Supply Chain Contracting Coordination for Fresh Products with Fresh-Keeping Effort

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Abstract

Purpose – Fresh product loss rates in supply chain operations are particularly high due to the nature of perishable products. This paper aims to maximize profit through the contract between retailer and supplier. The optimized prices for the retailer and the supplier, taking the fresh-keeping effort into consideration, are derived.

Design/methodology/approach – To address this issue, we consider a two-echelon supply chain consisting of a retailer and a supplier (i.e., wholesaler) for two scenarios: centralized and decentralized decision-making. We start from investigating the optimal decision in the centralized supply chain and then comparing the results with those of the decentralized decision. Meanwhile, a fresh-keeping cost-sharing contract and a fresh-keeping cost- and revenue-sharing contract are designed. Numerical examples are provided, and managerial insights are discussed at end.

Findings – The results show that (a) the centralized decision is more profitable than the decentralized decision; (b) a fresh product supply chain can only be coordinated through a fresh-keeping cost- and revenue-sharing contract; (c) the optimal retail price, wholesale price and fresh-keeping effort can all be achieved; (d) the profit of a fresh product supply chain is positively related to consumers' sensitivity to freshness and negatively correlated with their sensitivity to price.

Originality/value – Few studies have considered fresh-keeping effort as a decision variable in the modelling of supply chain. In this paper, a mathematical model for the fresh-keeping effort and for price decisions in a supply chain is developed. In particular, fresh-keeping cost sharing contract and revenue-sharing contract are examined simultaneously in the study of the supply chain coordination problem.

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Paper type Research paper

1 Introduction

One of biggest challenges in fresh product supply chain (FPSC) is maintaining product freshness. According to Cai et al. (2010), in developed countries, there is up to a 15% loss of product due to damage and spoilage. In developing countries, this loss rate is much higher. Overcoming this problem requires retailers and suppliers to work closely by coordinating operations across the supply chain. FPSC retailers and suppliers are severely affected by consumer value and product freshness and price; these considerations could invalidate such companies' original coordination schemes in cases lacking a contract. Therefore, research on the issue of coordinating FPSC management through contract is both meaningful and critical.

There have been numerous research on FPSC. The majority of research has focused on inventory management, pricing and ordering strategies. Dye (2007) developed a time-varying deterioration rate to formulate an inventory model for perishable products by assuming a constant loss rate for fresh products. Lodree and Uzochukwu (2008) investigated the inventory management of fresh products by assuming that consumer demand changes with the product deterioration rate. Ferguson and Koenigsberg (2007) studied a two-period model in which inventory is left over from the first period and a firm must decide whether to carry all, some or none of the leftover inventory to the next period. Such decisions affect reactions to new product production and pricing strategies. Cachon and Kök (2007) re-examined the newsvendor problem by assessing the product salvage value and then making optimal decisions on order quantity. Akcay et al. (2010) investigated the optimal joint dynamic pricing of various perishable products when considering strategic consumers using an algorithm of multinomial time. Wang and Li (2012) argued that, although it is difficult to forecast the quality of perishable products, it is possible to develop a pricing method to maximize profit based on more exact quality information. Gallego and Hu (2014) presented a joint pricing approach for competitive products in a special market environment, with perishable products consisting of substitutable and complementary products. Nakandala et al. (2016) developed an optimization model for considering quality and transportation and determined optimal pricing decisions to minimize total cost for fresh food. Halim et al. (2008) introduced the ordering strategy of stochastic demand in cases of product shortage using a fuzzy number deterioration rate. In these studies, inventory management and pricing and ordering strategies were studied separately.

Some researches have considered the three factors in combination. Li et al. (2009) studied the optimal levels of pricing and inventory simultaneously for perishable products, developing an optimal inventory replenishment strategy to reduce loss.

