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*Research Article*

# Emergency Coordination Model of Fresh Agricultural Products' Three-Level Supply Chain with Asymmetric Information

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In consideration of influence of loss, freshness, and secret retailer cost of products, how to handle emergency events during three-level supply chain is researched when market need is presumed to be a nonlinear function with retail price in fresh agricultural product market. Centralized and decentralized supply chain coordination models are studied based on asymmetric information. Optimal strategy of supply chain in dealing with retail price perturbation is caused by emergency events. The research reveals robustness for optimal production planning, wholesale price for distributors, wholesale price for retailers, and retail price of three-level supply chain about fresh agricultural products. The above four factors can keep constant within a certain perturbation of expectation costs for retailers because of emergency events; the conclusions are verified by numerical simulation. This paper also can be used for reference to the other related studies in how to coordinate the supply chain under asymmetric and punctual researches information response to disruptions.

## 1. Introduction

Nowadays, emergency events about fresh agricultural products happen frequently and seriously impact producing, selling, and demand, and faith of consumers on food safety such as poisonous beans emerging in Hainan province and swelling ingredients discovered in watermelons.

Supply chain of fresh agriculture products is a complex net with dynamics and open system consisted of farmers, wholesalers, distribution centers, and retailers [1–3]. However, emergency events are results of complexity and uncertainty in supply chain. Meanwhile, the special nature of fresh agricultural product determines that the supply chain is weaker in resisting risk. Thus, a sudden emergency event can partly impact the supply chain or even destroy the whole chain. In recent years, more and more researchers have studied emergency cooperation of fresh agricultural product. Chen and Dan investigated the emergency cooperation problem, respectively, based on value and entity loss [4]. Furthermore, Zhao and Wu analyzed cooperation of two-level supply chain with random production and demand based on benefit-sharing contract [5]. Under the same contract, Lin et al. researched cooperation of three-level supply chain [6]. Based on a punishment and revenue sharing contract, Zhang et al. studied the coordination issues among single manufacturer, distributor, and retailer in a three-level supply chain [7]. Liu and Shi took the retail price being endogenous variables or exogenous variables as the essential characteristic of differentiating unconventional emergencies and conventional emergencies and built emergencies contingency model with buy-back contract when unconventional emergencies occur [8].

Gürler and Parlar studied two-level supply chain composed of two production suppliers generating an object function revealing average expense in a long time and finally achieving respective optimal order and inventory quantity for two suppliers relying on the application of optimal strategy [9]. Chen and Ding researched supply chain including a producer, a dominant retailer, and some other weaker retailers and conclude that producer should adjust wholesale

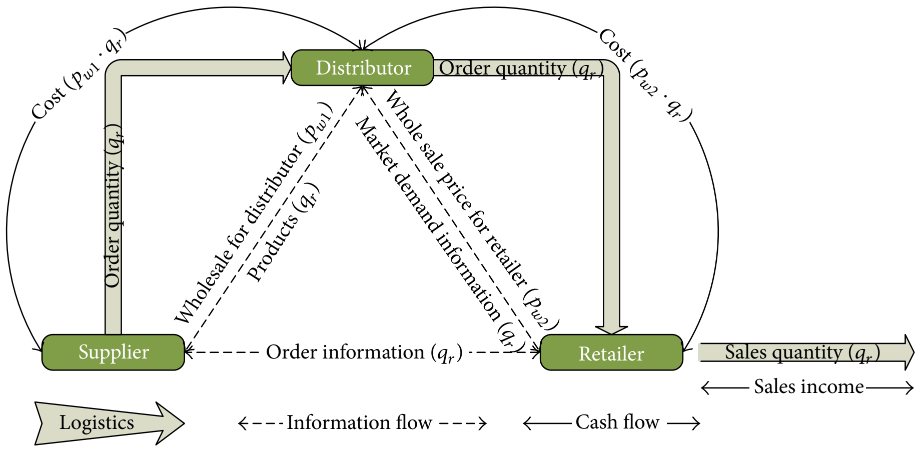


Figure 1: Three-supply-chain schematic for fresh agricultural product.

price with wholesale price contract when sudden demand emerges. The higher the market share of dominant retailer is, the lower the wholesale price determined by producer is. Thus, producer will preferentially take liner quantity discount contract into consideration when demand experiences a big change and production cost is quite low [10, 11]. Huo and Liu analyzed supply chain system composed of a producer and a retailer and renew original static production plan and supply chain coordination strategy when demand suddenly increases by applying wholesale quantity discount contract which realizes optimal potential profit in supply chains [12]. Zhang et al. researched supply chain system composed of a producer and two retailers, showing that, with sudden increase of demand, original benefit-sharing contract cannot perfectly coordinate supply chains system but a new one can which can be verified by numerical examples [13].

As transfer of leading right in the 21st century, retailers are playing an increasing important role in supply chain [14, 15]. Therefore study on coordination of three-level supply chain has practical value under sharp increasing demand. Munson and Rosenblatt launched a research on three-level supply chain composed of a production supplier, a producer, and a retailer and analyze how quantity discount contract affects decision of retailers and help increase profit of production suppliers [16]. Wang and Hu discussed optimal strategy on emergency events in three-level supply chain under centralized and decentralized condition by applying quantity discount contract [17]. Wang and Jiang constructed optimal strategy of three-level supply chain and model of optimal quantity discount which involves production suppliers, producers, and retailers under fuzzy random demand circumstance. Finally, practicality of model is verified by examples [18].

