (18)$$

$$P_T^{dc^*} = \frac{4\lambda[a+b(2c_T-c_M-c_R-c_F)]-(\xi^2k^2\lambda+2\delta^2\theta_0^2)c_T}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)} \quad (19)$$

$$e_T^{dc^*} = \frac{2\delta\theta_0[a-b(c_M+c_T+c_R+c_F)]}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)} \quad (20)$$

$$P_R^{dc^*} = \frac{10a\lambda+[2b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)](c_M+c_T+c_R+c_F)}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)} \quad (21)$$

Proof of Theorem 2 is provided in Appendix E. Theorem 2 shows the equilibrium solution in the decentralized FAPs' supply chain, which enable the three supply chain members to maximize their own profits.

According to the Theorem 2, we substitute Eq. (17)- (21) into Eq. (7), Eq. (9) and Eq. (13), the optimal expected profits of the fresh produce e-commerce enterprise, TPLSP and producer in the decentralized system are obtained:

$$\prod_M^{dc^*} = \frac{(8b-\xi^2k^2)\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} \quad (22)$$

$$\prod_T^{dc^*} = \frac{(8b\lambda^2-2\lambda\delta^2\theta_0^2)[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} \quad (23)$$

$$\prod_R^{dc^*} = \frac{4b\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} \quad (24)$$

And, the optimal online ordering quantity and total expected profit in the decentralized system are derived:

$$Q^{dc^*} = \frac{2b\lambda[a-b(c_M+c_T+c_R+c_F)]}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)} \quad (25)$$

$$\prod^{dc^*} = \frac{[20b\lambda^2-(\xi^2k^2\lambda^2+2\lambda\delta^2\theta_0^2)][a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} \quad (26)$$

4) COMPARISON OF CENTRALIZED AND DECENTRALIZED DECISIONS

Table 2 shows the optimal decisions and profits of centralized and decentralized FAPs' supply chain systems.

According to above theorems and Table 2, the following propositions are obtained.

Proposition 1.

(1) $\frac{\partial e_M^{c^*}}{\partial \xi} > 0$; $\frac{\partial e_T^{c^*}}{\partial \xi} > 0$; $\frac{\partial P_R^{c^*}}{\partial \xi} > 0$; $\frac{\partial Q^{c^*}}{\partial \xi} > 0$; $\frac{\partial \Pi^{c^*}}{\partial \xi} > 0$.

(2) $\frac{\partial e_M^{dc^*}}{\partial \xi} > 0$; $\frac{\partial e_T^{dc^*}}{\partial \xi} > 0$; $\frac{\partial P_R^{dc^*}}{\partial \xi} > 0$; $\frac{\partial Q^{dc^*}}{\partial \xi} > 0$; $\frac{\partial \Pi^{dc^*}}{\partial \xi} > 0$.

(3) $\frac{\partial e_M^{c^*}}{\partial \delta} > 0$; $\frac{\partial e_T^{c^*}}{\partial \delta} > 0$; $\frac{\partial P_R^{c^*}}{\partial \delta} > 0$; $\frac{\partial Q^{c^*}}{\partial \delta} > 0$; $\frac{\partial \Pi^{c^*}}{\partial \delta} > 0$.

(4) $\frac{\partial e_M^{dc^*}}{\partial \delta} > 0$; $\frac{\partial e_T^{dc^*}}{\partial \delta} > 0$; $\frac{\partial P_R^{dc^*}}{\partial \delta} > 0$; $\frac{\partial Q^{dc^*}}{\partial \delta} > 0$; $\frac{\partial \Pi^{dc^*}}{\partial \delta} > 0$.

(5) $\frac{\partial e_M^{c^*}}{\partial b} < 0$; $\frac{\partial e_T^{c^*}}{\partial b} < 0$; $\frac{\partial P_R^{c^*}}{\partial b} < 0$; $\frac{\partial Q^{c^*}}{\partial b} < 0$; $\frac{\partial \Pi^{c^*}}{\partial b} < 0$.

(6) $\frac{\partial e_M^{dc^*}}{\partial b} < 0$; $\frac{\partial e_T^{dc^*}}{\partial b} < 0$; $\frac{\partial P_R^{dc^*}}{\partial b} < 0$; $\frac{\partial Q^{dc^*}}{\partial b} < 0$; $\frac{\partial \Pi^{dc^*}}{\partial b} < 0$.

(7) $\frac{\partial e_M^{c^*}}{\partial \lambda} > 0$; $\frac{\partial e_T^{c^*}}{\partial \lambda} < 0$; $\frac{\partial P_R^{c^*}}{\partial \lambda} < 0$; $\frac{\partial Q^{c^*}}{\partial \lambda} < 0$; $\frac{\partial \Pi^{c^*}}{\partial \lambda} < 0$.

(8) $\frac{\partial e_M^{dc^*}}{\partial \lambda} > 0$; $\frac{\partial e_T^{dc^*}}{\partial \lambda} < 0$; $\frac{\partial P_R^{dc^*}}{\partial \lambda} < 0$; $\frac{\partial Q^{dc^*}}{\partial \lambda} < 0$; $\frac{\partial \Pi^{dc^*}}{\partial \lambda} < 0$.

Proof of Proposition 1 is provided in Appendix F.

TABLE 2. Optimal decisions and profits.

	Centralized system	Decentralized system
P_M	/	$\frac{4\lambda[a+b(2c_M-c_T-c_R-c_F)]-(\xi^2k^2\lambda+2\delta^2\theta_0^2)c_M}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$
e_M	$\frac{\xi^2k^2\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$	$\frac{\xi^2k^2\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$
P_T	/	$\frac{4\lambda[a+b(2c_T-c_M-c_R-c_F)]-(\xi^2k^2\lambda+2\delta^2\theta_0^2)c_T}{12b\lambda-(\xi^2\lambda+2\delta^2\theta_0^2)}$
e_T	$\frac{2\delta\theta_0[a-b(c_M+c_T+c_R+c_F)]}{4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$	$\frac{2\delta\theta_0[a-b(c_M+c_T+c_R+c_F)]}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$
P_R	$\frac{2a\lambda+[2b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)](c_M+c_T+c_R+c_F)}{4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$	$\frac{10a\lambda+[2b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)](c_M+c_T+c_R+c_F)}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$
Q	$\frac{2b\lambda[a-b(c_M+c_T+c_R+c_F)]}{4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$	$\frac{2b\lambda[a-b(c_M+c_T+c_R+c_F)]}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$
Π_M	/	$\frac{(8b-\xi^2k^2)\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$
Π_T	/	$\frac{(8b\lambda^2-2\lambda\delta^2\theta_0^2)[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$
Π_R	/	$\frac{4b\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2\lambda+2\delta^2\theta_0^2)]^2}$
Π	$\frac{[4b\lambda^2-(\xi^2k^2\lambda^2+2\lambda\delta^2\theta_0^2)][a-b(c_M+c_T+c_R+c_F)]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$	$\frac{[20b\lambda^2-(\xi^2k^2\lambda^2+2\lambda\delta^2\theta_0^2)][a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$

Proposition 1 shows that the optimal decisions and total expected profit in the centralized as well as decentralized system increase as ξ and δ increase, respectively. Whereas they decrease as b increases, respectively. And, e_M increases as λ increases, the rest of them decrease as λ increases, respectively. This indicates that e_M, e_T, P_R, Q and $\prod$ in the centralized as well as decentralized system are positively related to ξ and δ. e_M, e_T, P_R, Q and $\prod$ in the centralized as well as decentralized system are negatively related to b. e_T, P_R, Q and $\prod$ in the centralized as well as decentralized system are negatively related to λ. Whereas e_M in the centralized as well as decentralized system is positively related to λ.

It reveals that when there is higher consumers' sensitivity to safety traceability system availability and FAPs' freshness, it will promote the centralized and decentralized supply chain systems to increase safety traceability system availability investment and raise the freshness-keeping effort. At this point, the online selling price will be improved accordingly. Although the increased online selling price has a negative growth effect on FAPs' market demand, the increase in safety traceability system availability investment and freshness-keeping effort can improve the FAPs freshness and safety traceability system availability and further bring more market demand, resulting in an increase in entire system profits. When the market is more sensitive to the online selling price, the channels will lower the online selling price to increase online ordering quantities. At the moment, because the market sensitivity to safety traceability system availability and FAPs freshness does not change, the system will further increase profits by reducing safety traceability system availability investment and freshness-keeping effort. However, as the reduction of safety traceability system availability investment and freshness-keeping effort have reduced the market demand, the final system profits have been relatively reduced. When freshness-keeping costs are more sensitive to the freshness-keeping effort, the centralized and decentralized channels will reduce the freshness-keeping effort due to the increased cost. Meanwhile, the channels will increase the safety traceability system availability investment and reduce the online selling price so as to enhance the corresponding profit. However, the lower freshness-keeping effort will lead to a lower product freshness and further lead to a decrease in FAPs' market demand. And the decrease of market demand caused by the decline of freshness-keeping effort is much larger than the increase of market demand caused by the increase of safety traceability system availability investment and the increase of the online selling price. Then there will be a corresponding decline in total supply chain expected profits.

Proposition 2. (1) $e_M^{dc^*} < e_M^{c^*}$; $e_T^{dc^*} < e_T^{c^*}$.
(2) When $\xi^2k^2\lambda + 2\delta^2\theta_0^2 < 2b\lambda$, $P_R^{dc^*} > P_R^{c^*}$; When $2b\lambda < \xi^2k^2\lambda + 2\delta^2\theta_0^2 < 4b\lambda$, $P_R^{dc^*} < P_R^{c^*}$.
(3) $Q^{dc^*} < Q^{c^*}$; $\prod^{dc^*} < \prod^{c^*}$.

Proof of Proposition 2 is provided in Appendix G.

Proposition 2 indicates that the optimal safety traceability system availability investment, freshness-keeping effort, online ordering quantity and total expected profit in the decentralized system are less than that in the centralized system. When $\xi^2k^2\lambda + 2\delta^2\theta_0^2 < 2b\lambda$, the optimal unit online selling price in the decentralized system is higher than that in the centralized system. When $2b\lambda < \xi^2k^2\lambda + 2\delta^2\theta_0^2 < 4b\lambda$, the optimal unit online selling price in the decentralized system is less than that in the centralized system. Due to the less safety traceability system availability investment and the lower freshness-keeping effort in decentralized supply chain, the FAPs freshness and the safety traceability system availability are all affected and the market demand is relatively reduced. Although the fresh produce e-commerce enterprise makes optimal pricing decisions for different situations, it still leads to the overall profit of decentralized supply chain less than that of centralized supply chain.

It reveals that the optimal decisions in the centralized system are superior to the optimal decisions in the decentralized system. And, compared with the decentralized decision, the centralized decision is more profitable. The double marginal effect results in the loss of the performance of the decentralized supply chain. Therefore, it is necessary to design the corresponding contracts to coordinate the decentralized FAPs' supply chain to improve its performance and efficiency. In the next section, the total expected profit of the centralized FAPs' supply chain will be regarded as a benchmark. And different types of coordination policies will be designed to facilitate the coordination of the decentralized supply chain so as to achieve the benchmark while also improve the safety traceability system availability and freshness level of FAPs, and achieve the individual maximized profit.

IV. CONTRACT COORDINATION MODELS

According to the above proposition, when the supply chain channel increases the safety traceability system availability investment and promotes the freshness-keeping effort, the profit of the members of the supply chain will be damaged because of the rising cost. In addition, given that revenue sharing contract plays an important role in supply chain incentives [25], we consider to design the revenue sharing contract for the incentive compensation, and consider to share the safety traceability system availability investment and freshness-keeping cost to stimulate the motivation of supply chain channel members. When the members of the supply chain strictly abide by the decentralized quoted price, rebate contract can optimize the profit of two-layer supply chain to a certain extent [17], so we first try to achieve the goal of three-level supply chain channel coordination by combining the revenue sharing.

In this section, two different types of contracts namely cost-sharing and revenue-sharing contract(*CS&RS*); consolidated rebate and revenue-sharing contract(*CR&RS*) are proposed and designed for the FAPs' supply chain coordination. In the following sub-sections, we develop two contract coordination models. Firstly, the *CS&RS* contract is designed when the producer and the TPLSP may not have enough motivation to increase safety traceability system availability investment and improve freshness-keeping effort, respectively. Secondly, the *CR&RS* contract is developed under the scenario that the producer, TPLSP and fresh produce e-commerce enterprise strictly keep their quoted prices in line with the prices of the decentralized system. In the last sub-section, implementation of the contracts is further discussed.

A. COST-SHARING AND REVENUE-SHARING CONTRACT

Idea of the proposed contract: The producer and the TPLSP provide the higher safety traceability system availability investment and freshness-keeping effort can increase the FAPs market demand and further increase the profit of the fresh produce e-commerce enterprise. However, this will reduce the profits of the producer and the TPLSP relatively. If the fresh produce e-commerce enterprise is willing to compensate their loss by providing a fraction of its own revenues and sharing a certain proportion of their costs and enable them to obtain more profits, then it will encourage them to do that. On the other hand, if the produce e-commerce enterprise provides the optimal unit online selling price of the centralized, its own profits will be relatively reduced. If the producer and the TPLSP is willing to reduce their unit wholesale price and unit logistics distribution price as compensation for the produce e-commerce enterprise, then it will motivate the fresh produce e-commerce enterprise to do it.

Game sequence: First, the producer, TPLSP and fresh produce e-commerce enterprise jointly determine the *CS&RS* contract. The producer and TPLSP quote the unit wholesale price P_M and unit logistics distribution price P_T. The fresh produce e-commerce enterprise determines the freshness-keeping cost share coefficients η_1, η_2 and the revenue share contract coefficients ω_1, ω_2. Then producer determines the safety traceability system availability investment e_M, and the TPLSP determines the freshness-keeping effort e_T. Finally, on the basis of the safety traceability system availability investment e_M and freshness-keeping effort e_T, the fresh produce e-commerce enterprise determines the unit online selling price P_R.