Kanchanasuntorn and Techanitisawad (2006) developed an inventory model for perishable products with fixed life cycles, examining how product perishability and stockout influence supply chain profit, cost, service and inventory. Pasternack (2008) presented a hierarchical model to determine optimal pricing strategies and return policies for perishable products with short shelf or demand lives. Dong et al. (2009) determined optimal decisions for inventory and pricing when considering strategic consumers using a polynomial model. Herbon et al. (2014) examined a replenishment policy in regular time for perishable products and developed a dynamic pricing strategy to attract more consumers and generate greater profit. Chen et al. (2014) analysed the issue of joint pricing and inventory control for perishable products with fixed lifetimes over a finite horizon. Li et al. (2015) considered strategies of inventory control and joint dynamic pricing for perishable products in a stochastic inventory system. Chew et al. (2014) investigated optimal decision making for perishable products with multiple-cycle lifetimes, including decisions regarding price and order quantity. Avinadav et al. (2013) developed an optimization model for considering time-dependent and price-dependent demand and determined optimal order quantities, pricing decisions and replenishment periods for perishable products. Sainathan (2013) considered perishable products with two-period shelf lives in an infinite horizon and derived optimal pricing decisions and ordering strategies. None of these studies considered ways to coordinate FPSC with a contract.

The literature on FPSC contract coordination is very sparse. Most studies have focused on non-perishable products. Feng and Lu (2013) studied a two-echelon supply chain consisting of retailers and manufacturers and analysed contracting behaviours in different competitive scenarios. Xu et al. (2014) investigated how the risk aversion of dual-channel supply chain partners influences the coordination of contracts using a mean-variance mathematical model. Sommer and Loch (2009) suggested that employee effort can be motivated by incentive contracts in cases of unpredictable events. Xiao et al. (2011) examined how to coordinate the supply chain which contains a manufacturer and a retailer by revenue-sharing contract, proposed a product quality assurance policy, and consumer's utility is used in the model. Krishnan et al. (2004) investigated the effects of retailer promotional effort on consumer demand and develop a contract for channel coordination through consideration of this promotional effort. Shang and Yang (2015) investigated the choice of profit-sharing coefficient and the distribution of increased profit when the dual-channel supply chain is coordinated by profit-sharing contract, and risk preference and negotiation ability had an effect on the two factors. Jiang and Chen (2016) presented a newsvendor model to coordinate the supply chain, and characterized expectations equilibrium to obtain the optimal solutions when considering consumer's strategic behaviour. Lee et al., (2014) proposed procurement strategies and derived optimal procurement quantity so as to maximize firm's profit by forward contract, and finally realized the coordination of supply chain. Cachon and Lariviere (2005) developed a newsvendor model for one supplier and one retailer using a revenue-sharing contract and compared the profits generated by this contract to profits generated by other contracts in one period. He and Zhao (2012) investigated the coordination of multi-tier supply chains when supply and demand are not definite, showing that supply chains can be coordinated through wholesale price contracts with return strategies. Lau et al. (2008) suggested that purchase contracts are designed to coordinate supply chains when considering price-sensitive demand, thus allowing the dominant retailer to generate greater profit. Chen and Bell (2011) examined supply chain coordination with buy-back contracts using fixed percentages of consumer returns. Sana and Chaudhuri (2008) analysed how to coordinate supply chains to maximize profit using credit and price-discount contracts when considering time-dependent demands. Ma et al. (2013) discussed the issue of channel coordination in a two-tier supply chain, proposing an innovative supply chain contract to induce effort on the parts of both the retailer and the manufacturer. Xiao et al. (2010) coordinated a supply chain using a buyback contract and a markdown money contract, respectively, under a partial refund policy. Furthermore, they analysed how changes to some model parameters affected supply chain profit. However, their models did not consider the characteristics of fresh products.

A few studies have examined the coordination of FPSC in consideration of product loss rates. Ketzenberg and Ferguson (2008) investigated the value of information sharing between retailers and suppliers for perishable products, considering the effects of information sharing on deterioration and demand for supply chain coordination. Blackburn and Scudder (2009) presented a combined strategy involving mixed product speed and efficiency for perishable products to coordinate FPSC. Rong et al. (2011) modelled the production and distribution of perishable food items and studied their quality and cost in a supply chain with mixed-integer linear programming. Cai et al. (2013) designed an incentive scheme to coordinate the FPSC, examining whether the incentive contract could remove the "double marginalization" that exists in supply chains and encourage partners to act in a coordinated way. Wang and Webster (2009) showed that percent markdown money contracts and quantity markdown money contracts can coordinate the supply chains for perishable goods with clearance pricing. However, the extant literature has not yet simultaneously examined fresh-keeping cost sharing contracts and revenue-sharing contracts in the study of the FPSC coordination problem.