Qi and Yu studied simple supply chain only involving a production supplier and a retailer. Firstly, market demand for retailers is supposed to be a liner function with price. Then when demand fluctuates, how to apply whole units quantity discount contract should be discussed in handling emergency events and keeping supply chain coordinate [19, 20]. Wu et al. began with study of solving emergency events happening in two-level supply chain composed of a production supplier and two retailers who compete with each other and then further study about coordinate strategy under fluctuation of production cost, market demand, and price sensitive coefficient. Meanwhile, liner quantity discount is applied to realize supply chain coordination with the influence of several factors [21–24].

Qin et al. analyzed the condition when market demand of two-level supply chain varies with emergency events in stochastic market as well as supply chain coordination after emergency only with asymmetric demand information [25]. Meanwhile, they study synchronous variations of market demand and marginal costs of retailers and also investigate coordination effectiveness of buy-back contract on supply chain after the emergency when marginal costs information of retailers are asymmetric [26].

In this paper, the study object is a three-level supply chain of fresh agriculture products composed of a production supplier $M$, a distributer $L$, and a retailer $R$. Meanwhile, retailers play a leading role in system and distributor predominates over producers. In single cycle model, retailers make order of goods at the beginning of sales cycle.

The above three-level supply chain is operated in detail in Figure 1 [15, 27].

In consideration of loss in number and decrease in freshness during transportation of fresh agricultural product, this paper discusses how to achieve optimal system and realize robustness of the system and maximum profit of all members in system. The above study can provide theory foundation for decision-makers to draw strategy.

## 2. Supply Chain Coordination with Symmetric Information

The following prerequisite hypothesis should be met in this study. Firstly, all business deals happen among companies along with supply chain and producer cannot directly supply goods for retailers. Secondly, production suppliers have symmetric information with retailers. Thirdly, the study object is fresh agriculture products which only have short life cycle. Surplus products have no value and there does not exist goods order cycle. The research also does not take into consideration the loss of short supply, inventory, and inventory costs. All information is shared such as costs and market demands. The supply chain coordination is studied within a sale cycle, and thus influence of fixed facilities costs can be ignored because they keep constant. Besides all decision-makers undertake medium risk and seek the maximum profit for themselves.

All parameters used in the models are listed as follows:

$q_r$—market demand forecasted by retailers or order quantity of retailers;

$t$—transportation time which can affect quality of fresh agricultural product;

$T$—effective life cycle of fresh agricultural product which is also valid transportation time constraint for retailers, $0 \le t \le T$;

$p_r$—retail price;

$p_{w1}$—wholesale price for distributors;

$p_{w2}$—wholesale price for retailers;

$\lambda$—sensitive coefficient of price, $\lambda > 0$;

$m$—market demand scale (maximum);

$c_s$—production cost unit of production supplier;

$c_l$—transportation costs unit for distributors;

$c_r$—marginal costs for retailers.

Fourthly, the study describes characteristics of fresh agricultural products supply chain and defines $\phi(t) = 1 - t^2/T^2$, a monotonic continuous reduction function, as freshness factor of the products and $\phi(t) \in [0,1]$ as parameter of reveling composite quality characteristics such as water content, luster degree on the surface, and decay degree. Composite quality characteristic is one of the most important factors which affects practical supply quantity and market demand. Freshness degree $\phi(t)$ is mainly influenced by preservation, management, moving, and other behaviors during transportation. $\alpha(t)$ is generated to show rate coefficient of entity loss in transportation, meeting the function $\alpha(t) = e^{(\ln 2)/T} - 1$.

If effective rate factor $\beta(t) = 1 - \alpha(t) = 2 - e^{((\ln 2)/T)t}$ exists, $\beta(t) \in [0,1]$, which is corresponding with transportation time. Then order made by retailers can be expressed as $q_r/2 - e^{((\ln 2)/T)t}$ with goal of receiving maximum profit for retailers. It can be seen from the above derivations that the transportation time can influence supply and practical demand of goods in cooperation across different regions. Theoretically, the shorter the transportation time is the fresher the goods are. Meanwhile, supply rate of goods is higher and entity loss is less. Thus, the market demand will increase.

$q_r$ is supposed to be a nonlinear function of retail price. The function is denoted as $q_r = (m p_r^{-\lambda}/\ln 2)\ln(2 - t^2/T^2)$; retailers order a certain amount of products at wholesale price and then sell them at the retail price, $p_r = (m\ln(2 - t^2/T^2)/q_r \ln 2)^{1/\lambda}$.

The simple supply chain is usually dominated by a decision-maker to seek the maximum profit for the whole system, which only involves a production supplier, a distributer, and a retailer:

$$\pi(q_r) = q_r\left(p_r - \frac{c_r + c_s + c_l}{2 - e^{((\ln 2)/T)t}}\right) = q_r\left(\left(\frac{m\ln\left(2 - t^2/T^2\right)}{q_r \ln 2}\right)^{1/\lambda} - \frac{c_r + c_s + c_l}{2 - e^{((\ln 2)/T)t}}\right). \quad (1)$$

The study depends on first-order optimality conditions, $\partial\pi(q_r)/\partial q_r = 0$. The supply chain system is supposed to be able to achieve maximum profit for the whole system and have an unique optimal point for order, $q_r^*$.