From what we have described above, it can be obtained the expected profit functions of the three supply chain members as follows:

$$\prod_M^{cc} = (P_M - c_M)(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) - \eta_1 e_M + \omega_1 P_R(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) \quad (27)$$

$$\prod_T^{cc} = (P_T - c_T)(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) - \frac{\eta_2 \lambda {e_T}^2}{2} + \omega_2 P_R(a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) \quad (28)$$

$$\prod_R^{cc} = [(1 - \omega_1 - \omega_2)P_R - P_M - P_T - c_R - c_F](a - bP_R + \xi k\sqrt{e_M} + \delta e_T\theta_0) - (1 - \eta_1)e_M - \frac{(1-\eta_2)\lambda {e_T}^2}{2} \quad (29)$$

Theorem 3. *Under the CS&RS contract, for any given unit wholesale price P_M, safety traceability system availability investment e_M, unit logistics distribution price P_T, freshness-keeping effort e_T, cost share ratios η_1 and η_2 and revenue share coefficients ω_1 and ω_2, the optimal unit online selling price is*

$$P_R^{cc^*} = \frac{(1-\omega_1-\omega_2)[a+\xi k\sqrt{e_M}+\delta e_T\theta_0]+b(P_M+P_T+c_R+c_F)}{2b(1-\omega_1-\omega_2)} \quad (30)$$

Proof of Theorem 3 is provided in Appendix H. Theorem 3 describes the optimal online selling price decision for the fresh produce e-commerce enterprise to maximize its own profit under the contract. According to the Theorem 3, we derive the following Theorems.

Theorem 4. *The optimal freshness-keeping effort is*

$$e_T^{cc^*} = \frac{(P_T-c_T)b\delta\theta_0+\omega_2\delta\theta_0(a+\xi k\sqrt{e_M})}{2b\eta_2\lambda-\omega_2\delta^2\theta_0^2} \quad (31)$$

Proof of Theorem 4 is provided in Appendix I.

Theorem 5. *The optimal safety traceability system availability investment is*

$$e_M^{cc^*} = \frac{(P_M-c_M)b\xi k+\omega_1\xi k(a+\delta e_T\theta_0)}{4b\eta_1-\omega_1\xi^2k^2} \quad (32)$$

Proof of Theorem 5 is provided in Appendix J.

Theorems 4 and 5 respectively present the optimal safety traceability system availability investment and freshness-keeping effort for the producer and TPLSP to maximize their own profits under this contract. Iterative solving the Eq. (31) and Eq. (32), we derive the specific expressions of $\mathrm{e}_{\mathrm{M}}^{\mathrm{cc}^*}$ and $e_T^{cc^*}$ as follows:

$$e_T^{cc^*} = \frac{[b(P_T-c_T)+\omega_2 a]\delta\theta_0(4b\eta_1-\omega_1\xi^2k^2)+\omega_2\delta\theta_0\xi^2k^2[b(P_M-c_M)+\omega_1 a]}{8b^2\eta_1\eta_2-2b\eta_2\omega_1\xi^2k^2\lambda-4b\eta_1\omega_2\delta^2\theta_0^2} \quad (33)$$

$$e_M^{cc^*} = \left\{\frac{[b(P_M-c_M)+\omega_1 a]\xi k\left(2b\eta_2\lambda-\omega_2\delta^2\theta_0^2\right)+\omega_1\xi k\delta^2\theta_0^2[b(P_T-c_T)+\omega_2 a]}{8b^2\eta_1\eta_2-2b\eta_2\omega_1\xi^2k^2\lambda-4b\eta_1\omega_2\delta^2\theta_0^2}\right\}^2 \quad (34)$$

On the basis of the Theorem 1, Theorem 3-5 and the above expression, the following Propositions can be derived.

Proposition 3. *If the contract parameters are satisfied by* $(1 - \omega_1 - \omega_2)(c_M + c_T + c_R + c_F) = P_M + P_T + c_R + c_F$, $\eta_1 = \omega_1$, $\eta_2 = \omega_2$, $\eta_1\eta_2 = 1/2b$, $(P_T - c_T)(4b\eta_1 - \omega_1\xi^2k^2) + \omega_2\xi^2k^2(P_M - c_M) = -2(c_M + c_T + c_R + c_F)$, *and* $(P_M - c_M)(2b\eta_2\lambda - \omega_2\delta^2\theta_0^2) + \omega_1\delta^2\theta_0^2(P_T - c_T) = -\lambda(c_M + c_T + c_R + c_F)$, *then* $\prod_M^{cc^*} + \prod_T^{cc^*} + \prod_R^{cc^*} = \prod^{c^*}$ *can be achieved.*

Proof of Proposition 3 is provided in Appendix K.

Proposition 3 indicates that the decentralized supply chain can achieve the profit level of the centralized supply chain when the contract coefficients satisfy certain conditions. In this case, the overall performance of the FAPs' supply chain system is improved.

Proposition 4. *If the contract parameters are satisfied by proposition 3,* $\omega_1 \geq \frac{(8b-\xi^2k^2)[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}{(4b-\xi^2k^2)[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$, $\omega_2 \geq \frac{(8b\lambda-2\delta^2\theta_0^2)[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}{(4b\lambda-2\delta^2\theta_0^2)[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$, *and* $(4b\lambda - \xi^2k^2\lambda)\omega_1 + (4b\lambda - 2\delta^2\theta_0^2)\omega_2 \leq \frac{(4b\lambda-2\delta^2\theta_0^2-\xi^2k^2\lambda)[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2-4b\lambda[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$*, the decentralized FAPs' supply chain can be coordinated and Pareto improvement can be achieved.*

Proof of Proposition 4 is provided in Appendix L.

Proposition 4 indicates that the *CR&RS* contract can perfectly coordinate this FAPs' supply chain and achieve the Pareto improvement of the three supply chain members. This means that the profits of each supply chain member are improved compared with the decentralized FAPs' supply chain without a contract. A win-win situation emerged for all supply chain members. In addition, from Proposition 3 and Proposition 4, one can see that $-c_R - c_F \leq P_M + P_T \leq c_M + c_T$, due to $0 \leq (1 - \omega_1 - \omega_2) \leq 1$. This means the CR&RS contract can not only motivate the producer and TPLSP to increase safety traceability system availability investment and improve the freshness-keeping effort, but also motivate them to reduce their quotations. As their quotations gradually decrease, they can receive more compensation revenues from the fresh produce e-commerce enterprise. From this contract, we can also find that $\eta_1 = \omega_1$, $\eta_2 = \omega_2$. That means if the producer and TPLSP takes on more safety traceability system availability investment and freshness-keeping effort costs, they will get extra compensation. If they can get extra profits, they will be willing to accept it. This is enough to see the important incentive role of the proposed contract.

B. CONSOLIDATED REBATE AND REVENUE-SHARING CONTRACT

Idea of the proposed contract: The producer offers the rebate $\emptyset_1$ and safety traceability system availability investment e_M and the TPLSP offers the rebate $\emptyset_2$ and freshness-keeping effort e_T. This will bring more FAPs online ordering quantities and make the fresh produce e-commerce enterprise more profitable but reduce the profits of the producer and the TPLSP. If the fresh produce e-commerce enterprise provides extra compensation for them by sharing a portion of his revenues and entices them to obtain extra profits than before, then it will be acceptable for the producer and the TPLSP.

Game sequence: First, the producer announces the unit wholesale price P_M and safety traceability system availability investment e_M, and the TPLSP announces the unit logistics distribution price P_T and freshness-keeping effort e_T. Then, based on the unit wholesale price P_M, safety traceability system availability investment e_M, unit logistics distribution price P_T and freshness-keeping effort e_T, the fresh produce e-commerce enterprise announces the unit online selling price P_R. Third, the three supply chain members jointly determine the *CR&RS* contract. The producer determines the rebate $\emptyset_1$ and safety traceability system availability investment e_M, and the TPLSP determines the rebate $\emptyset_2$ and freshness-keeping effort e_T. On the basis of the rebate $\emptyset_1$, safety traceability system availability investment e_M, rebate $\emptyset_2$ and freshness-keeping effort e_T, the fresh produce e-commerce enterprise determines the revenue share coefficients ω_1 and ω_2.

According to the above description, we get the expected profit functions of the producer, TPLSP and fresh produce e-commerce enterprise as follows:

$$\prod_M^{rc} = (P_M - c_M - \emptyset_1)[a - b(P_R - \emptyset_1 - \emptyset_2) + \xi k\sqrt{e_M} + \delta e_T\theta_0] - e_M + \omega_1 P_R[a - b(P_R - \emptyset_1 - \emptyset_2) + \xi k\sqrt{e_M} + \delta e_T\theta_0] \quad (35)$$

$$\prod_T^{rc} = (P_T - c_T - \emptyset_2)[a - b(P_R - \emptyset_1 - \emptyset_2) + \xi k\sqrt{e_M} + \delta e_T\theta_0] - \frac{\lambda e_T{}^2}{2} + \omega_2 P_R[a - b(P_R - \emptyset_1 - \emptyset_2) + \xi k\sqrt{e_M} + \delta e_T\theta_0] \quad (36)$$

$$\prod_R^{rc} = [(1 - \omega_1 - \omega_2)P_R - P_M - P_T - c_R - c_F][a - b(P_R - \emptyset_1 - \emptyset_2) + \xi k\sqrt{e_M} + \delta e_T\theta_0] \quad (37)$$

Based on the above, we can derive the following Proposition.

Proposition 5. *The FAPs' supply chain can be coordinated and Pareto improvement of profits of the three channel members can be achieved with contract parameters satisfying* $\emptyset_1 + \emptyset_2 = \frac{16ab\lambda^2 - 8b\lambda(2b\lambda-\tau)\upsilon - 8a\lambda\tau}{(12b\lambda-\tau)(4b\lambda-\tau)}$, $\omega_1 \geq \frac{12b\lambda-\tau}{10a\lambda+(2b\lambda-\tau)\upsilon}\left\{\frac{[-64b^2\lambda^2-\xi^2k^2\lambda^2(2b\lambda-\tau)](a-b\upsilon)}{2b(12b\lambda-\tau)^2} + \frac{\xi^2k^2\lambda^2(a-b\upsilon)}{2b(4b\lambda-\tau)} + \emptyset_1\right\}$, $\omega_2 \geq \frac{12b\lambda-\tau}{10a\lambda+[2b\lambda-\tau]\upsilon}\left\{\frac{[-64b^2\lambda^2-2\delta^2\theta_0^2(4b\lambda-\tau)](a-b\upsilon)}{2b(12b\lambda-\tau)^2} + \frac{2\delta^2\theta_0^2(a-b\upsilon)}{b(4b\lambda-\tau)} + \emptyset_2\right\}$, $\omega_1 + \omega_2 \leq 1 - \left\{\frac{2\lambda(a-b\upsilon)(4b\lambda-\tau)}{(12b\lambda-\tau)[10a\lambda+(2b\lambda-\tau)\upsilon]} + \frac{8a\lambda+(4b\lambda-\tau)\upsilon}{10a\lambda+(2b\lambda-\tau)\upsilon}\right\}$. *Among them,* $\tau = (\xi^2k^2\lambda + 2\delta^2\theta_0^2)$ *and* $\upsilon = c_M + c_T + c_R + c_F$.

Proof of Proposition 5 is provided in Appendix M.

Proposition 5 implies that the CR&RS contract can coordinate the supply chain and make the supply chain members get more profits than that without the CR&RS contract. Under this contract, the producer and the TPLSP undertake the safety traceability system availability investment and freshness-keeping effort, and provide the consolidated rebate, which improve the supply chain performance and bring more profits to the fresh produce e-commerce enterprise. Then by sharing the revenues with them, the fresh produce e-commerce enterprise makes the three supply chain parties profit together. Therefore, the three supply chain members will have enough motivation to accept this contract.

C. FURTHER DISCUSSION OF THE COORDINATION CONTRACTS

In this sub-section, we further discuss the implementation of the contracts. Note that the difference between the profit after the coordination of the supply chain and the profit before the coordination of the supply chain is $\frac{64b^2\lambda^3[a-b(c_M+c_T+c_R+c_F)]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)][12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$. Its value increases with the increase of ξ, and δ, respectively, and decreases with the increase of b (The Proofs are provided in Appendix N). This means that when consumers in the e-commerce market are more sensitive to FAPs freshness and safety traceability system availability, the profit difference between after and before the coordination will become greater. Then, the supply chain members are relatively easier to accept the contracts, and supply chain is relatively easier to coordinate. Whereas when the consumers in the e-commerce market are more sensitive to the online selling price of FAPs, the profit difference between after and before the coordination will become smaller. At this point, the supply chain members are relatively less liable to accept the contracts, and the supply chain is relatively difficult to coordinate. Therefore, when the channel members are planning to carry out a negotiation contract, a comprehensive survey should be made on the e-commerce market environment of the FAPs to clarify the main driving factors of the consumers market so as to facilitate the better implementation of the contracts. Besides, in the above, we give the scope of implementation of the contract parameters. As for the specific parameter values, it depends on the negotiation ability of the supply chain members. In the real supply chain, those who are in the dominant position and have stronger bargaining power are often more likely to get more incremental profits. However, in order to promote the long-term cooperation and cooperative development of the party with the weaker negotiating ability, the party in a strong position should make the concession appropriately. Within the scope of maintaining Pareto's improved contractual parameters, the supply chain members with stronger negotiating power should give the relatively weak supply chain members more profit sharing. Only in this way can other supply chain members be more motivated to integrate closely with it, cooperate sincerely and develop in the long run. And only in this way can the implementation of the contracts has a more far-reaching impact.