From the above review, it suggests: first, the food supply chain is a relative less studied area; second, taking freshness of the food into consideration is rather scarce; third, simultaneously examining fresh-keeping cost and revenue issues is rare. This motives our research in developing a model by taking these two tactics, i.e. fresh-keeping cost sharing and revenue-sharing, into consideration.

This paper examines the coordination of a two-echelon supply chain consisting of a retailer and a supplier by considering fresh-keeping effort as a decision variable in the modelling of supply chain. In this research, the supplier refers to the wholesaler. We present a mathematical model for the fresh-keeping effort and for price decisions in centralized and decentralized FPSC, respectively; provide optimal solutions for both supplier and retailer, including with respect to retail price, wholesale price and fresh-keeping effort; and analyse the impacts of consumer sensitivities to price and freshness on FPSC profit. We investigate how FPSC coordination and a win-win outcome can be achieved through cost-sharing and revenue-sharing contracts between retailer and supplier. We also derive the optimal cost-sharing and revenue-sharing coefficients to realize a win-win result. Figure 1 demonstrates the research framework for a FPSC.

Inset: Figure 1 Research Framework for a FPSC

The rest of the paper is organized as follows. Section 2 describes the model and assumptions. Section 3 studies a centralized and a decentralized coordination model for a FPSC coordinated without a contract. Section 4 investigates two types of contracts for coordinating between the retailer and the supplier: a fresh-keeping cost sharing contract and a fresh-keeping cost- and revenue-sharing contract. Section 5 uses some numerical examples to illustrate the model. Section 6 concludes.

2 Model description

We consider a FPSC consisting of one supplier and one retailer. It costs c per unit for the supplier to procure the product. The supplier then sells the product to the retailer at a wholesale price w, and the retailer sells the product to consumers at a retail price p. We use a continuous variable τ to measure the level of effort (Cai et al., 2010) used by the retailer to preserve the fresh product. This effort is called the fresh-keeping effort. The relationships of events in FPSC are presented in Figure 2.

Insert: Figure 2 Relationships of Events under Consideration

Let θ denotes a freshness index in the range of [0,1], with θ=1 and θ=0 representing a “fully fresh” and “completely decayed” product, respectively. We adopt the freshness index function developed by Avinadav et al. (2013):

$$\theta(t)=\theta_0-\eta\left(\frac{t}{T}\right)^{\frac{1}{2}},\quad t\in[0,T] \tag{1}$$

where T is the sale period of the fresh product; θ_0 is the initial value of freshness; and η is the product's perishability rate. From Eq. (1), we know that if the perishability rate η increases, the product freshness will decrease sharply at the end of the sale period.

Furthermore, η is a function of τ, as follows: $\eta=(1-k\tau)\eta_0$ (Dan et al., 2012), where k is the coefficient of τ, and $k\in(0,1)$, $\tau\in(0,1)$.

A fresh-keeping effort implies a certain cost, which is denoted as $c(\tau)$. According to Ma et al. (2013), we assume that the fresh-keeping cost function is $c(\tau)=\frac{1}{2}m\tau^2$, where m is the fresh-keeping cost coefficient.

The assumptions in the model are:

(1) Order quantity of retailer and supplier is equal to the demand (Ma et al., 2013a; Xiao and Xu, 2013; Zhang et al., 2012).

(2) In a sale period T, the consumer arrival rate δ at any time is constant.

(3) In any cycle, the lead time is negligible, and shortages are not allowed.

(4) The retailer and supplier are risk-neutral, therefore they always purse the maximum profit.

Similar to Xu et al. (2012), we assume that the utility faced by the consumer is a linear function of retail price and freshness of product. The utility function of fresh product is given as:

$$U(t)=U_0-\alpha p+\beta\theta(t) \tag{2}$$

where U_0 represents the initial value of the fresh product and follows a uniform distribution of $[0,1]$, α denotes consumers' sensitivity to the product price and β denotes consumers' sensitivity to the product freshness.