Optimal sale quantity,

$$q_r^* = \frac{m\ln\left(2 - t^2/T^2\right)}{q_r \ln 2} \cdot \left(\frac{(\lambda - 1)\left(2 - e^{((\ln 2)/T)t}\right)}{\lambda\left(c_r + c_s + c_l\right)}\right)^{\lambda}. \quad (2)$$

Corresponding optimal retail price,

$$p_r^* = \frac{\lambda\left(c_r + c_s + c_l\right)}{(\lambda - 1)\left(2 - e^{((\ln 2)/T)t}\right)}. \quad (3)$$

Maximum profit for the whole three-level supply chain system,

$$\pi(q_r^*) = \frac{m\ln\left(2 - t^2/T^2\right)}{\ln 2} \cdot \frac{1}{\lambda^{\lambda}} \cdot \left(\frac{(\lambda - 1)\left(2 - e^{((\ln 2)/T)t}\right)}{\lambda\left(c_r + c_s + c_l\right)}\right)^{\lambda - 1}. \quad (4)$$

## 3. Supply Chain Coordination with Asymmetric Information

In practical life, condition of only having asymmetric information wildly exists in three-level supply chain system of fresh agricultural products. The following prerequisite hypothesis should be met in this research.

Firstly, information is asymmetric among production suppliers, distributors, and retailers. However, $c_r$ are known by retailers and distributors but not by production suppliers who can only infer the following information from functions $c_r \in [c_r^-, c_r^+]$. Distribution function, probability density function, and expectation are, respectively, $F(c_r)$, $f(c_r)$, and $\mu$, with the range of $0 \le c_r^- \le c_r^+ < \infty$. $F(c_r)$ is a differentiable and strictly increasing function and $F(0) = 0$, $\overline{F}(c_r) = 1 - F(c_r)$.

Secondly, production suppliers, distributors, and retailers all undertake medium risk and seek for the maximum profit for themselves.

Thirdly, other parameters are open information for retailers, distributors, and production suppliers.

Under decentralized control, retailers decide order quantity $q_r$ according to random market demand $m$. Distributers must provide order quantity $q_r$ made by retailers in order to get maximum profit. Thus distributers will buy $q_r$ unit goods at the wholesale price $p_{w1}$ and then sell them to retailers at a reasonable wholesale price $p_{w2}$ to receive maximum profits. For production suppliers, they should first provide goods in order quantity of $q_r$ and at the same time make sure how to decide wholesale price $p_{w1}$ to distributers to receive maximum profits. Form the above descriptions, it can be concluded that profit of retailers, distributors, and production suppliers is, respectively, as follows.

For production suppliers, maximizing their profit is the one that should be optimized. The optimizing problem and object function can be, respectively, shown as

$$\begin{aligned} &\max_{p_{\omega1}} \quad E\left[\pi_s\left(p_{\omega1}\right)\right] = \max_{p_{\omega1}} \quad \int_{c_r^-}^{c_r^+} \pi_s^S\left(p_{\omega1}\right) f\left(c_r\right) dc_r \\ &\text{s.t.} \quad \text{IC}: q_r = \arg\max_{q_r} \quad \pi_r^N\left(p_r\right). \end{aligned} \tag{5}$$

Function (1) shows IC constraints in incentive compatibility of retailers. Retailers determine order quantity to be $q_r$ to maximize their profits; expectation profits of production suppliers depend on order quantity $q_r$ made by retailers who make their decision relying on incentive compatibility constraints.

*(1) Optimizing Problem of Retailers*. Expectation profit function of retailers can be described as

$$\begin{aligned} \pi_r\left(p_r\right) &= q_r\left(p_r - \frac{c_r + p_{\omega2}}{2 - e^{((\ln 2)/T)t}}\right) \\ &= \frac{m\ln\left(2 - t^2/T^2\right)}{\ln 2} p_r^{-\lambda}\left(p_r - \frac{c_r + p_{\omega2}}{2 - e^{((\ln 2)/T)t}}\right). \end{aligned} \tag{6}$$

Based on first-order optimality conditions, $\partial_r\pi(p_r)/\partial p_r = 0$, optimal retail price can be determined:

$$p_r\left(p_{\omega2}\right) = \frac{\lambda\left(c_r + p_{\omega2}\right)}{(\lambda - 1)\left(2 - e^{((\ln 2)/T)t}\right)}. \tag{7}$$

The corresponding optimal sales quantity,

$$\begin{aligned} &q_r\left(p_{\omega2}\right) \\ &\quad = \frac{m\ln\left(2 - t^2/T^2\right)}{\ln 2}\left(\frac{(\lambda - 1)\left(2 - e^{((\ln 2)/T)t}\right)}{\lambda\left(c_r + p_{\omega2}\right)}\right)^{\lambda}. \end{aligned} \tag{8}$$

*(2) Optimizing Problem of Distributers.* Expectation profit function of distributers can be denoted:

$$\begin{aligned} &\max_{p_{\omega2}} \quad E\left[\pi_s\left(p_{\omega2}\right)\right] \\ &\quad = E\left[\frac{q_r\left(p_{\omega2}\right)}{2 - e^{((\ln 2)/T)t}}\left(p_{\omega2} - c_s - c_l\right)\right]. \end{aligned} \tag{9}$$

We can deduce Theorem 1 based on first-order optimality conditions, $\partial E[\pi_s(p_{\omega2})]/\partial p_{\omega2} = 0$.