In addition, from the above derived formulas, one can find that the profits of both decentralized and centralized supply chain system are positively proportional to the market potential (It is easy to observe from the formulas derived above, so proof is omitted). This indicates that while achieving the efficiency and performance of the centralized FAPs supply chain system through contracts coordination policies, it is also necessary for the decentralized supply chain members to work more closely together to promote the concept of freshness, green, healthy and environmental safety of FAPs so as to explore the market potential imperceptibly. The means, such as WeChat, mobile APP, news media, Internet micro-blogs, FAPs e-commerce platform, can be used as information tools to develop the potential market, cultivate the market so as to obtain more profits.

Overall, the development of the society and the change of consumers' consumption concept have led to more and more individualized demand for higher freshness and safety of FAPs, especially under the environment of fresh e-commerce. As aforementioned proposition, this is beneficial to the FAPs' supply chain, because it can promote the profits of the supply chain. Whereas the double marginalization effect often makes decentralized supply chain lose many benefits. Since centralized supply chain is not universal in reality, it is very necessary to make the decisions and supply chain efficiency of decentralized channel to achieve the effect of the centralized channel. As an effective means of supply chain coordination, the design of contract mechanism is very meaningful. When FAPs freshness and safety traceability system availability are favored by the market, the proposed contracts will be easier to coordinate the supply chain. Through the implementation of the contract, the FAPs freshness and safety traceability system availability can be improved significantly, the profits of the supply chain members can be better improved, supply chain integration can be promoted [57], and members of the supply chain will be brought together to move forward in closer collaboration.

V. NUMERICAL ANALYSIS

In the above sections, we theoretically reason and compare the differences between centralized and decentralized FAPs' supply chains, demonstrate the impact of correlation coefficient on the decisions and supply chain profits, and study how to coordinate the decentralized FAPs' supply chain to improve the safety traceability system availability and freshness level, and improve the supply chain performance by contracts. In order to further clearly show its internal principles and examine the effect of various relevant factors on the production and operations decisions of the three supply chain members and the entire performance of the whole system in the real world, a numerical analysis is provided in this section.

From the above we know that $a-b(c_M+c_T+c_R+c_F)>0$, $\xi^2k^2<4b$ and $2(\delta^2\theta_0^2-2b\lambda)+\xi^2k^2\lambda<0$. In order to ensure that our research is within the feasible region, we specify that the market potential a as 100, the price-elasticity of the market demand b as 10, the sensitivity coefficient affecting safety traceability system availability k as 1, the producer's unit production cost c_M as 3, the sensitivity coefficient affecting the freshness level θ_0 as 1, the TPLSP's unit logistics distribution cost c_T as 2, the fresh produce e-commerce enterprise's unit operating cost c_R as 1.5, unit FAPs home delivery cost c_F as 1.5, and the freshness-keeping cost coefficient λ as 1. And the corresponding results are shown in Fig. 2-9.

From Fig. 2, it can be seen that the profits of the centralized and decentralized FAPs' supply chain are proportional to consumers' sensitivity to safety traceability system availability and freshness level. It means that if consumers are more sensitive to safety traceability system availability and freshness level, the profits of the FAPs' supply chain will increase by improving the safety traceability system availability investment and freshness-keeping effort. However, the safety traceability system availability investment and freshness-keeping effort in the decentralized FAPs' supply chain is less than that in the centralized FAPs' supply chain because of the decentralized decisions and channel conflict (Fig. 3 and Fig. 4). And the online selling price in the decentralized system is larger than that in the centralized system (Fig. 5). The lower safety traceability system availability investment and lower freshness-keeping effort reduce the safety degree and freshness level of FAPs, the higher online selling price reduce the consumers' consumption enthusiasm, and then further affect the market demand of FAPs (Fig. 6), clearly resulting in the profit in the decentralized FAPs' supply chain is less than that in the centralized FAPs' supply chain (Fig. 2). Through the contracts among the three FAPs' supply chain members, the safety traceability system availability investment and freshness-keeping effort are enhanced (Fig. 3 and Fig. 4), the online selling price is cut down (Fig. 5), the online ordering quantity is increased (Fig. 6), the performance of the supply chain is improved (Fig. 2), and the profits of producer, TPLSP and fresh produce e-commerce enterprise are raised respectively (Fig. 7, Fig. 8 and Fig. 9). It's interesting to find that the coordination contracts play an important role in improving the safety degree and freshness level of FAPs, eliminating the channel conflict, improving the overall profit of the FAPs' supply chain, and improving the profits of the three supply chain members.

When comparing the results in the Fig. 3 and Fig. 4, we also find that although consumers' sensitivity to safety traceability system availability and freshness have positive effects on safety traceability system availability investment and freshness-keeping effort respectively, the consumers' sensitivity to safety traceability system availability has a greater positive effect on safety traceability system availability investment but less positive effect on freshness-keeping effort. Similarly, the consumers' sensitivity to freshness has a greater positive effect on freshness-keeping effort but less positive effect on safety traceability system availability investment. It illustrates that the more sensitive the consumer is to safety traceability system availability, the more it can motivate the FAPs' supply chain members to increase safety traceability system availability investment, and the more sensitive the consumer is to the freshness, the more it can motivate the FAPs' supply chain members to improve freshness-keeping effort.

Fig. 7, Fig. 8 and Fig. 9 reveal that compared with the decentralized scenario without a contract, the two different types of contracts bring more profit to the supply chain participants. Under the two contracts, the profit of each channel member in the decentralized channel is no less than that in the decentralized channel without the contracts. Pareto improvement is achieved. Meanwhile, as can be seen from Fig. 7-9, under the *CS&RS* contract, the profit of each supply chain member increases with the increase of ξ and δ. However, under the *CR&RS* contract, the profit of producer increases as δ increases and decreases as ξ increases; the profit of TPLSP decreases as δ increases and increases as ξ increases; whereas the profit of fresh produce e-commerce enterprise has an increasing trend with the increase of ξ and δ. It indicates that under the *CS&RS* contract, when consumers are more sensitive to safety traceability system availability and freshness, *CS&RS* contract can make the three supply chain members obtain more additional profits on the basis of no less than the decentralized decision-making profits. Therefore, when drawing up *CS&RS* contracts, the three channel members should strengthen the publicity of freshness and safety traceability system availability, which can not only help improve the overall performance of the supply chain, but also make them benefit separately. Under the *CR&RS* contract, when consumers are more sensitive to freshness, the producer can obtain more additional profit increments, but when consumers are more sensitive to safety traceability system availability, the profit increments of producer will be reduced. This is because the increased consumer sensitivity to safety traceability system availability has stimulated the producer to invest more in safety traceability system availability, resulting in a relative increase in its own cost. Then the additional incremental profits generated by producer are relatively reduced. Therefore, the producer should increase freshness publicity and optimize the investment structure of safety traceability system availability to increase their incremental profits directly or indirectly. Similarly, TPLSP can gain more additional profit growth when consumers are more sensitive to safety traceability system availability, but less profit growth when consumers are more sensitive to freshness. This is because consumers are more sensitive to freshness, which has stimulated TPLSP's efforts to keep FAPs freshness. As a result, the cost of freshness-keeping is relatively increased, thus the extra incremental profit gained by producers is relatively reduced. Therefore, the TPLSP should increase the publicity of safety traceability system availability and develop low-cost and high-efficient freshness-keeping technology to promote more profit growth. For the fresh produce e-commerce enterprise, the effect of *CR&RS* contract and *CS&RS* contract is similar. When consumers are more sensitive to freshness and safety traceability system availability, fresh e-commerce can obtain relatively more additional profits. This also indicates that fresh e-commerce should increase the freshness, safety traceability system availability publicity, and improve the FAPs' freshness and safety traceability awareness, so as to make itself more profitable. But in any case, under the two contracts, the profits of each member of the three supply chains achieve Pareto improvement. The results also explain the reason why the producer, TPLSP and fresh produce e-commerce enterprise would cooperate with each other so as to benefit more from the coordinating mechanisms.

In summary, although decentralized decisions lead to a lower safety traceability system availability and freshness level of FAPs and a lower profit of supply chain, the decentralized supply chain can be coordinated through the proposed contracts. When the consumers in the market are sensitive to safety traceability system availability and freshness level, the three supply chain members should make joint efforts to improve the safety traceability system availability and freshness, which is beneficial to them, not only for the short term economic performance, but also for the long term economic performance. Through the reasonable implementation of these contracts, the total profit of the supply chain can be promoted, the Pareto improvement of the channel members can be realized, and the safety degree and freshness level of FAPs can be improved. At that time, the supply chain members will have better profits and consumers will have higher quality FAPs. Therefore, the coordination contracts proposed are of great significance for improving the production and operation performance of FAPs' supply chains.

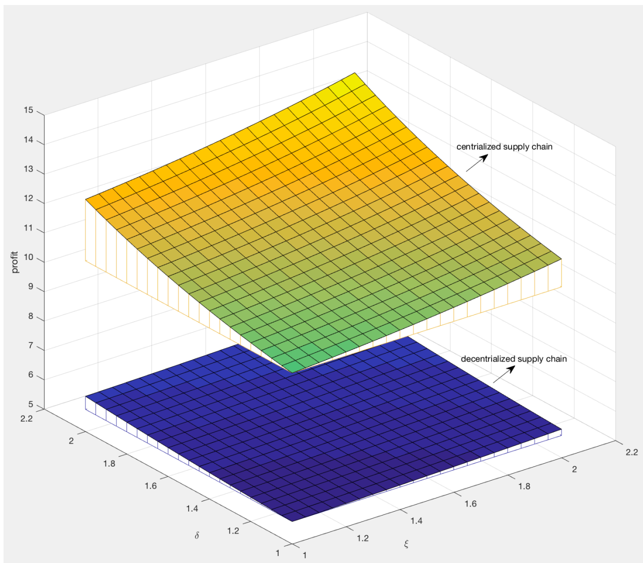

FIGURE 2. The effect of ξ and δ on FAPs' supply chain profit.

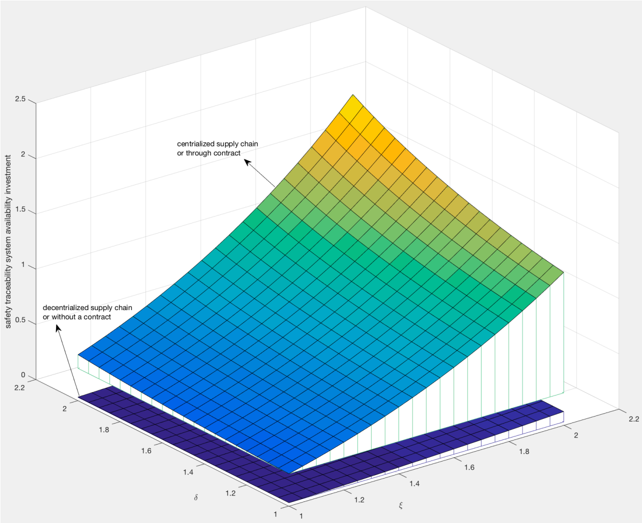

FIGURE 3. The effect of ξ and δ on safety traceability system availability investment.

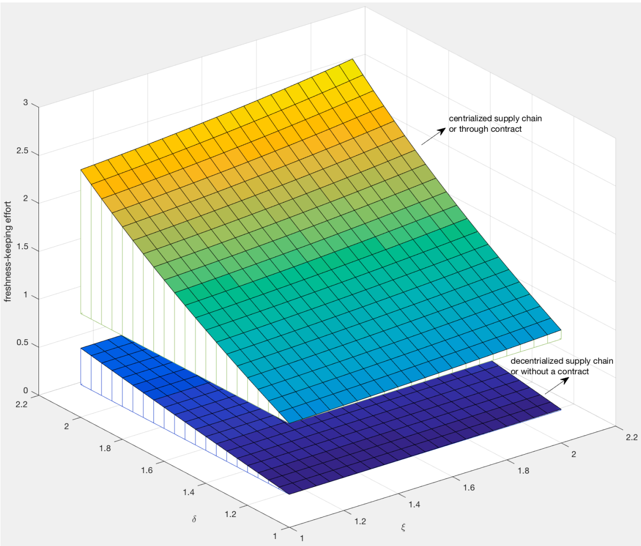

FIGURE 4. The effect of ξ and δ on freshness-keeping effort.

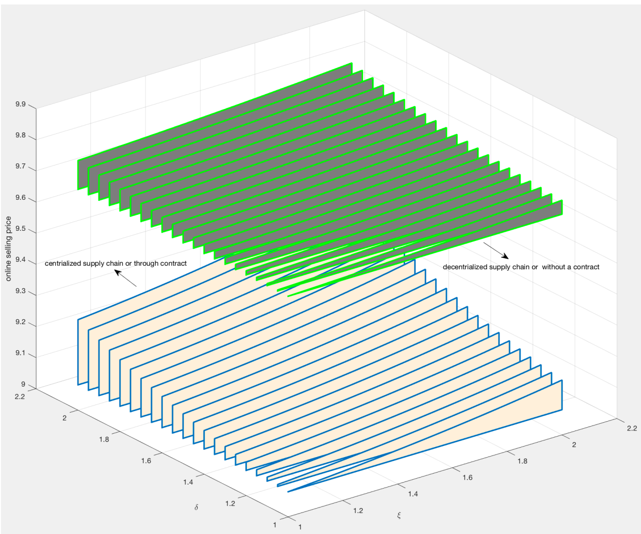

FIGURE 5. The effect of ξ and δ on online selling price.