The following notation is used in the model:

c: supplier's procurement cost per unit of fresh product;

Q_c: retailer's ordering quantity in the centralized FPSC;

p_c: retail price of the fresh product in the centralized FPSC;

π_c: total profit in the centralized FPSC;

w_i: wholesale price of the supplier in the decentralized FPSC;

Q_d: retailer's ordering quantity in the decentralized FPSC;

p_d: retail price in the decentralized FPSC;

π_{ri}: retailer profit in the decentralized FPSC;

π_{si}: supplier profit in the decentralized FPSC;

π_i: total profit in the decentralized FPSC;

i: $i=1$ without a contract; $i=2$ for a fresh-keeping cost-sharing contract; $i=3$ for a fresh-keeping cost- and revenue-sharing contract.

3 A coordination model without contract

In this section, we examine the optimal decisions for retail price and fresh-keeping effort in a centralized and a decentralized FPSC without contract.

3.1 Decisions in centralized FPSC

In the centralized FPSC, the supplier and retailer are treated as one entity. They make optimal decisions to maximize their total profit.

From a consumer point of view, the decision to purchase a fresh product is based on the expectation of a positive utility function i.e. $U(t)>0$; otherwise, the consumer will walk away. Therefore, the market demand of a fresh product at any time t is $D(t)=\delta P(U_t>0)$. $P(U_t>0)$ is the probability when consumers' utility function is positive. Substituting Eq. (1) and Eq. (2) into the market demand function, we obtain:

$$\begin{aligned} D(t) &= \delta P(U_0-\alpha p_c+\beta(\theta_0-\eta(\frac{t}{T})^{\frac{1}{2}})>0) \\ &= \delta P(U_0>\alpha p_c-\beta(\theta_0-\eta(\frac{t}{T})^{\frac{1}{2}}))=\delta(1-\alpha p_c+\beta(\theta_0-\eta(\frac{t}{T})^{\frac{1}{2}})) \end{aligned} \tag{3}$$

Eq. (3) represents the whole market demand in the FPSC at any time. Therefore, in a sale period T, the actual ordering quantity of fresh product is:

$$Q_c=\int_0^T D(t)=\int_0^T \delta(1-\alpha p_c+\beta(\theta_0-\eta(\frac{t}{T})^{\frac{1}{2}}))dt \tag{4}$$

Then, the total profit function π_c in the centralized FPSC is given by:

$$\begin{aligned} \pi_c &= [(p_c-w)+(w-c)]Q_c-c(\tau) \\ &= (p_c-c)\int_0^T \delta(1-\alpha p_c+\beta(\theta_0-\eta(\frac{t}{T})^{\frac{1}{2}}))dt-\frac{1}{2}m\tau^2 \end{aligned} \tag{5}$$

In Eq. (5), we notice that wholesale price w disappears in the centralized FPSC. We seek to determine the optimal decisions for the price p_c and the fresh-keeping effort τ to coordinate the supply chain.

Theorem 1 In the centralized FPSC, for any given parameters $(\alpha, \beta, \eta_0, k)$, the optimal retail price of a fresh product is $p_c^*=\dfrac{3m(3\alpha c+B_1)+4B_2c}{2(9\alpha m-2B_2)}$ and the optimal fresh-keeping effort of the fresh product is $\tau_c^*=\dfrac{\delta\beta T\eta_0 k(B_1-3\alpha c)}{9\alpha m-2B_2}$, where $B_1=3(1+\beta\theta_0)-2\beta\eta_0$, $B_2=\delta T\beta^2\eta_0^2k^2$.

Proof.

To find the optimal retail price and fresh-keeping effort to maximize π_c, we differentiate π_c with respect to p_c and τ_c, setting both them equal to 0. Solving $\frac{\partial \pi_c}{\partial p_c}=0$ and $\frac{\partial \pi_c}{\partial \tau_c}=0$, we find that the optimal retail price is $p_c^*=\frac{3m(3\alpha c+B_1)+4B_2c}{2(9\alpha m-2B_2)}$ and the optimal fresh-keeping effort is $\tau_c^*=\frac{\delta\beta T\eta_0 k(B_1-3\alpha c)}{9\alpha m-2B_2}$.