*(3) Optimizing Problem of Production Suppliers*. Expectation profit function of production suppliers can be displayed as

$$\max_{p_{\omega1}} \quad E\left[\pi_s\left(p_{\omega1}\right)\right] = E\left[\frac{q_r\left(p_{\omega1}\right)}{2 - e^{((\ln 2)/T)t}}\left(p_{\omega1} - c_s\right)\right]. \tag{10}$$

We can deduce Theorem 1 based on first-order optimality conditions, $\partial E[\pi_s(p_{\omega1})]/\partial p_{\omega1} = 0$.

**Theorem 1.** *Under decentralized control coordination contract of three-level supply chain is without emergency and symmetric information.*

*Optimal wholesale price for distributors is*

$$p_{\omega1}^N = \frac{\lambda c_s + \mu}{\lambda - 1}; \tag{11}$$

*optimal wholesale price for retailers is*

$$p_{\omega2}^N = \frac{\lambda\left(c_s + c_l\right) + \mu}{\lambda - 1}; \tag{12}$$

*optimal retail price is*

$$p_r^N = \left(\frac{\lambda}{\lambda - 1}\right)^3\left(\frac{c_s + c_l + \mu}{2 - e^{((\ln 2)/T)t}}\right); \tag{13}$$

*optimal sales quantity for retailers is*

$$\begin{aligned} &q_r^N \\ &\quad = \frac{m\ln\left(2 - t^2/T^2\right)}{\ln 2}\left(\frac{\lambda - 1}{\lambda}\right)^{2\lambda}\left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \mu}\right)^{\lambda}. \end{aligned} \tag{14}$$

*Corresponding expectation profit of retailers is*

$$\begin{aligned} \pi_r^N &= \frac{m\ln\left(2 - t^2/T^2\right)}{\ln 2}\left(\frac{\lambda - 1}{\lambda}\right)^{2\lambda - 3} \\ &\quad \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \mu}\right)^{\lambda - 1}. \end{aligned} \tag{15}$$

*Expectation profit of distributors is*

$$\begin{aligned} \pi_{\omega2}^N &= \left(\lambda\left(c_s + c_l\right) + \mu\right)\frac{m\ln\left(2 - t^2/T^2\right)}{\ln 2} \\ &\quad \cdot \frac{(\lambda - 1)^{2\lambda - 1}}{\lambda^{2\lambda}}\left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \mu}\right)^{\lambda}. \end{aligned} \tag{16}$$

*Expectation profit of production suppliers is*

$$\begin{aligned} \pi_{\omega1}^N &= \frac{m\ln\left(2 - t^2/T^2\right)}{\ln 2} \\ &\quad \cdot \frac{(\lambda - 1)^{2\lambda - 1}\left[\lambda c_s + \mu\right]}{\lambda^{2\lambda}}\left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \mu}\right)^{\lambda}. \end{aligned} \tag{17}$$

## 4. Supply Chain Coordination Mechanism under Emergency and Asymmetric Information

When selling season is approaching, retailers make optimal order quantity and then distributers and production suppliers arrange distribution plan and producing strategy with the order quantity. If emergency affects retailer cost distribution function but without having any effect on other parameters, then $F(c_r)$ and density function $Y(c_r)$ will be, respectively, substituted by $f(c_r)$ and $y(c_r)$. $Y(c_r)$ is also differentiable and strictly increasing like $F(c_r)$, with $Y(0) = 0$, $\overline{Y}(c_r) = 1 - Y(c_r)$, and expected to be $\mu_Y$.

Optimal order quantity made by retailers, $q_r^D/(2 - e^{((\ln 2)/T)t})$, is also changed after emergency events; thus $q_r^D/(2 - e^{((\ln 2)/T)t}) > q_r^N/(2 - e^{((\ln 2)/T)t})$, and optimal order quantity has to be renewed. However, original producing plan is also broken. Then new producing cost $\rho_1$ is generated for productions which is added in order plan after emergency events, $(q_r^D - q_r^N)/(2 - e^{((\ln 2)/T)t})$. Otherwise, when order quantity $q_r^N/(2-e^{((\ln 2)/T)t})$ is less than original one, then extra distribution payment $\rho_2$ will be generated because of surplus products $(q_r^N - q_r^D)/(2-e^{((\ln 2)/T)t})$. Moreover, if order quantity by retailer $q_r^N/(2 - e^{((\ln 2)/T)t})$ is less than that by distributers, additional disposal cost $\rho_3$, $(k)^+ = \max(0, k)$, is yielded because of these surplus products $(q_r^N - q_r^D)/(2 - e^{((\ln 2)/T)t})$.