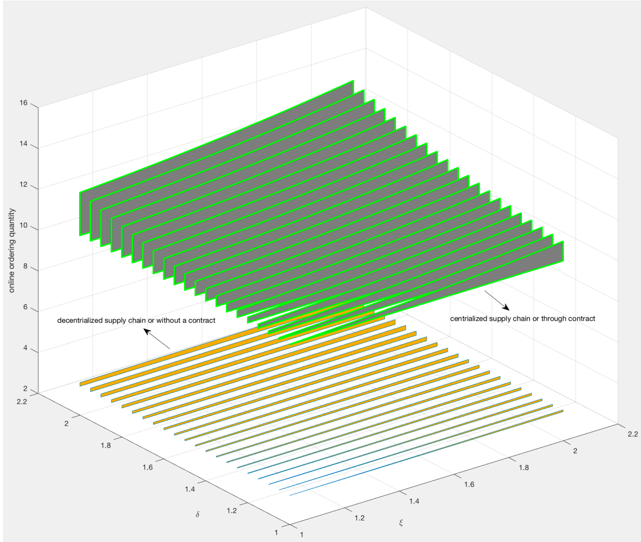

FIGURE 6. The effect of ξ and δ on online ordering quantity.

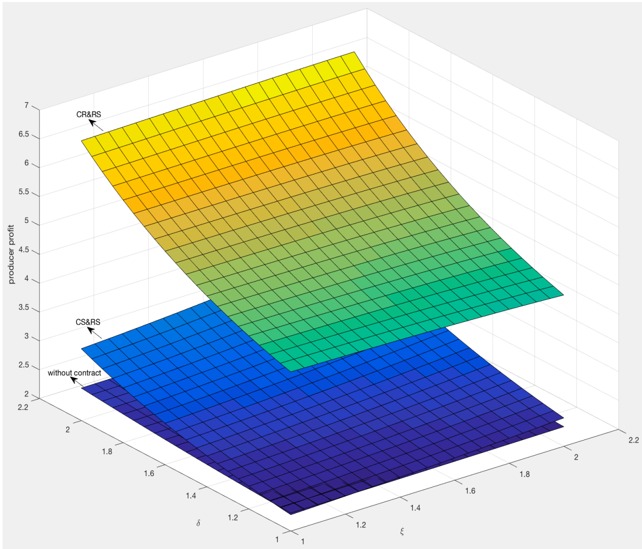

FIGURE 7. The effect of ξ and δ on producer's profit.

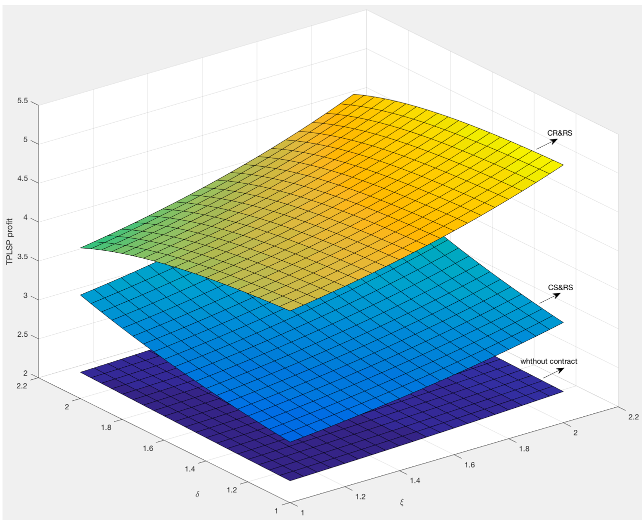

FIGURE 8. The effect of ξ and δ on TPLSP's profit.

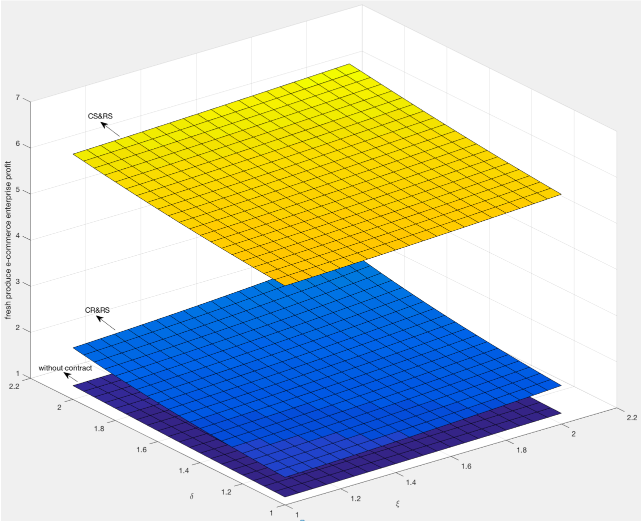

FIGURE 9. The effect of ξ and δ on fresh produce e-commerce enterprise's profit.

VI. CONCLUDING REMARKES

With the rapid development of FAPs e-commerce and the improvement of people's living standards, the quality and safety of FAPs has been highly concerned. In FAPs' supply chain production and operation, how to improve the freshness and safety of FAPs has become an important problem for the supply chain members. How to design reasonable incentive mechanisms to coordinate the supply chain so as to maximize channel profit has become another crucial issue. All these are not only related to the consumers' consumption safety and health, but also related to the interests of channel members and sustainable long-term development of whole supply chain. This paper tries to answer these questions.

In this paper, we have explored the decision and coordination of the FAPs' three-layer e-commerce supply chain under the safety traceability system availability and freshness level sensitive demand. The main contributions of this paper are summarized as follows:

(1) Due to the lack of literature on the decision and coordination of the supply chain presented in this paper, in order to fill the research gap, we make the first attempt to consider a new and innovative FAPs supply chain framework and do some research on it. On the basis of the e-commerce background and the characteristics of FAPs, new models have been established to address the decision and coordination issues of the three channel parities that consist of a producer, a TPLSP and a fresh produce e-commerce enterprise. One feature of the models is taking the safety traceability system availability investment and the freshness-keeping effort as decision variables. This paper is the first to explore the impact of multiple factors on demand for FAPs. Another feature of this research is proposing two different types of contract mechanisms for the FAPs' supply chain coordination. We investigate the coordination of FAPs' three-layer e-commerce supply chain with different contracts for the first time. In addition, the five decision variables, i.e., unit wholesale price, safety traceability system availability investment, unit logistics distribution price, freshness-keeping effort and unit online selling price in this research are all endogenous variables, which also makes the decision and coordination situation more complicated and closer to reality. All of these are significantly different from the previous studies.

(2) The optimal decisions of the three supply chain members and the optimal profits of the centralized and decentralized system have been characterized and compared respectively. In particular, we analyze the impact of consumers' sensitivities to safety traceability system availability, freshness and other factors on the supply chain decisions and performance, which is also one of the highlights of this paper.

(3) Two different types of contracts: *CS&RS* contract and *CR&RS* contract are designed to coordinate the decentralized FAPs' three-layer e-commerce supply chain. And we also have made a further discussion about the impact of the market preferences on the implementation of the contracts. As one of the highlights of our research, this also helps to further promote the development of contract theory in the application of the FAPs' e-commerce supply chain management.

(4) Numerical experiments are carried out to further better understand the theoretical results and show the application of our research in the real FAPs' supply chain world.

We find that as compared with the centralized system, the optimal safety traceability system availability investment, freshness-keeping effort, online ordering quantity and total expected profit in the decentralized system are lower, whereas the optimal unit online selling price in the decentralized system depends on the corresponding parameter conditions. Thus, we draw a conclusion that the optimal decisions in the centralized system are superior to the optimal decisions in the decentralized system, and compared with the decentralized decision, the centralized decision is more profitable. In addition, we find that the two types of contracts can improve the safety traceability system availability investment and freshness-keeping effort, make the profit of the decentralized FAPs' supply chain reach the optimal level of profit of the centralized FAPs' supply chain, and enable the three channel participants to make some additional profits in comparison to decentralized FAPs' supply chain. Thus, another conclusion can be drawn that the two contracts proposed can perfectly coordinate this supply chain. And the Pareto improvement can be achieved while also the environmental degree and freshness level of FAPs can be enhanced. Besides, we find that the decisions and the profits of the FAPs' supply chain are proportional to consumers' sensitivity to safety traceability system availability and freshness level. Thus, we come to another conclusion that the more sensitive the consumers are to safety traceability system availability and freshness level, the more profitable the supply chain will be. Finally, we find that when consumers are more sensitive to safety traceability system availability and freshness, the contract coordination policies are easier to implement and the supply chain is easier to coordinate; however, when consumers are more sensitive to online selling price, the contract coordination policies is relatively difficult to implement and the supply chain is not easy to coordinate.

Our findings convey many interesting managerial implications. Effective FAPs' supply chain management is not only the need for the development of the enterprise, but also the need for the development of the supply chain, as well as the need for the healthy and safe development of social consumption. From the perspective of the enterprises, we have derived the optimal unit wholesale price, optimal safety traceability system availability investment, optimal unit logistics distribution price, optimal freshness-keeping effort, optimal unit online selling price and optimal online ordering quantity under the different scenarios, which will provide reference for the three supply chain members to make the optimal decisions so as to improve their profits. From the perspective of the overall FAPs' supply chain, we have proposed two different types of contracts. Under different circumstances, the supply chain node enterprises can coordinate their interests by adjusting the contract parameters appropriately. Through reasonable implementation of these contracts, the supply chain node enterprises will cooperate more closely. This will make the supply chain more competitive and make it more stable, sustainable, cooperative and strategic. From the perspective of the society and consumers, through close cooperation, these three channel members can jointly make active efforts to improve the safety traceability system availability, freshness and safety of FAPs. This will not only provide necessary support for the harmonious development of the society, but also make consumers more comfortable with the consumption of FAPs. When the utility of society and consumers is well reflected, it will in turn promote the development of the three supply chain enterprises and the development of the whole supply chain. Then the performance and efficiency of the entire supply chain will be better improved.

Although this paper provides some insightful results and managerial implications, still it has some limits and there are several interesting yet challenging topics worthy of further study. First, we only study the FAPs' supply chain coordination under the additive online selling price, freshness-keeping effort and safety traceability system availability sensitive demand function, and do not discuss other demand functions, such as the multiplicative demand function [41] and the iso-elastic demand function [17], which makes the adaptability of the models have some limitations. In the further work, we will explore other types of demand functions and examine the suitable contract coordination mechanisms. In addition, this paper merely explores the case of complete information, so there is an interesting topic that is to consider the incomplete information scenario [58] in which all channel members not have common knowledge on information such as the cost structure and the profit form, and then to discover the corresponding coordination policies. Besides, in our models, we only consider one producer, one TPLSP and one fresh produce e-commerce enterprise. However, in the real FAPs supply chain, there are usually multiple fresh e-commerce enterprises, or multiple TPLSPs or multiple producers. Then, another interesting topic is to study the coordination issues under different FAPs' supply chain structures [9], [59].

APPENDIX

Appendix A

Proof of Theorem 1. We differentiate $\prod^c$ with respect to P_R, e_M and e_T. $\frac{\partial \prod^c}{\partial P_R} = -2bP_R + a + \xi k\sqrt{e_M} + \delta e_T\theta_0 + b(c_M + c_T + c_R + c_F)]$, $\frac{\partial^2 \prod^c}{\partial P_R^2} = -2b < 0$. $\frac{\partial \prod^c}{\partial e_M} = \frac{(P_R - c_M - c_T - c_R - c_F)\xi k}{2\sqrt{e_M}} - 1$, $\frac{\partial^2 \prod^c}{\partial e_M^2} = -\frac{(P_R - c_M - c_T - c_R - c_F)\xi k}{4\sqrt{e_M^3}} < 0$, $\frac{\partial \prod^c}{\partial e_T} = (P_R - c_M - c_T - c_R - c_F)\delta\theta_0 - \lambda e$, $\frac{\partial^2 \prod^c}{\partial e_T^2} = -\lambda < 0$.

The Hessian matrix of $\prod^c$ is

$$H(\prod^c) = \begin{bmatrix} -2b & \frac{\xi k}{2\sqrt{e_M}} & \delta\theta_0 \\ \frac{\xi k}{2\sqrt{e_M}} & -\frac{(P_R - c_M - c_T - c_R - c_F)\xi k}{4\sqrt{e_M^3}} & 0 \\ \delta\theta_0 & 0 & -\lambda \end{bmatrix}$$

The K-order principal minor*(-1) ^*k*>0, and the Hessian matrix of $\prod^c$ is negative definite if $\xi^2 k^2 < 4b$ and $2(\delta^2\theta_0^2 - 2b\lambda) + \xi^2 k^2 \lambda < 0$. Then $\prod^c$ is concave function of P_R, e_M and e_T. By solving $\frac{\partial \prod^c}{\partial P_R} = 0$, $\frac{\partial \prod^c}{\partial e_M} = 0$ and $\frac{\partial \prod^c}{\partial e_T} = 0$, we obtain the optimal values of P_R, e_M and e_T: $P_R^*(e_M, e_T) = \frac{a + \xi k\sqrt{e_M} + \delta e_T\theta_0 + b(c_M + c_T + c_R + c_F)}{2b}$, $e_M^*(P_R) = \frac{\xi^2 k^2 (P_R - c_M - c_T - c_R - c_F)^2}{4}$, $e_T^*(P_R) = \frac{\delta\theta_0(P_R - c_M - c_T - c_R - c_F)}{\lambda}$. Solving the Equations, we derive Equations (2), (3) and (4).

Appendix B

Proof of Lemma 1. Taking the first derivative and second derivative of Eq. (7) with respect to P_R, we get $\frac{\partial \prod_R^{dc}}{\partial P_R} = -2bP_R + a + \xi k\sqrt{e_M} + \delta e_T\theta_0 + b(P_M + P_T + c_R + c_F)$, $\frac{\partial^2 \prod_R^{dc}}{\partial P_R^2} = -2b < 0$, which is concave to P_R. Solving $\frac{\partial \prod_R^{dc}}{\partial P_R} = 0$, we derive Eq. (8).