However, to ensure that the first order derivation is the optimal result, we need to prove that the function is concave. The Hessian matrix is $H=\begin{bmatrix}\frac{\partial^2\pi_c}{\partial p_c^2} & \frac{\partial^2\pi_c}{\partial p_c\partial\tau_c}\\ \frac{\partial^2\pi_c}{\partial\tau_c\partial p_c} & \frac{\partial^2\pi_c}{\partial\tau_c^2}\end{bmatrix}=\begin{bmatrix}-2\alpha\delta T & \frac{2\eta_0\beta T\delta k}{3}\\ \frac{2\eta_0\beta T\delta k}{3} & -m\end{bmatrix}$. This shows that the Hessian matrix of π_c is a negative definite for all values of p_c and τ_c if $2\alpha\delta Tm-(\frac{2\eta_0\beta T\delta k}{3})^2>0$. Therefore, total profit π_c is concave to p_c and τ_c. Hence, theorem 1 holds.

Substituting p_c and τ_c into Eq. (5), we obtain the optimal total profit in centralized FPSC as follows:

$$\pi_c^*=\frac{\delta Tm(B_1-3\alpha c)^2}{4(9\alpha m-2B_2)} \tag{6}$$

Since $2\alpha\delta Tm-(\frac{2\eta_0\beta T\delta k}{3})^2>0$, we can obtain $9\alpha m-2T\delta(\eta_0\beta k)^2>0$, which is $9\alpha m-2B_2>0$. Therefore, the optimal total profit is positive.

Note that $9\alpha m-2B_2>0$ is considered in the rest paper. In addition, the optimal fresh-keeping effort $\tau_c^*\in(0,1)$; thus, we can derive that $0<B_1-3\alpha c<\frac{9\alpha m-2B_2}{\delta\beta T\eta_0 k}$.

3.2 Decisions in decentralized FPSC

In this subsection, we consider a decentralized supply chain in which the retailer and supplier make their decisions independently. This section aims to determine the optimal retail price, the optimal fresh-keeping effort and the optimal wholesale price to maximize expected individual profit.

3.2.1 Optimal decisions of the fresh product retailer

In the decentralized FPSC, the retailer makes optimal decisions according to the wholesale price w_1, which is given by the supplier. The retailer's process of deducing its market demand function and ordering quantity function is similar to that in the centralized supply chain. Thus, the profit function of a fresh product retailer is:

$$\begin{aligned}\pi_{r1} &= (p_d - w_1)Q_d - c(\tau) \\ &= (p_d - w_1)\int_0^T \delta(1-\alpha p_d + \beta(\theta_0 - (1-k\tau)\eta_0(\frac{t}{T})^{\frac{1}{2}}))dt - \frac{1}{2}m\tau^2\end{aligned} \tag{7}$$

From Eq. (7), we can obtain the optimal retail price and the optimal fresh-keeping effort.

Lemma 1 In the decentralized FPSC, for any given supplier's wholesale price w_1, the optimal retail price is $p_d^*(w_1) = \dfrac{3m(3\alpha w_1 + B_1) + 4B_2 w_1}{2(9\alpha m - 2B_2)}$ and the optimal fresh-keeping effort is $\tau_d^*(w_1) = \dfrac{\delta\beta T\eta_0 k(B_1 - 3\alpha w_1)}{9\alpha m - 2B_2}$.

Proof.

As in the proof of Theorem 1, to find the optimal retail price and the optimal fresh-keeping effort to maximize π_{r1}, we differentiate π_{r1} with respect to p_d and τ_d, respectively, setting these equal to 0.