Emergency is supposed to cause increase of retailer costs. With $\overline{Y}(c_r) \geq \overline{F}(c_r)$, $q_r^D \geq q_r^N$ exists for arbitrary $c_r \geq 0$.

Expectation profits function is

$$\tilde{\pi}_s(p_{\omega1}) = \frac{1}{2 - e^{((\ln 2)/T)t}} \left[ q_r (p_{\omega1} - c_s) - \rho_1 (q_r^D - q_r^N) \right]. \tag{18}$$

Optimal problem of producing supplier is

$$\begin{aligned} &\max_{p_{\omega1}} \quad E[\tilde{\pi}_s(p_{\omega1})] = \max_{p_{\omega1}} \quad \int_{c_r^-}^{c_r^+} \tilde{\pi}_s(p_{\omega1})\, y(c_r)\, dc_r \\ &\text{s.t.} \quad \text{IC}: q_r = \arg\max_{q_r} \quad \tilde{\pi}_r(p_r), \\ &\tilde{\pi}_r(p_r) = q_r \left( p_r - \frac{c_l + c_r + p_{\omega1}}{2 - e^{((\ln 2)/T)t}} \right) \\ &\qquad = \frac{m \ln(2 - t^2/T^2)}{\ln 2} p_r^{-\lambda} \left( p_r - \frac{c_l + c_r + p_{\omega1}}{2 - e^{((\ln 2)/T)t}} \right). \end{aligned} \tag{19}$$

It can be concluded from first-order optimality conditions $\partial\tilde{\pi}_r(p_r)/\partial p_r = 0$ that optimal retail price

$$p_r(p_{\omega1}) = \frac{\lambda (c_l + c_r + p_{\omega1})}{(\lambda - 1)(2 - e^{((\ln 2)/T)t})}. \tag{20}$$

Corresponding optimal sale quantity is

$$q_r(p_{\omega1}) = \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left( \frac{(\lambda - 1)(2 - e^{((\ln 2)/T)t})}{\lambda (c_l + c_r + p_{\omega1})} \right)^{\lambda}. \tag{21}$$

Relying on first-order optimality conditions $\partial E[\tilde{\pi}_s(p_{\omega1})]/\partial p_{\omega1} = 0$, optimal wholesale price for distributers is

$$p_{\omega1}^D = \frac{\lambda (c_s + \rho_1) + \mu_Y}{(\lambda - 1)}. \tag{22}$$

Optimal wholesale price for retailers is

$$p_{\omega2}^D = \frac{\lambda (c_s + c_l + \rho_1 + \rho_2) + \mu_Y}{(\lambda - 1)}. \tag{23}$$

Corresponding optimal sale quantity is

$$\begin{aligned} q_r^D &= \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left( \frac{\lambda - 1}{\lambda} \right)^{3\lambda} \cdot \left( \frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \rho_1 + \rho_2 + \mu_Y} \right)^{\lambda} < q_r^N \\ &= \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left( \frac{\lambda - 1}{\lambda} \right)^{3\lambda} \left( \frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \mu} \right)^{\lambda}. \end{aligned} \tag{24}$$

However, the conclusion is in contradiction with hypothesis. Therefore, for arbitrary $c_r \geq 0$, $q_r^D \leq q_r^N$ exists when emergency events cause increase of retailer costs, $\overline{Y}(c_r) \geq \overline{F}(c_r)$. As is applied with same theory, $q_r^D \geq q_r^N$ exists when emergency events cause decrease of retailer costs, $\overline{Y}(c_r) \leq \overline{F}(c_r)$.

In the following part, coordination mechanism of the above two conditions is discussed.

For arbitrary $c_r \geq 0$, Situation 1 $q_r^D \leq q_r^N$ exists when emergency events cause increase of retailer costs, $\overline{Y}(c_r) \leq \overline{F}(c_r)$; Situation 2 $q_r^D \leq q_r^N$ exists when emergency events cause decrease of retailer costs with $\overline{Y}(c_r) \geq \overline{F}(c_r)$.

Profit function of production supplier is

$$\begin{aligned} \tilde{\pi}_{s1}(p_{\omega1}) &= \frac{1}{2 - e^{((\ln 2)/T)t}} \left[ q_r (p_{\omega1} - c_s) - \rho_1 (q_r^D - q_r^N) \right], \\ \tilde{\pi}_{s2}(p_{\omega1}) &= \frac{1}{2 - e^{((\ln 2)/T)t}} \left[ q_r (p_{\omega1} - c_s) - (\rho_2 + \rho_3)(q_r^N - q_r^D) \right]. \end{aligned} \tag{25}$$

Optimizing problem of production supplier is

$$\begin{aligned} &\max_{p_{\omega1}} \quad E[\tilde{\pi}_{s1}(p_{\omega1})] = \max_{p_{\omega1}} \quad \int_{c_r^-}^{c_r^+} \tilde{\pi}_{s1}(p_{\omega1})\, y(c_r)\, dc_r \\ &\max_{p_{\omega1}} \quad E[\tilde{\pi}_{s2}(p_{\omega1})] = \max_{p_{\omega1}} \quad \int_{c_r^-}^{c_r^+} \tilde{\pi}_{s2}(p_{\omega1})\, y(c_r)\, dc_r \\ &\text{s.t.} \quad \text{IC}: q_r = \arg\max_{q_r} \quad \tilde{\pi}_r(p_r). \end{aligned} \tag{26}$$