Appendix C

Proof of Lemma 2. In order to get the optimal unit logistics distribution price and freshness-keeping effort, we differentiate $\prod_T^{dc}$ with respect to P_T and e_T. $\frac{\partial \Pi_T^{dc}}{\partial P_T} = \frac{1}{2}[a + \xi k\sqrt{e_M} + \delta e_T\theta_0 - b(P_M + c_R + c_F - c_T) - 2bP_T]$, $\frac{\partial^2 \Pi_T^{dc}}{\partial p_T^2} = -b < 0$. $\frac{\partial \Pi_T^{dc}}{e_T} = \frac{1}{2}\delta\theta_0(P_T - c_T) - 2\lambda e$, $\frac{\partial^2 \Pi_T^{dc}}{\partial e_T^2} = -2\lambda < 0$.

The Hessian matrix of $\prod_{\mathrm{T}}^{\mathrm{dc}}$ is

$$H(\prod_T^{dc}) = \begin{bmatrix} -b & \frac{\delta\theta_0}{2} \\ \frac{\delta\theta_0}{2} & -\lambda \end{bmatrix}$$

The K-order principal minor*(-1) ^k>0, and the Hessian matrix of $\prod_T^{dc}$ is negative definite if $\delta^2\theta_0^2 < 4b\lambda$. Then $\prod_{\mathrm{T}}^{\mathrm{dc}}$ is concave function of P_T and e_T. By solving $\frac{\partial \Pi_T^{dc}}{\partial P_T} = 0$ and $\frac{\partial \Pi_T^{dc}}{\partial e_T} = 0$, we derive Eq. (11) and Eq. (12).

Appendix D

Proof of Lemma 3. In order to obtain the optimal unit wholesale price and safety traceability system availability investment, we differentiate $\prod_{\mathrm{M}}^{\mathrm{dc}}$ with respect to P_M and e_M. $\frac{\partial \Pi_M^{dc}}{\partial P_M} = \frac{1}{2}[a + \xi k\sqrt{e_M} + \delta e_T\theta_0 - b(P_T + c_R + c_F - c_M) - 2bP_M]$, $\frac{\partial^2 \Pi_M^{dc}}{\partial p_M^2} = -b < 0$. $\frac{\partial \Pi_M^{dc}}{e_M} = \frac{\xi k(P_M - c_M)}{4\sqrt{e_M}} - 1$, $\frac{\partial^2 \Pi_M^{dc}}{\partial e_M^2} = -\frac{\xi k(P_M - c_M)}{8\sqrt{e_M^3}} < 0$.

The Hessian matrix of $\prod_M^{dc}$ is

$$H(\prod_M^{dc}) = \begin{bmatrix} -b & \frac{\xi k}{4\sqrt{e_M}} \\ \frac{\xi k}{4\sqrt{e_M}} & -\frac{\xi k(P_M - c_M)}{8\sqrt{e_M^3}} \end{bmatrix}$$

The K-order principal minor*(-1) ^k>0, and the Hessian matrix of $\prod_{\mathrm{T}}^{\mathrm{dc}}$ is a negative definite matrix if $\xi^2k^2 < 8b$. Then $\prod_{\mathrm{T}}^{\mathrm{dc}}$ is concave function of P_M and e_M. By solving $\frac{\partial \Pi_M^{dc}}{\partial P_M} = 0$ and $\frac{\partial \Pi_M^{dc}}{\partial M} = 0$, we can derive Eq. (15) and Eq. (16).

Appendix E

Proof of Theorem 2. Solving the equations consisting of Eq. (11), Eq. (12), Eq. (15) and Eq. (16), we can derive the equations $P_M^{dc^*} = \frac{4\lambda[a+b(2c_M-c_T-c_R-c_F)]-(\xi^2k^2\lambda+2\delta^2\theta_0^2)c_M}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$, $e_M^{dc^*} = \frac{\xi^2k^2\lambda^2[a-bv]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$, $P_T^{dc^*} = \frac{4\lambda[a+b(2c_T-c_M-c_R-c_F)]-(\xi^2k^2\lambda+2\delta^2\theta_0^2)c_T}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$ and $e_T^{dc^*} = \frac{2\delta\theta_0[a-bv]}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$. Substituting them into Eq. (8), then we can obtain $P_R^{dc^*} = \frac{10a\lambda+[2b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]v}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}$.

Appendix F

Proof of Proposition 1. Differentiating $e_M^{c^*}$, $e_T^{c^*}$, $P_R^{c^*}$, Q^{c^*}, $\prod^{c^*}$, $e_M^{dc^*}$, $e_T^{dc^*}$, $P_R^{dc^*}$, Q^{dc^*} and $\prod^{dc^*}$ with respect to the ξ, δ, b and λ, we obtain the following formulas. $\frac{\partial e_M^{c^*}}{\partial \xi} = \frac{[a-bv]^2\{2\xi^3k^3\lambda^3+2\xi k\lambda^2[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]\}}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} > 0$, $\frac{\partial e_T^{c^*}}{\partial \xi} = \frac{4\xi k\lambda\delta\theta_0[a-bv]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial P_R^{c^*}}{\partial \xi} = \frac{4[a-bv]\xi k^2\lambda^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial Q^{c^*}}{\partial \xi} = \frac{4b\xi k\lambda^2[a-bv]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial \prod^{c^*}}{\partial \xi} = \frac{2\lambda^2\xi k[a-bv]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial e_M^{c^*}}{\partial \delta} = \frac{4\delta\theta_0^2\xi^2k^2\lambda^2[a-bv]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} > 0$, $\frac{\partial e_T^{c^*}}{\partial \delta} = \frac{2\theta_0[a-bv](4b\lambda-\xi^2k^2\lambda+2\delta^2\theta_0^2)}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial P_R^{c^*}}{\partial \delta} = \frac{8[a-bv]\lambda\delta^2\theta_0^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial Q^{c^*}}{\partial \delta} = \frac{8b\lambda\delta\theta_0^2[a-bv]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial \prod^{c^*}}{\partial \delta} = \frac{2\lambda\delta\theta_0^2[a-bv]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial e_M^{dc^*}}{\partial \xi} = \frac{[a-bv]^2\{2\xi^3k^3\lambda^3+2\xi k\lambda^2[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]\}}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} > 0$, $\frac{\partial e_T^{dc^*}}{\partial \xi} = \frac{4\xi k\lambda\delta\theta_0[a-bv]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial P_R^{dc^*}}{\partial \xi} = \frac{20[a-bv]\xi k^2\lambda^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial Q^{dc^*}}{\partial \xi} = \frac{4b\xi k\lambda^2[a-bv]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial \prod^{dc^*}}{\partial \xi} = \frac{\{2\xi k\lambda^2[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]+4\xi k\lambda^2[20b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]\}[a-bv]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} > 0$, $\frac{\partial e_M^{dc^*}}{\partial \delta} = \frac{4\delta\theta_0^2\xi^2k^2\lambda^2[a-bv]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} > 0$, $\frac{\partial e_T^{dc^*}}{\partial \delta} = \frac{2\theta_0[a-bv](4b\lambda-\xi^2k^2\lambda+2\delta^2\theta_0^2)}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial P_R^{dc^*}}{\partial \delta} = \frac{40[a-bv]\lambda\delta^2\theta_0^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$, $\frac{\partial Q^{dc^*}}{\partial \delta} = \frac{8b\lambda\delta\theta_0^2[a-bv]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} > 0$ and $\frac{\partial \prod^{dc^*}}{\partial \delta} = \frac{\{4\lambda\delta\theta_0^2[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]+4\lambda\delta\theta_0^2[20b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]\}[a-bv]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} > 0$, that is, they are the increasing function with respect to ξ and δ. $\frac{\partial e_M^{c^*}}{\partial b} = \frac{-2\xi^2k^2\lambda v[a-bv][4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]-8\xi^2k^2\lambda^2[a-bv]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} < 0$, $\frac{\partial e_T^{c^*}}{\partial b} = \frac{-2\delta\theta_0 v[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]-8\delta\theta_0\lambda(4b-\xi^2k^2)[a-bv]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} < 0$, $\frac{\partial P_R^{c^*}}{\partial b} = \frac{2\lambda(\xi^2k^2\lambda+2\delta^2\theta_0^2)v-8a\lambda^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$. As $\xi^2k^2\lambda + 2\delta^2\theta_0^2 < 4b\lambda$, we obtain $2\lambda(\xi^2k^2\lambda + 2\delta^2\theta_0^2)(c_M + c_T + c_R + c_F) < 4b\lambda(c_M + c_T + c_R + c_F)$. Meanwhile, because $a - b(c_M + c_T + c_R + c_F)$, we derive the numerator is less than 0, thus $\frac{\partial P_R^{c^*}}{\partial b} < 0$. $\frac{\partial Q^{c^*}}{\partial b} = \frac{-8b^2\lambda^2v+2\lambda(\xi^2k^2\lambda+2\delta^2\theta_0^2)[2bv-a]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$. Since $2\lambda(\xi^2k^2\lambda + 2\delta^2\theta_0^2) < 8b\lambda^2$, we have $2\lambda(\xi^2k^2\lambda + 2\delta^2\theta_0^2)[2b(c_M + c_T + c_R + c_F) - a] < 8b\lambda^2[2b(c_M + c_T + c_R + c_F) - a]$, then the numerator is less than $8b\lambda^2[b(c_M + c_T + c_R + c_F) - a]$. Therefore, $\frac{\partial Q^{c^*}}{\partial b} < 0$. $\frac{\partial \prod^{c^*}}{\partial b} = \frac{-2\lambda[a-bv]\{v+2\lambda[a-bv]\}}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} < 0$, $\frac{\partial e_M^{dc^*}}{\partial b} = \frac{-2\xi^2k^2\lambda v[a-bv][12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]-24\xi^2k^2\lambda^2[a-bv]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} < 0$, $\frac{\partial e_T^{dc^*}}{\partial b} = \frac{-2\delta\theta_0 v[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]-24\delta\theta_0\lambda(4b-\xi^2k^2)[a-bv]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} < 0$, $\frac{\partial P_R^{dc^*}}{\partial b} = \frac{10\lambda(\xi^2k^2\lambda+2\delta^2\theta_0^2)v-10a\lambda^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} < 0$. $\frac{\partial Q^{dc^*}}{\partial b} = \frac{-24b^2\lambda^2v+2\lambda(\xi^2k^2\lambda+2\delta^2\theta_0^2)[2bv-a]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2} < 0$. $\frac{\partial \prod^{dc^*}}{\partial b} = -\frac{\lambda^2[240b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)][a-bv]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3} - \frac{2v[a-bv][20b\lambda^2-(\xi^2k^2\lambda^2+2\lambda\delta^2\theta_0^2)][12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3}$. The first term is less than 0 and the second term is less than 0, thus we derive $\frac{\partial \prod^{dc^*}}{\partial b} < 0$. Similarly, $\frac{\partial e_M^{c^*}}{\partial \lambda} =$

$\frac{2\xi^2k^2\lambda[a-bv][4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]+2\xi^2k^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3}>0$, $\frac{\partial e_T^{c^*}}{\partial\lambda}=\frac{-\delta\theta_0[a-bv](4b-\xi^2k^2)}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}<0$, $\frac{\partial P_R^{c^*}}{\partial\lambda}=\frac{-4\delta^2\theta_0^2[a-bv]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}<0$, $\frac{\partial Q^{c^*}}{\partial\lambda}=\frac{-2b\delta^2\theta_0^2[a-bv]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}<0$, $\frac{\partial\Pi^{c^*}}{\partial\lambda}=\frac{-2\delta^2k^2\theta_0^2[a-bv]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}<0$, $\frac{\partial e_M^{dc^*}}{\partial\lambda}=\frac{2\xi^2k^2\lambda[a-bv][12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]+2\xi^2k^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3}>0$, $\frac{\partial e_T^{dc^*}}{\partial\lambda}=\frac{-\delta\theta_0[a-bv](12b-\xi^2k^2)}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}<0$, $\frac{\partial P_R^{dc^*}}{\partial\lambda}=\frac{-10\delta^2\theta_0^2[a-bv]}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}<0$, $\frac{\partial Q^{dc^*}}{\partial\lambda}=\frac{-2b\delta^2\theta_0^2[a-bv]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}<0$, $\frac{\partial\Pi^{dc^*}}{\partial\lambda}=\frac{\{\lambda(20b-\xi^2k^2)[12b\lambda-\tau]-\lambda(24b-2\xi^2k^2)[20b\lambda-\tau]\}[a-bv]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^3}$. Because $\xi^2k^2<4b$, so $\lambda(20b-\xi^2k^2)<\lambda(24b-2\xi^2k^2)$. Besides, because $12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)<20b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)$, therefore, $\frac{\partial\Pi^{dc^*}}{\partial\lambda}<0$. That means they are the increasing function with respect to λ. Where $\tau=(\xi^2k^2\lambda+2\delta^2\theta_0^2)$ and $v=c_M+c_T+c_R+c_F$. Therefore, the Proposition 1 can be derived.