The Hessian matrix is $H=\begin{bmatrix} -2\alpha\delta T & \frac{2\eta_0\beta T\delta k}{3} \\ \frac{2\eta_0\beta T\delta k}{3} & -m \end{bmatrix}$. This shows that the Hessian matrix of π_{r1} returns a negative definite for all values of p_d and τ_d if $2\alpha\delta Tm-(\frac{2\eta_0\beta T\delta k}{3})^2>0$. Therefore, we find that the optimal retail price is $p_d^*(\tau_d)=\frac{3(\beta\theta_0+\alpha w_1+1)-2\beta\eta_0(1-k\tau_d)}{6\alpha}$ and the optimal fresh-keeping effort is $\tau_d^*(p_d)=\frac{2(p_d-w_1)\beta\eta_0 T\delta k}{3m}$. Simultaneously, from the two equations, we can obtain

$p_d^*(w_1)=\frac{3m(3\alpha w_1+B_1)+4B_2 w_1}{2(9\alpha m-2B_2)}$ and $\tau_d^*(w_1)=\frac{\delta\beta T\eta_0 k(B_1-3\alpha w_1)}{9\alpha m-2B_2}$.

Lemma 1 shows that the optimal retail price and the optimal fresh-keeping effort are functions of the supplier's wholesale price w_1. The supplier determines its optimal wholesale price according to the retailer's reaction function.

3.2.2 Optimal decisions of the fresh product supplier

For any given wholesale price w_1 of a fresh product supplier, the retailer has a corresponded ordering quantity. The profit function of a fresh product supplier is:

$$\begin{aligned}\pi_{s1}&=(w_1-c)Q_d\\&=(w_1-c)\int_0^T\delta(1-\alpha p_d+\beta(\theta_0-(1-k\tau_d)\eta_0(\frac{t}{T})^{\frac{1}{2}}))dt\end{aligned}\tag{8}$$

Substituting $p_d^*(w_1)$ and $\tau_d^*(w_1)$ into Eq. (8), we obtain the optimal supplier profit in the decentralized FPSC. The profit function has only one decision variable: w_1.

Lemma 2 In the decentralized FPSC, the optimal wholesale price of a fresh product supplier is $w_1^*=\frac{3m(B_1+3\alpha c)+2B_2 c}{2(9\alpha m-B_2)}$.

Proof.

Taking the first derivative of Eq. (8) with respect to wholesale price w_1, we set it equal to 0. Taking the second derivative of Eq. (8) with respect to w_1, we have $\frac{\partial^2 \pi_{s1}}{\partial w_1^2} = -\delta\alpha T < 0$, which is the fresh product supplier's profit function π_{s1} and which is concave to w_1. Therefore, we find that the optimal wholesale price is $w_1^* = \frac{3m(B_1 + 3\alpha c) + 2B_2 c}{2(9\alpha m - B_2)}$.

Lemma 2 gives an optimal wholesale price w_1^*. By substituting w_1^* into Lemma 1, we can obtain the optimal retail price and the optimal fresh-keeping effort.

Theorem 2 In the decentralized FPSC, the optimal retail price of the fresh product is $p_d^* = \frac{9m(B_1 + 3\alpha c) + 4B_2 c}{4(9\alpha m - B_2)}$ and the optimal fresh-keeping effort of fresh product is $\tau_d^* = \frac{\delta\beta T\eta_0 k_1 (B_1 - 3\alpha c)}{2(9\alpha m - B_2)}$.

Proof.

Substituting the optimal wholesale price of the fresh product supplier $w_1^* = \frac{3m(B_1 + 3\alpha c) + 2B_2 c}{2(9\alpha m - B_2)}$ into $p_d^*(w_1)$ and $\tau_d^*(w_1)$, we obtain $p_d^* = \frac{9m(B_1 + 3\alpha c) + 4B_2 c}{4(9\alpha m - B_2)}$ and $\tau_d^* = \frac{\delta\beta T\eta_0 k (B_1 - 3\alpha c)}{2(9\alpha m - B_2)}$.