Profit function of distributers is

$$\tilde{\pi}_{s1}(p_{\omega 2}) = \frac{1}{2 - e^{((\ln 2)/T)t}} \left[ q_r (p_{\omega 2} - c_s - c_l) - (\rho_1 + \rho_2)(q_r^D - q_r^N) \right],$$
$$\tilde{\pi}_{s2}(p_{\omega 2}) = \frac{1}{2 - e^{((\ln 2)/T)t}} \left[ q_r (p_{\omega 2} - c_s - c_l) - \rho_3 (q_r^N - q_r^D) \right]. \quad (27)$$

Optimizing problem of distributers is

$$\max_{p_{\omega 2}} \; E[\tilde{\pi}_{s1}(p_{\omega 2})] = \max_{p_{\omega 2}} \int_{c_r^-}^{c_r^+} \tilde{\pi}_{s1}(p_{\omega 2})\, y(c_r)\, dc_r$$
$$\max_{p_{\omega 2}} \; E[\tilde{\pi}_{s2}(p_{\omega 2})] = \max_{p_{\omega 2}} \int_{c_r^-}^{c_r^+} \tilde{\pi}_{s2}(p_{\omega 2})\, y(c_r)\, dc_r \quad (28)$$
$$\text{s.t.} \quad \text{IC}: q_r = \arg\max_{q_r} \; \tilde{\pi}_r(p_r).$$

Based on first-order optimality conditions, $\partial E[\tilde{\pi}_s(p_{\omega 1})]/\partial p_{\omega 1} = 0$, $\partial E[\tilde{\pi}_s(p_{\omega 2})]/\partial p_{\omega 2} = 0$, optimal wholesale price for distributers is

$$p_{\omega 1-1}^D = \frac{\lambda(c_s + \rho_1) + \mu_Y}{(\lambda - 1)},$$
$$p_{\omega 1-2}^D = \frac{\lambda(c_s - \rho_2 - \rho_3) + \mu_Y}{(\lambda - 1)}. \quad (29)$$

Optimal wholesale price for retailers is

$$p_{\omega 2-1}^D = \frac{\lambda(c_s + c_l + \rho_1 + \rho_2) + \mu_Y}{(\lambda - 1)},$$
$$p_{\omega 2-2}^D = \frac{\lambda(c_s + c_l - \rho_3) + \mu_Y}{(\lambda - 1)}. \quad (30)$$

Optimal retail price and sales quantity are, respectively,

$$p_{r1}^D = \left(\frac{\lambda}{\lambda - 1}\right)^3 \frac{(c_s + c_l + \rho_1 + \rho_2 + \mu_Y)}{(2 - e^{((\ln 2)/T)t})},$$
$$p_{r2}^D = \left(\frac{\lambda}{\lambda - 1}\right)^3 \frac{(c_s + c_l - \rho_3 + \mu_Y)}{(2 - e^{((\ln 2)/T)t})},$$
$$q_{r1}^D = \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \rho_1 + \rho_2 + \mu_Y}\right)^{\lambda},$$
$$q_{r2}^D = \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l - \rho_3 + \mu_Y}\right)^{\lambda}. \quad (31)$$

Expectation profit for retailers is

$$\tilde{\pi}_{r1}^D = \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda - 3} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \rho_1 + \rho_2 + \mu_Y}\right)^{\lambda - 1},$$
$$\tilde{\pi}_{r2}^D = \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda - 3} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l - \rho_3 + \mu_Y}\right)^{\lambda - 1}. \quad (32)$$

Expectation profit for distributers is

$$\tilde{\pi}_{\omega 1-1}^D = \frac{\lambda(c_s + \rho_1) + \mu_Y}{(\lambda - 1)} \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \rho_1 + \rho_2 + \mu_Y}\right)^{\lambda} + \rho_1 q_r^N,$$
$$\tilde{\pi}_{\omega 1-2}^D = \frac{\lambda(c_s - \rho_2) + \mu_Y}{(\lambda - 1)} \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l - \rho_3 + \mu_Y}\right)^{\lambda} - (\rho_2 + \rho_3) q_r^N. \quad (33)$$

Expectation profit for production supplier is

$$\tilde{\pi}_{\omega 2-1}^D = \frac{\lambda(c_s + c_l + \rho_1 + \rho_2) + \mu_Y}{(\lambda - 1)} \cdot \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l + \rho_1 + \rho_2 + \mu_Y}\right)^{\lambda} + (\rho_1 + \rho_2) q_r^N,$$
$$\tilde{\pi}_{\omega 2-2}^D = \frac{\lambda(c_s + c_l - \rho_3) + \mu_Y}{(\lambda - 1)} \cdot \frac{m \ln(2 - t^2/T^2)}{\ln 2} \left(\frac{\lambda - 1}{\lambda}\right)^{3\lambda} \cdot \left(\frac{2 - e^{((\ln 2)/T)t}}{c_s + c_l - \rho_3 + \mu_Y}\right)^{\lambda} - \rho_3 q_r^N. \quad (34)$$