Appendix G

Proof of Proposition 2. We derive that $\frac{e_M^{dc^*}}{e_M^*}=\frac{\frac{\xi^2k^2\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}}{\frac{\xi^2k^2\lambda^2[a-b(c_M+c_T+c_R+c_F)]^2}{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}}=\frac{[4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]^2}$. The numerator is smaller than the denominator, then it can be got $e_M^{dc^*}<e_M^*$. By the same token, we get that $\frac{e_T^{dc^*}}{e_T^*}=\frac{\frac{2\delta\theta_0[a-b(c_M+c_T+c_R+c_F)]}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}}{\frac{2\delta\theta_0[a-b(c_M+c_T+c_R+c_F)]}{4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}}=\frac{4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}<1$, $\frac{Q^{dc^*}}{Q^*}=\frac{\frac{2b\lambda[a-b(c_M+c_T+c_R+c_F)]}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}}{\frac{2b\lambda[a-b(c_M+c_T+c_R+c_F)]}{4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}}=\frac{4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}{12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)}<1$. Then we drive that $e_T^{dc^*}<e_T^*$, $Q^{dc^*}<Q^*$. $P_R^{dc^*}-P_R^*=\frac{8\lambda[2b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)][a-b(c_M+c_T+c_R+c_F)]}{[12b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)][4b\lambda-(\xi^2k^2\lambda+2\delta^2\theta_0^2)]}$, Then, we obtain that when $\xi^2k^2\lambda+2\delta^2\theta_0^2<2b\lambda$, $P_R^{dc^*}>P_R^{c^*}$; When $2b\lambda<\xi^2k^2\lambda+2\delta^2\theta_0^2<4b\lambda$, $P_R^{dc^*}<P_R^{c^*}$. Similarly, it can be obtained that $\frac{\Pi^{dc^*}}{\Pi^{c^*}}=\frac{80b^2\lambda^2+(\xi^2k^2\lambda+2\delta^2\theta_0^2)^2-24b\lambda(\xi^2k^2\lambda+2\delta^2\theta_0^2)}{144b^2\lambda^2+(\xi^2k^2\lambda+2\delta^2\theta_0^2)^2-24b\lambda(\xi^2k^2\lambda+2\delta^2\theta_0^2)}<1$, and then $\Pi^{dc^*}<\Pi^{c^*}$ can be reasoned out.

Appendix H

Proof of Theorem 3. According to dynamic game theory, the optimal unit online selling price can be gained by using backward induction. We differentiate Π_R^{cc} with respect to P_R. $\frac{\partial\Pi_R^{cc}}{\partial P_R}=-2b(1-\omega_1-\omega_2)P_R+(1-\omega_1-\omega_2)(a+\xi k\sqrt{e_M}+\delta e_T\theta_0)+b(P_M+P_T+c_R+c_F)]$, $\frac{\partial^2\Pi_R^{cc}}{\partial P_R^2}=-2b(1-\omega_1-\omega_2)<0$. It can be found that Π_R^{cc} is a concave function of P_R. Solving the equation $\frac{\partial\Pi_R^{cc}}{\partial P_R}=0$, we obtain Eq. (30).

Appendix I

Proof of Theorem 4. Substituting Eq. (30) into Eq. (28) and simplifying the equation, we obtain that $\Pi_T^{cc}=\frac{(P_T-c_T)[(1-\omega_1-\omega_2)(a+\xi k\sqrt{e_M}+\delta e_T\theta_0)-b\rho]}{2(1-\omega_1-\omega_2)}-\frac{\eta_2\lambda e_T{}^2}{2}+\frac{\omega_2\{(1-\omega_1-\omega_2)[a+\xi k\sqrt{e_M}+\delta e_T\theta_0+b\rho]\}[a+\xi k\sqrt{e_M}+\delta e_T\theta_0-b\rho]}{4b(1-\omega_1-\omega_2)^2}$, where, $\rho=P_M+P_T+c_R+c_F$. We differentiate Π_T^{cc} with respect to e_T. $\frac{\partial\Pi_T^{cc}}{e_T}=\frac{1}{2}\delta\theta_0(P_T-c_T)-\eta_2\lambda e_T-\frac{\omega_2\delta\theta_0[a+\xi k\sqrt{e_M}+\delta e_T\theta_0]}{2b}$, $\frac{\partial^2\Pi_T^{cc}}{\partial e_T^2}=\frac{\omega_2\delta^2\theta_0^2}{2b}-\eta_2\lambda<0$. Solving $\frac{\partial\Pi_T^{cc}}{e_T}=0$, we derive Eq. (31).

Appendix J

Proof of Theorem 5. Substituting Eq. (30) into Eq. (27) and simplifying the equation, we get that $\Pi_M^{cc}=\frac{(P_M-c_M)[(1-\omega_1-\omega_2)(a+\xi k\sqrt{e_M}+\delta e_T\theta_0)-b\rho]}{2(1-\omega_1-\omega_2)}-\eta_1 e_M\frac{\omega_1\{(1-\omega_1-\omega_2)[a+\xi k\sqrt{e_M}+\delta e_T\theta_0+b\rho]\}[a+\xi k\sqrt{e_M}+\delta e_T\theta_0-b\rho]}{4b(1-\omega_1-\omega_2)^2}$, where, $\rho=P_M+P_T+c_R+c_F$.. We differentiate Π_M^{cc} with respect to e_M. $\frac{\partial\Pi_M^{cc}}{e_M}=\frac{\xi k(P_M-c_M)}{4\sqrt{e_M}}-\eta_1-\frac{\omega_1\xi k[a+\xi k\sqrt{e_M}+\delta e_T\theta_0]}{8b\sqrt{e_M}}$, $\frac{\partial^2\Pi_M^{cc}}{\partial e_M^2}=-\frac{\xi k(P_M-c_M)}{8\sqrt{e_M^3}}-\frac{\omega_1\xi k[a+\xi k\sqrt{e_M}+\delta e_T\theta_0]}{8b\sqrt{e_M^3}}-\frac{\omega_1\xi k}{8b\sqrt{e_M}}<0$. Solving the equation $\frac{\partial\Pi_M^{cc}}{e_M}=0$, we derive Eq. (32).

Appendix K

Proof of Proposition 3. Let $P_R^{cc^*}=P_R^{c^*}$, that is $(1-\omega_1-\omega_2)[a+\xi k\sqrt{e_M}+\delta e_T\theta_0]+b(P_M+P_T+c_R+c_F)=(1-\omega_1-\omega_2)[a+\xi k\sqrt{e_M}+\delta e_T\theta_0+b(c_M+c_T++c_R+c_F)]$. Thus, we can obtain $(1-\omega_1-\omega_2)(c_M+c_T+c_R+c_F)=P_M+P_T+c_R+c_F$. Similarly, let $e_M^{cc^*}=e_M^{c^*}$, we get $\omega_1 a\xi k(2b\eta_2\lambda-\omega_2\delta^2\theta_0^2)+\omega_1\xi k\delta^2\theta_0^2\omega_2 a=\xi k\lambda a$, $b(P_M-c_M)\xi k(2b\eta_2\lambda-\omega_2\delta^2\theta_0^2)+\omega_1\xi k\delta^2\theta_0^2\,b(P_T-c_T)=-\xi k\lambda b(c_M+c_T+c_R+c_F)$, $2b\eta_1\eta_2=1$, $2b\eta_2\omega_1=1$, $2b\eta_1\omega_2=1$. Therefore, we have $(P_M-c_M)(2b\eta_2\lambda-\omega_2\delta^2\theta_0^2)+\omega_1\delta^2\theta_0^2 b(P_T-c_T)=-\lambda(c_M+c_T+c_R+c_F)$, $\eta_1=\omega_1$, $\eta_2=\omega_2$ and $\eta_1\eta_2=\frac{1}{2b}$. Let $e_T^{cc^*}=e_T^{c^*}$, we obtain $\omega_2\delta^2\theta_0^2 a(4b\eta_1-\omega_1\xi^2k^2)+\omega_2\delta\theta_0\xi^2k^2\omega_1 a=2\delta\theta_0 a$, $b(P_T-c_T)\delta\theta_0(4b\eta_1-\omega_1\xi^2k^2)+\omega_2\delta\theta_0\xi^2k^2 b(P_M-c_M)=-2\delta\theta_0(c_M+c_T+c_R+c_F)$, $2b\eta_1\eta_2=1$, $2b\eta_2\omega_1=1$, $2b\eta_1\omega_2=1$. Therefore, we obtain $(P_T-c_T)(4b\eta_1-\omega_1\xi^2k^2)+\omega_2\xi^2k^2(P_M-c_M)=-2(c_M+c_T+c_R+c_F)$,

$\eta_1 = \omega_1, \eta_2 = \omega_2$ and $\eta_1 \eta_2 = \frac{1}{2b}$. When $P_R^{cc^*} = P_R^*$, $e_M^{cc^*} = e_M^*$ and $e_T^{cc^*} = e_T^*$, there is $\prod_M^{cc^*} + \prod_T^{cc^*} + \prod_R^{cc^*} = \prod^{c^*}$.

Appendix L

Proof of Proposition 4. In order to make the members participate in the cooperation, the profits of them should be not less than the decentralized model without the contract respectively. According to the contract parameters in Proposition 3, we simplify the Eq. (27), Eq. (28) and Eq. (29), we obtain $\prod_M^{cc^*} = \frac{\omega_1(4b\lambda^2 - \xi^2 k^2 \lambda)[a - b(c_M + c_T + c_R + c_F)]^2}{[4b\lambda - (\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2)]^2}$, $\prod_T^{cc^*} = \frac{\omega_2(4b\lambda^2 - 2\delta^2 \theta_0^2 \lambda)[a - b(c_M + c_T + c_R + c_F)]^2}{[4b\lambda - (\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2)]^2}$,

$\prod_R^{cc^*} = \frac{[(1-\omega_1-\omega_2)4b\lambda^2 - (1-\omega_1)\xi^2 k^2 \lambda^2 - (1-\omega_2)2\delta^2 \theta_0^2 \lambda)[a - b(c_M + c_T + c_R + c_F)]^2}{[4b\lambda - (\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2)]^2}$. Simplifying the inequalities $\prod_M^{cc^*} \geq \prod_M^{dc^*}$, $\prod_T^{cc^*} \geq \prod_T^{dc^*}$ and $\prod_R^{cc^*} \geq \prod_R^{dc^*}$, we derive Proposition 4.

Appendix M

Proof of Proposition 5. When the prices of the three channel members are kept in line with the prices of the decentralized system, if the producer and the TPLSP jointly carry out the rebate value $P_R^{dc^*} - P_R^{c^*}$, the optimal safety traceability system availability investment e_M^* and the optimal freshness-keeping effort e_T^* for the supply chain system, and the fresh produce e-commerce enterprise provides the revenue share coefficient ω_1 and ω_2 for the producer and the TPLSP, $\prod_M^{rc} + \prod_T^{rc} + \prod_R^{rc} = \prod^c$ is achieved. The Pareto improvement will be realized only when their expected profits are no less than that in the decentralized scenario respectively. Then $\emptyset_1 + \emptyset_2 = P_R^{dc^*} - P_R^{c^*}$, $\prod_M^{rc^*} \geq \prod_M^{dc^*}$, $\prod_T^{rc^*} \geq \prod_T^{dc^*}$ and $\prod_R^{rc^*} \geq \prod_R^{dc^*}$. That is $\emptyset_1 + \emptyset_2 = \frac{10a\lambda + (2b\lambda - \tau)\upsilon}{12b\lambda - \tau} - \frac{2a\lambda + (2b\lambda - \tau)\upsilon}{4b\lambda - \tau}$, $\left\{\frac{4\lambda(a - b\upsilon)}{12b\lambda - \tau} - \emptyset_1 + \frac{\omega_1[10a\lambda + (2b\lambda - \tau)\upsilon]}{12b\lambda - \tau}\right\} \frac{2b\lambda(a - b\upsilon)}{4b\lambda - \tau} \geq \frac{(8b - \xi^2 k^2)\lambda^2 (a - b\upsilon)^2}{(12b\lambda - \tau)^2} + \frac{\xi^2 k^2 \lambda^2 (a - b\upsilon)^2}{(4b\lambda - \tau)^2}$, $\left\{\frac{4\lambda(a - b\upsilon)}{12b\lambda - \tau} - \emptyset_2 + \frac{\omega_2[10a\lambda + (2b\lambda - \tau)\upsilon]}{12b\lambda - \tau}\right\} \frac{2b\lambda(a - b\upsilon)}{4b\lambda - \tau} \geq \frac{(8b\lambda^2 - 2\lambda\delta^2 \theta_0^2)(a - b\upsilon)^2}{(12b\lambda - \tau)^2} + \frac{2\delta^2 \theta_0^2 \lambda (a - b\upsilon)^2}{(4b\lambda - \tau)^2}$, $\frac{(1 - \omega_1 - \omega_2)[10a\lambda + (2b\lambda - \tau)\upsilon]}{12b\lambda - \tau} - \frac{8a\lambda + (4b\lambda - \tau)\upsilon}{12b\lambda - \tau} \geq \frac{4b\lambda^2 (a - b\upsilon)^2}{(12b\lambda - \tau)^2} \frac{4b\lambda - \tau}{2b\lambda(a - b\upsilon)}$. Among them, $\tau = (\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2)$ and $\upsilon = c_M + c_T + c_R + c_F$. Simplifying the equation and inequalities, we derive Proposition 5.