Substituting p_d^*, τ_d^* and w_1^* into (7) and (8), we obtain the retailer's optimal profit and the supplier's optimal profit in the decentralized FPSC:

$$\pi_{r1}^* = \frac{\delta T m (9\alpha m - 2B_2)(B_1 - 3\alpha c)^2}{16(9\alpha m - B_2)^2} \tag{9}$$

$$\pi_{s1}^* = \frac{9\delta\alpha T m^2 (B_1 - 3\alpha c)^2}{8(9\alpha m - B_2)^2} \tag{10}$$

Because $9\alpha m-2B_2>0$, as given previously, we know that $B_2=\delta T\beta^2\eta_0^2 k_1^2>0$. Hence, $9\alpha m-B_2>0$; therefore, $p_d^*>0$. Similarly, the optimal fresh-keeping effort $\tau_c^*\in(0,1)$, $\tau_d^*=\dfrac{\delta\beta T\eta_0 k_1(B_1-3\alpha c)}{2(9\alpha m-B_2)}$; thus, we only consider the situation in which $0<B_1-3\alpha c<\dfrac{9\alpha m-2B_2}{\delta\beta T\eta_0 k}<\dfrac{9\alpha m-B_2}{\delta\beta T\eta_0 k}$.

3.2.3 Comparison of centralized and decentralized decisions

In the above discussions, Theorem 1 provides the optimal retail price and the optimal fresh-keeping effort for a centralized FPSC, while Theorem 2 provides the optimal retail price and the optimal fresh-keeping effort for a decentralized FPSC. We can obtain Proposition 1 by contrasting the centralized supply chain and the decentralized supply chain with regard to optimal retail price, optimal fresh-keeping effort and total profit.

Proposition 1 1） $\tau_d^*<\tau_c^*$;

2）when $2B_2<9\alpha m<4B_2$, $p_d^*<p_c^*$; when $9\alpha m>4B_2$, $p_d^*>p_c^*$;

3） $\pi_{r1}^*+\pi_{s1}^*<\pi_c^*$.

Proof.

1) $\tau_d^*-\tau_c^*=\dfrac{\delta\beta T\eta_0 k(B_1-3\alpha c)}{2(9\alpha m-B_2)}-\dfrac{\delta\beta T\eta_0 k(B_1-3\alpha c)}{9\alpha m-2B_2}$. Since the numerator is same, the denominator $2(9\alpha m-B_2)=18\alpha m-2B_2>9\alpha m-2B_2$. Thus, we get $\tau_d^*-\tau_c^*<0$. Therefore, $\tau_d^*<\tau_c^*$.

2) $9\alpha m-2B_2>0$ has been previously given. The retail price is positive; thus, $9\alpha m-B_2>0$. Therefore:

$$p_d^* - p_c^* = \frac{9m(3\alpha c + B_1) + 4B_2 c}{4(9\alpha m - B_2)} - \frac{3m(3\alpha c + B_1) + 4B_2 c}{2(9\alpha m - 2B_2)}$$
$$= \frac{9m(9\alpha m - 4B_2)(B_1 - 3\alpha c)}{2(9\alpha m - B_2)(9\alpha m - 2B_2)}$$

Then, we find that when $9\alpha m - 4B_2 > 0$, $p_d^* > p_c^*$, while when $9\alpha m - 4B_2 < 0$, $2B_2 < 9\alpha m < 4B_2$ and $p_d^* < p_c^*$.

3) Using the sum of the retailer's profit (Eq. [9]) and the supplier's profit (Eq. [10]), we can determine the total profit of the decentralized FPSC. $\pi_{r1}^*(p_d^*, \tau_d^*) + \pi_{s1}^*(p_d^*, \tau_d^*) = \frac{\delta T m (B_1 - 3\alpha c)^2 (27\alpha m - 2B_2)}{16(9\alpha m - B_2)^2}$, $\pi_c^*(p_c^*, \tau_c^*)$ is the total profit of the centralized FPSC. Therefore,

$$\frac{\pi_c^*(p_c^*, \tau_c^*)}{\pi_{r1}^*(p_d^*, \tau_d^*) + \pi_{s1}^*(p_d^*, \tau_d^*)} = \frac{4(9\alpha m - B_2)^2}{(9\alpha m - 2B_2)(27\alpha m - 2B_2)} = \frac{324\alpha^2 m^2 - 72\alpha m B_2 + 4B_2^2}{243\alpha^2 m^2 - 72\alpha m B_2 + 4B_2^2} > 1,$$

giving us: $\pi_{r1}^*(p_d^*, \tau_d^*) + \pi_{s1}^*(p_d^*, \tau_d^*) < \pi_c^*(p_c^*, \tau_c^*)$.