## 5. Example Analysis

Specific example is analyzed to verify the models constructed in the paper. Suppose $m = 6000$, $\lambda = 2$, $c_s = 10$, $t = 3$, $T = 18$, $\rho_1 = 3$, $\rho_2 = 1$, and $\rho_3 = 2$; cost function of retailers $F(c_r)$ is in even distribution with $\mu = 12$. Disturbing scope of retail cost expectation is presumed to be [1, 20]. In the following part, influence of retail cost variation will be discussed, respectively, on wholesale price of distributors and

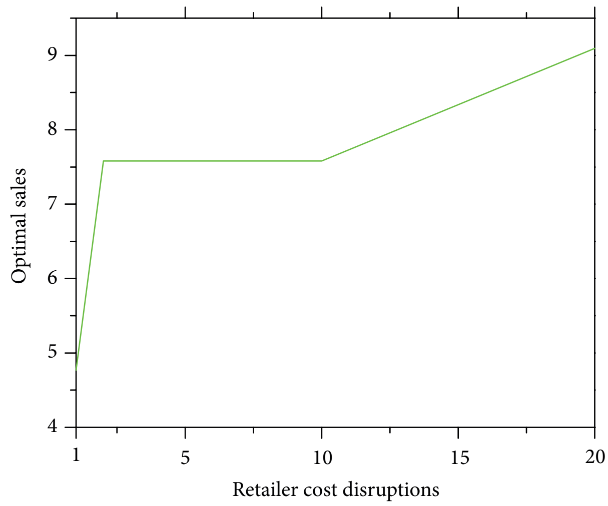


FIGURE 2: Relationship of $\mu_Y$ with the optimal sales.

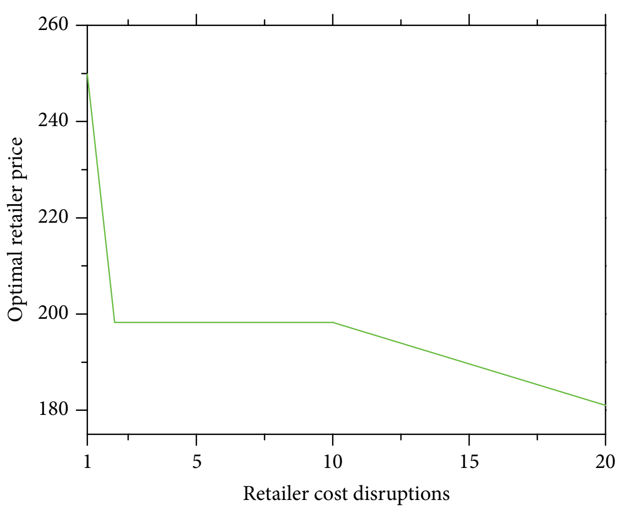


FIGURE 3: Relationship of $\mu_Y$ with the optimal sales price.

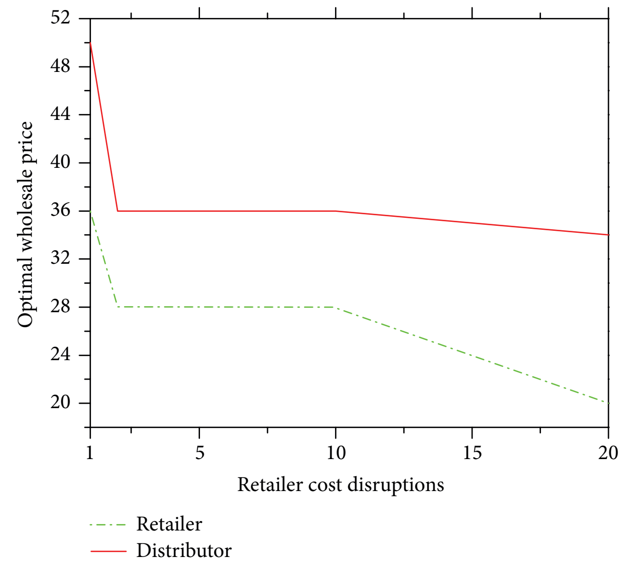


FIGURE 4: Relationship between $\mu_Y$ and the optimal sales price of retailer and distributor.

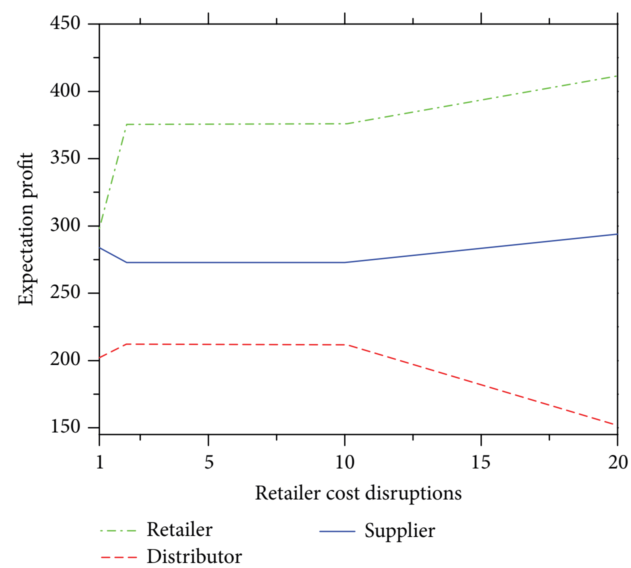


FIGURE 5: Relationship between $\mu_Y$ and expectation profit for retailers, distributers, and supplier.

retailers, sale quantity, retail price, and expectation profit of production suppliers, distributors, retailers, and the whole three-level supply chain system.