Appendix N

Proof. We define Δ as the difference between before and after the coordination. Then $\Delta = \frac{[4b\lambda^2 - \tau\lambda][a - b\upsilon]^2}{[4b\lambda - \tau]^2} - \frac{[20b\lambda^2 - \tau\lambda][a - b\upsilon]^2}{[12b\lambda - \tau]^2} = \frac{\lambda[a - b\upsilon]^2 \{[12b\lambda - \tau]^2 - [20b\lambda - \tau][4b\lambda^2 - \tau]\}}{[4b\lambda - \tau][12b\lambda - \tau]^2} = \frac{64b^2 \lambda^3 [a - b\upsilon]^2}{[4b\lambda - \tau][12b\lambda - \tau]^2}$. $\frac{\partial \Delta}{\partial \xi} = \frac{64b^2 \lambda^3 [a - b\upsilon]^2 (-1)\{-2\xi k^2 \lambda [12b\lambda - \tau] - 4\xi k^2 \lambda [4b\lambda - \tau]\}}{[4b\lambda - \tau]^2 [12b\lambda - \tau]^3} = \frac{64b^2 \lambda^3 [a - b\upsilon]^2 \{2\xi k^2 \lambda [20b\lambda - 3\tau]\}}{[4b\lambda - \tau]^2 [12b\lambda - \tau]^3}$. $\frac{\partial \Delta}{\partial \delta} = \frac{64b^2 \lambda^3 [a - b\upsilon]^2 (-1)\{-4\delta\theta_0^2 [12b\lambda - \tau] - 8\xi k^2 \lambda [4b\lambda - \tau]\}}{[4b\lambda - \tau]^2 [12b\lambda - \tau]^3} = \frac{64b^2 \lambda^3 [a - b\upsilon]^2 \{4\delta\theta_0^2 [20b\lambda - 3\tau]}{[4b\lambda - \tau]^2 [12b\lambda - \tau]^3}$. Where $\tau = (\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2)$ and $\upsilon = c_M + c_T + c_R + c_F$. Due to $\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2 < 4b\lambda$, then $3(\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2) < 20b\lambda$.Therefore we get $\frac{\partial \Delta}{\partial \xi} > 0$, $\frac{\partial \Delta}{\partial \delta} > 0$. Similarly $\frac{\partial \Delta}{\partial \delta} = \frac{-128b\lambda^3 [a - b\tau]^2 [24b^2 \lambda^2 - (\tau)^2 + 2b\lambda\tau]}{[4b\lambda - \tau]^2 [12b\lambda - \tau]^3}$. Since $(\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2)^2 < 16b^2 \lambda^2$, we derive $24b^2 \lambda^2 - (\xi^2 k^2 \lambda + 2\delta^2 \theta_0^2)^2 > 0$. Because molecule is smaller than 0 and denominator is greater than 0, then we obtain $\frac{\partial \Delta}{\partial \delta} < 0$.

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Decision and Coordination of Fresh Produce Three-layer E-commerce Supply Chain: A New Framework

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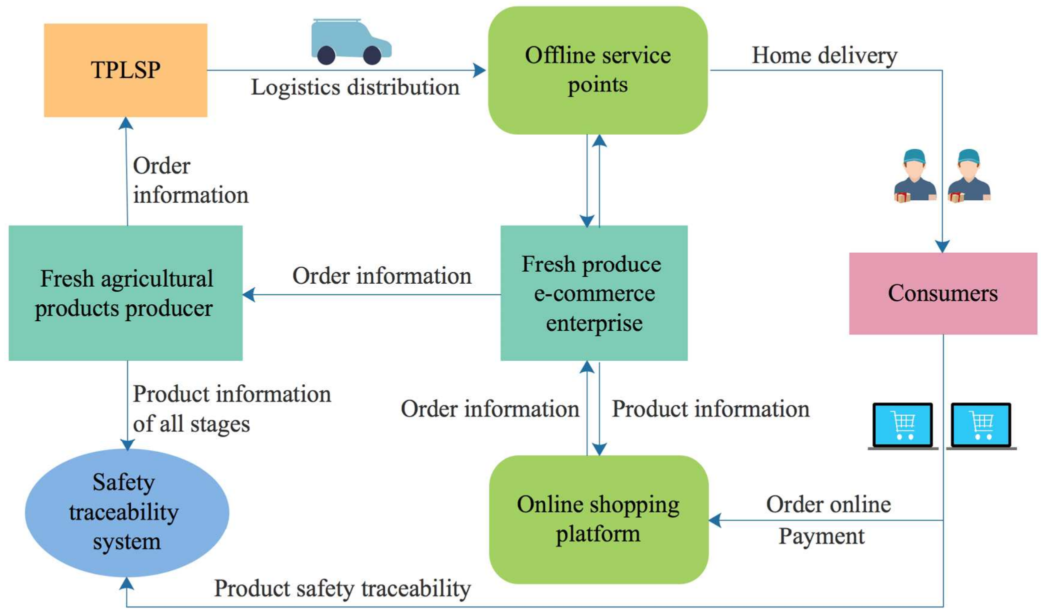

FIGURE 1. **FAPs' supply chain under consideration.**

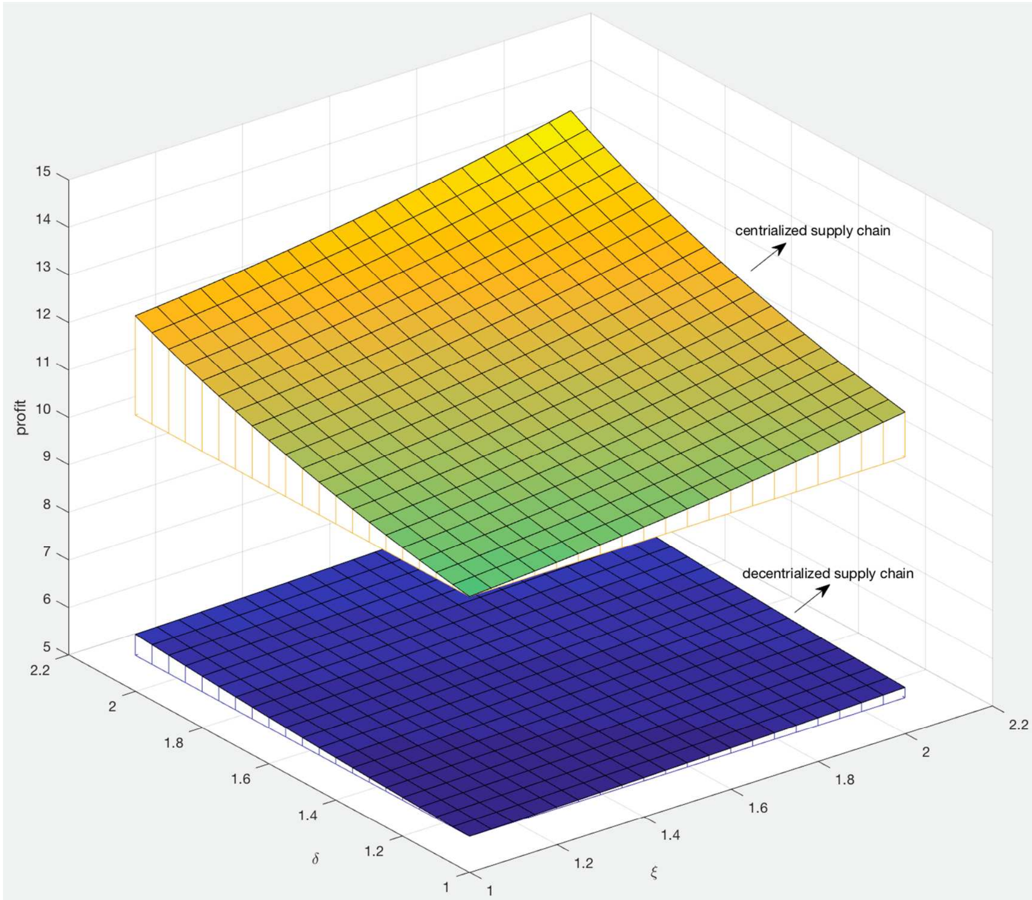

FIGURE 2. **The effect of ξ and δ on FAPs' supply chain profit.**

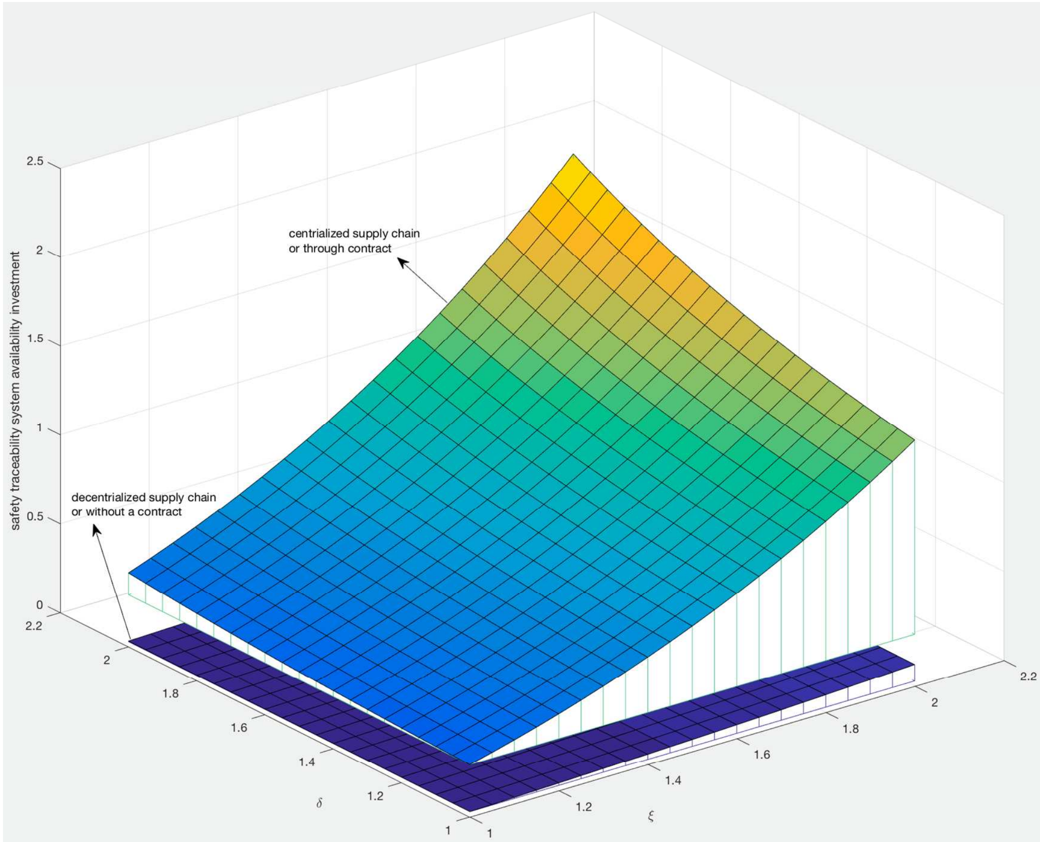

FIGURE 3. **The effect of ξ and δ on safety traceability system availability investment.**

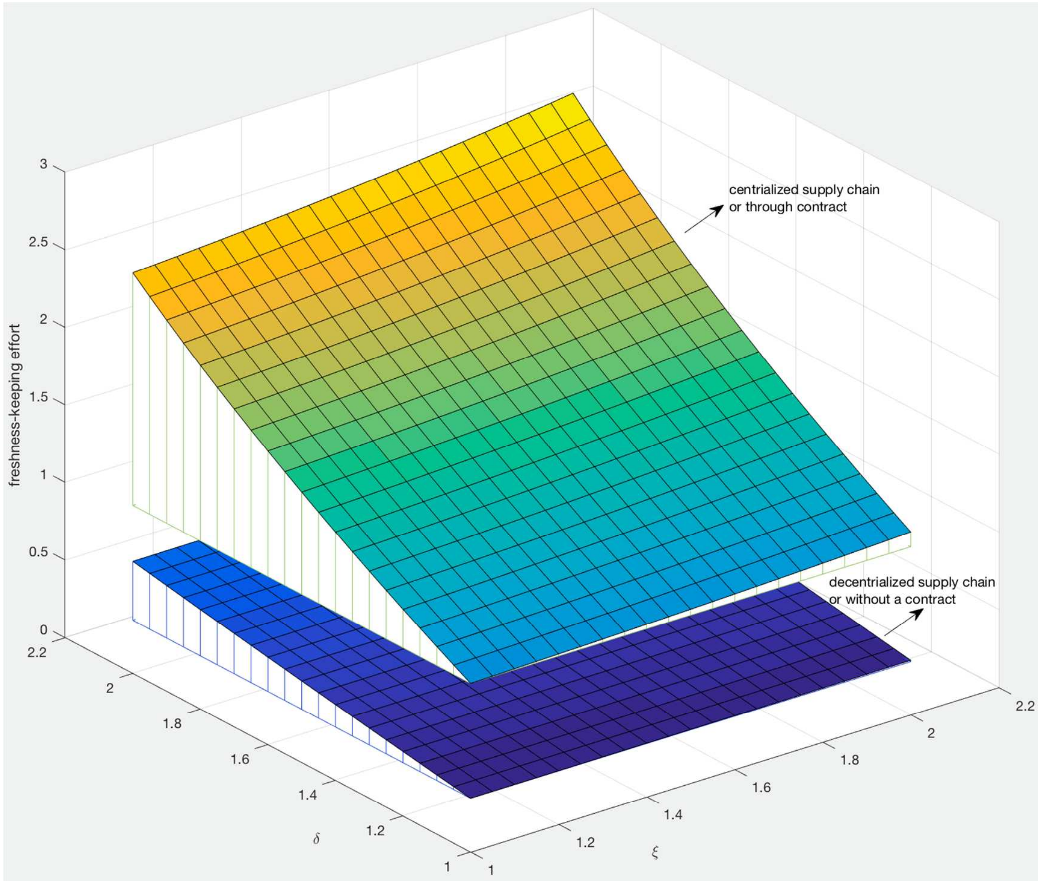

FIGURE 4. The effect of ξ and δ on freshness-keeping effort.

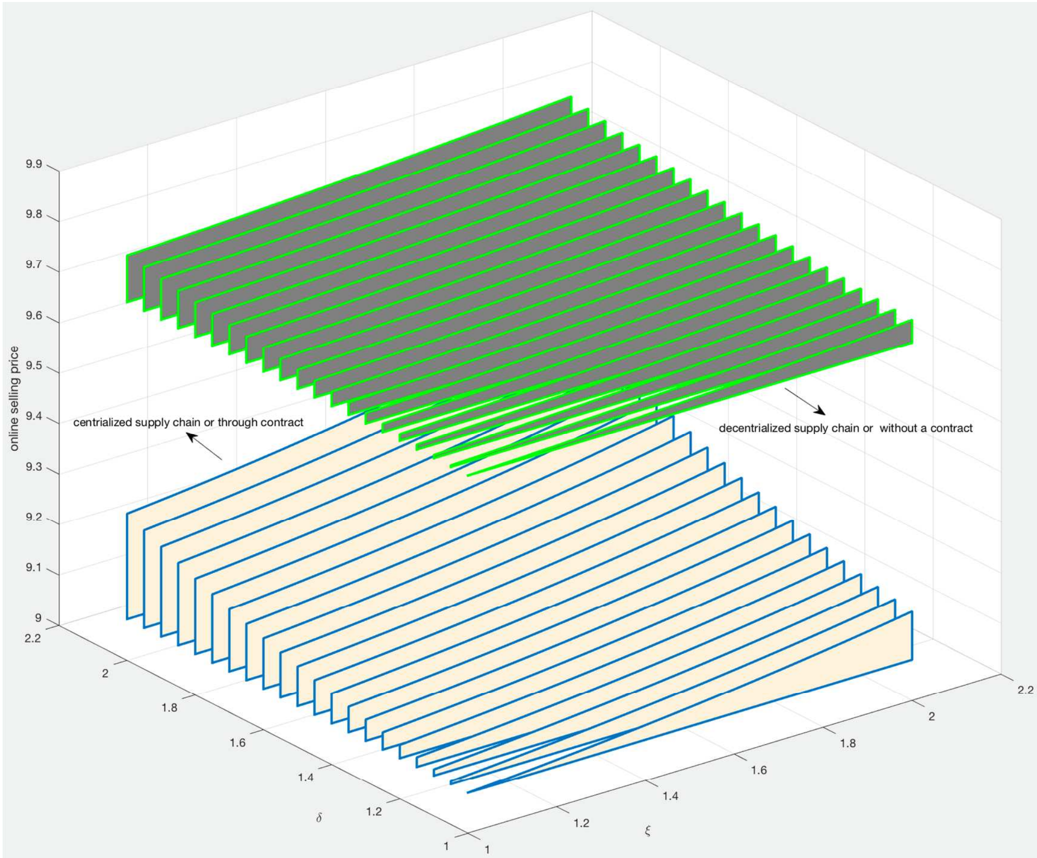

FIGURE 5. **The effect of ξ and δ on online selling price.**

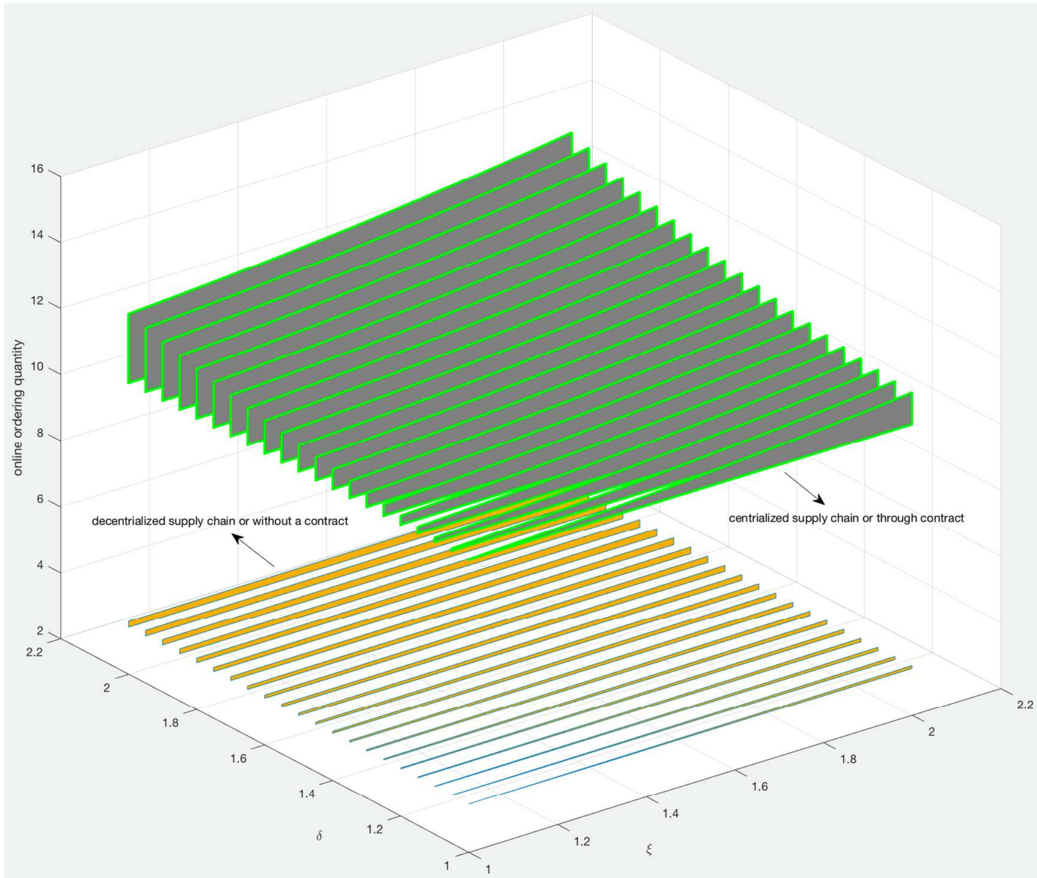

FIGURE 6. **The effect of ξ and δ on online ordering quantity.**

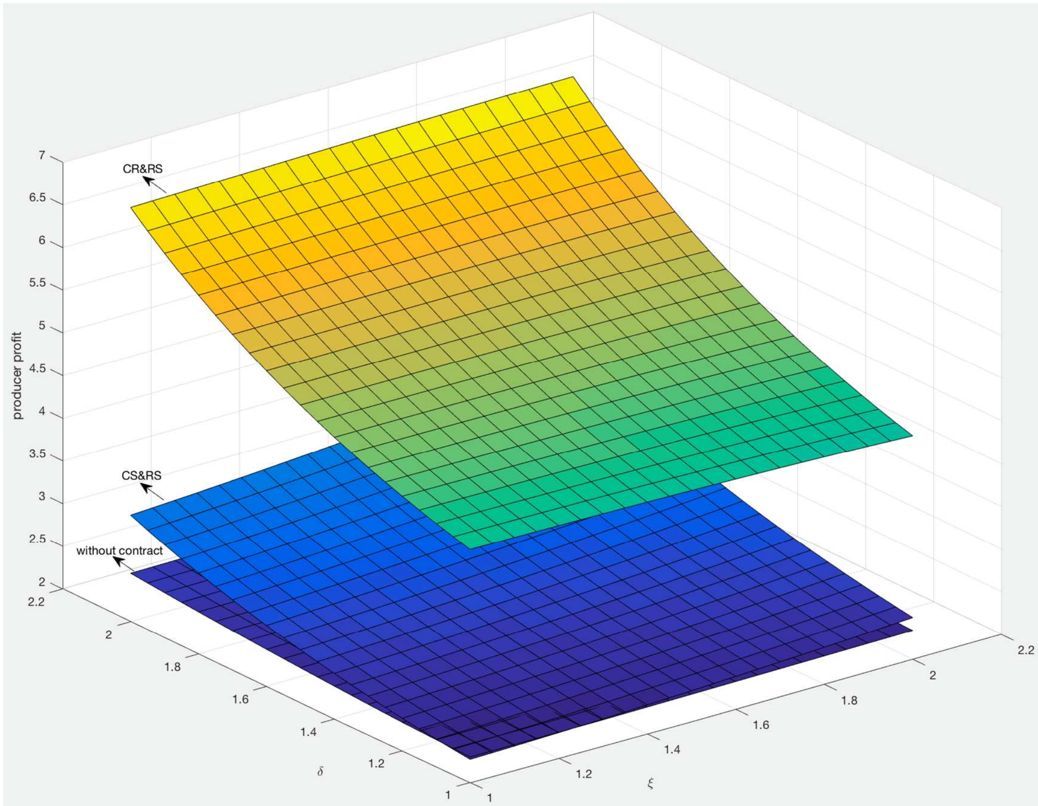

FIGURE 7. **The effect of ξ and δ on producer's profit.**

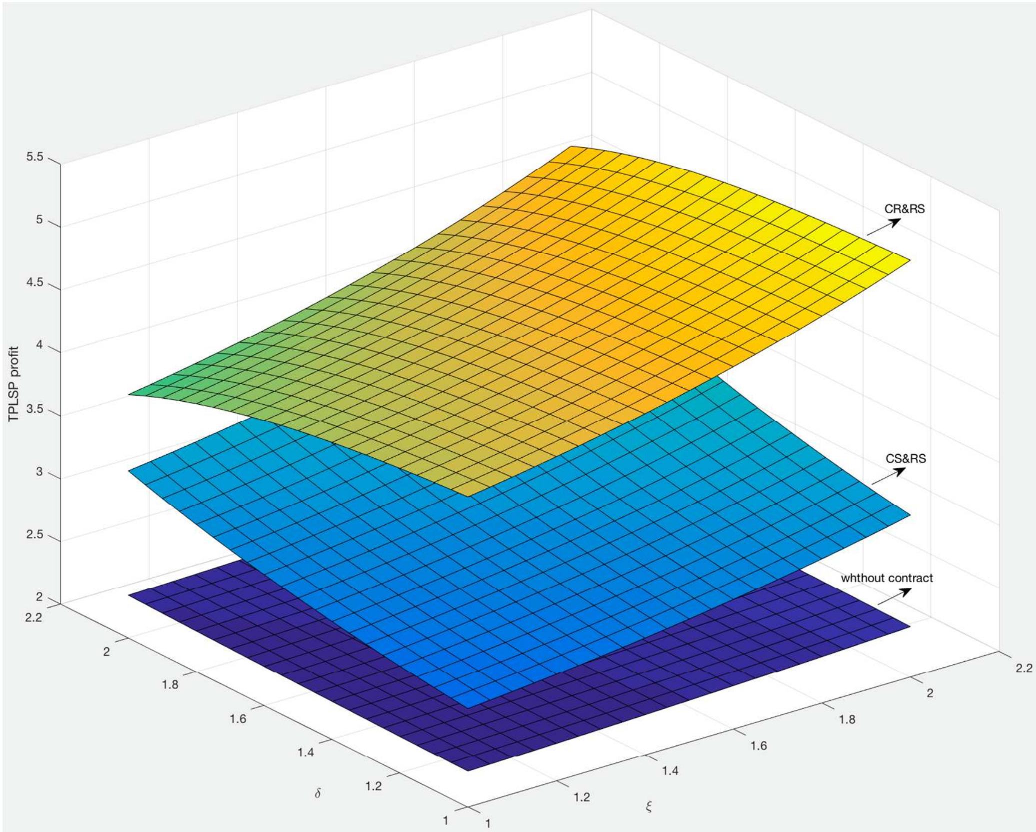

FIGURE 8. The effect of ξ and δ on TPLSP's profit.

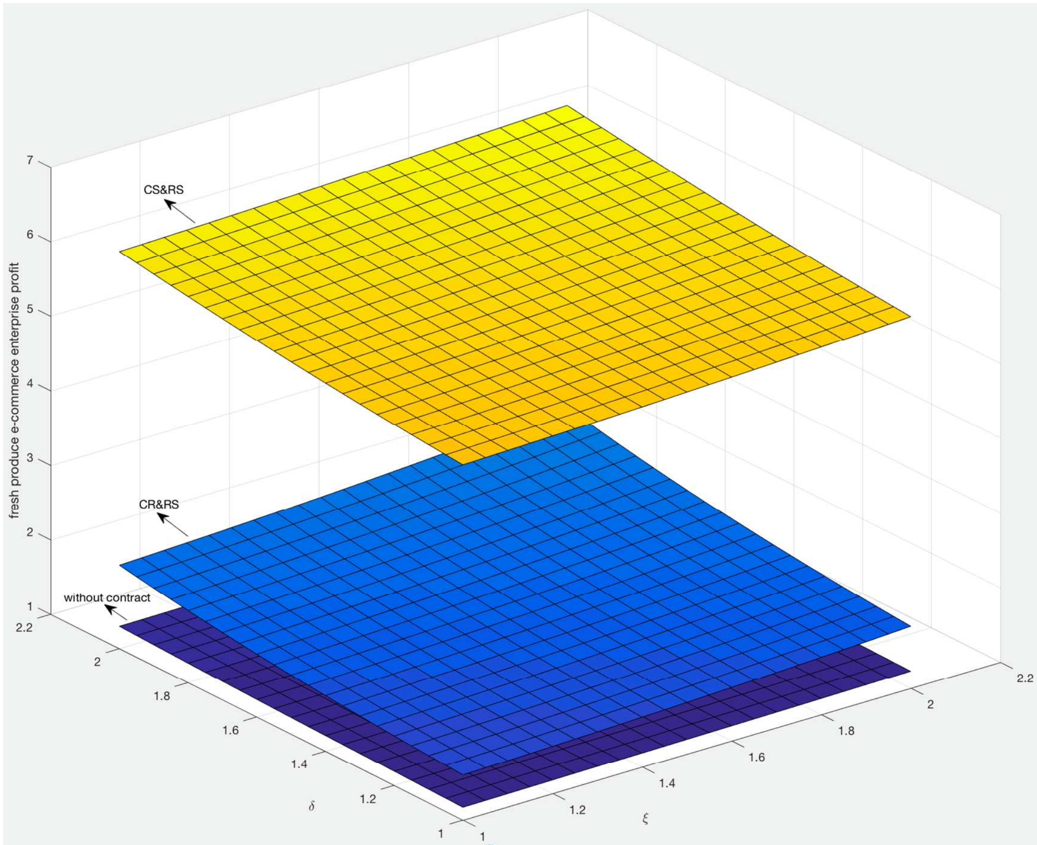

FIGURE 9. **The effect of ξ and δ on fresh produce e-commerce enterprise's profit.**