The following conclusions can be achieved from Figures 2–5 when there are emergency events. Under emergency and asymmetric information, three-level supply chain coordination mechanism shows optimal sales quantity $q_r^D$, optimal retail price $p_r^D$, optimal wholesale price for retailers $p_{\omega 2}^D$, and optimal wholesale price for distributers $p_{\omega 1}^D$.

From Tables 1 and 2, the following conclusions can be drawn.

Firstly, original producing plan has quite strong robustness under emergency events. Thus in a certain range of retailers cost change, the original coordination mechanism can be effective to coordinate three-level supply chain.

Secondly, when the change is out that range, then original coordination mechanism should be renewed to achieve new coordination.

## 6. Conclusions

This paper discusses three-level supply chain coordination mechanism with asymmetric information and under emergency and draws the following conclusions.

(1) When emergency has little influence on retail price, then original optimal strategy can be coordinated by its robustness. That is to say that all plans can keep the same but all members of supply chain system can still achieve the optimal profits.

(2) When retail price is seriously influenced by emergency, then original optimal strategy should be adjusted to coordinate the supply chain system. That

Table 1: Expectation profit for retailers, distributers, supplier, and three-level supply chain system.

| Conditions | Optimal sales quantity $q_r^D$ | Optimal retail $p_r^D$ | Retailers $p_{\omega 2}^D$ | Distributers $p_{\omega 1}^D$ |
|---|---|---|---|---|
| $\mu_Y < \mu - \rho_1 - \rho_2$ | $q_{r1}^D\ (> q_r^N)$ | $p_{r1}^D\ (< p_r^N)$ | $p_{\omega 2-1}^D\ (< p_{\omega 2}^N)$ | $p_{\omega 1-1}^D\ (< p_{\omega 1}^N)$ |
| $\mu - \rho_1 - \rho_2 \le \mu_Y \le \mu + \rho_3$ | $q_r^N$ | $p_r^N$ | $p_{\omega 2}^N$ | $p_{\omega 1}^N$ |
| $\mu_Y > \mu + \rho_3$ | $q_{r2}^D\ (< q_r^N)$ | $p_{r2}^D\ (> p_r^N)$ | $p_{\omega 2-2}^D\ (> p_{\omega 2}^N)$ | $p_{\omega 1-2}^D\ (> p_{\omega 1}^N)$ |

Table 2: Expectation profit for retailers, distributers, and supplier.

| Conditions | Retailers $\widetilde{\pi}_r^D$ | Distributers $\widetilde{\pi}_{\omega 1}^D$ | Supplier $\widetilde{\pi}_{\omega 2}^D$ |
|---|---|---|---|
| $\mu_Y < \mu - \rho_1 - \rho_2$ | $\widetilde{\pi}_{r1}^D\ (> \widetilde{\pi}_r^N)$ | $\widetilde{\pi}_{\omega 1-1}^D\ (> \widetilde{\pi}_{\omega 1}^N)$ | $\widetilde{\pi}_{\omega 2-1}^D\ (> \widetilde{\pi}_{\omega 2}^N)$ |
| $\mu - \rho_1 - \rho_2 \le \mu_Y \le \mu + \rho_3$ | $\widetilde{\pi}_r^N$ | $\widetilde{\pi}_{\omega 1}^N$ | $\widetilde{\pi}_{\omega 2}^N$ |
| $\mu_Y > \mu + \rho_3$ | $\widetilde{\pi}_{r2}^D\ (< \widetilde{\pi}_r^N)$ | $\widetilde{\pi}_{\omega 1-2}^D\ (< \widetilde{\pi}_{\omega 1}^N)$ | $\widetilde{\pi}_{\omega 2-2}^D\ (< \widetilde{\pi}_{\omega 2}^N)$ |

is to say that all plans should have corresponding adjustment to solve emergency events and achieve the optimal profits for members of supply chain system. These plans include that of original producing plan, wholesale price for distributers and retailers, and retail price.

In practical life, condition of only having asymmetric information wildly exists in three-level supply chain system of fresh agricultural products. Asymmetric information runs through processes of producing, supplying, and distribution, which causes a serious loss in fresh agricultural products and also a big difficulty for supply chain managers. It is a direction for further research to study emergency cooperation of supply chain with consideration of asymmetric information and risk preference of supply chain. Therefore, this paper provides a novel thought for emergency cooperation of three-level supply chain for fresh agricultural product with asymmetric information. A fundamental train of thought and a frame for coordinating the fresh agricultural product supply chain under asymmetric information response to disruptions are provided in this study.

## Competing Interests

The authors declare that they have no competing interests.

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