Proposition 1 indicates that the total profit of a decentralized FPSC is less than that of a centralized FPSC. The optimal fresh-keeping effort in a decentralized supply chain is lower than that in a centralized supply chain. This suggests that, in a decentralized FPSC, the total profit is not optimal due to the double marginal effect of supply chain. Therefore, it is necessary to design proper contracts to coordinate FPSC.

We highlight that a decision to centralize may achieve maximum profit. In the following sections, we take π_c as a target for a decentralized supply chain, serving as the motivation behind the supplier-retailer contract, that is, both retailer and supplier intend to achieve individual maximised profit whilst also maximised total profit in the supply chain.

4 Contracting to facilitate coordination

In this section, we first examine whether the fresh-keeping cost-sharing contract is effective or not. Then, we investigate the best way to coordinate the FPSC by sharing both costs and revenues in fresh-keeping contracts. It is expected that the FPSC will be more effective if it is bonded by a contract. It is also understandable that parties will accept such a contract only when they do not need to scarify their own profit (compared to situations with no contract).

4.1 Fresh-keeping cost-sharing contract

From Proposition 1, we know that $\tau_d^* < \tau_c^*$. Therefore, to achieve the optimal fresh-keeping effort τ_c^* in the decentralized supply chain, a retailer must pay a higher fresh-keeping cost; however, the supplier may not have enough motivation to do this. Thus, it is necessary to design a cost-sharing contract to coordinate both parties.

A cost-sharing contract typically includes two parameters. The first is the wholesale price w_2, which the retailer pays. The second is the cost-sharing coefficient of the supplier, represented by φ_1 ($0 < \varphi_1 < 1$).

According to the above description, we know that the profit function of retailer is

$$\begin{aligned}\pi_{r2} &= (p_d - w_2)Q_d - (1-\varphi_1)c(\tau) \\ &= (p_d - w_2)\int_0^T \delta(1-\alpha p_d + \beta(\theta_0 - (1-k\tau_d)\eta_0(\frac{t}{T})^{\frac{1}{2}}))dt - \frac{1}{2}(1-\varphi_1)m\tau_d^2\end{aligned} \quad (11)$$

The profit function of the supplier is

$$\begin{aligned}\pi_{s2} &= (w_2 - c)Q_d - \varphi_1 c(\tau) \\ &= (w_2 - c)\int_0^T \delta(1-\alpha p_d + \beta(\theta_0 - (1-k\tau_d)\eta_0(\frac{t}{T})^{\frac{1}{2}}))dt - \frac{1}{2}\varphi_1 m\tau_d^2\end{aligned} \quad (12)$$

Based on the above, we can derive Theorem 3.

Theorem 3 Under the fresh-keeping cost-sharing contract, for any given fresh-keeping cost sharing coefficient φ_1, the optimal retail price is $p_d^* = \frac{9m(1-\varphi_1)(B_1+3\alpha c)+4B_2 c}{4(9(1-\varphi_1)\alpha m - B_2)}$, and the optimal fresh-keeping effort is $\tau_d^* = \frac{\delta\beta T\eta_0 k(B_1-3\alpha c)}{2(9(1-\varphi_1)\alpha m - B_2)}$.

Proof.

Taking the second derivative of Eq. (11) with respect to p_d and τ_d, we get $\frac{\partial^2\pi_{r2}}{\partial p_d^2} = -2\delta\alpha T < 0$, $\frac{\partial^2\pi_{r2}}{\partial\tau_d^2} = -m(1-\varphi_1) < 0$. The Hessian matrix is $H = \begin{bmatrix} -2\alpha\delta T & \frac{2\eta_0\beta T\delta k}{3} \\ \frac{2\eta_0\beta T\delta k}{3} & -m(1-\varphi_1) \end{bmatrix}$. This shows that the Hessian matrix of π_{r2} is a negative definite for all values of p_d and τ_d if $2\alpha\delta Tm(1-\varphi_1) - (\frac{2\eta_0\beta T\delta k}{3})^2 > 0$. Therefore, we find that, if π_{r2} is concave in p_d and τ_d, the optimal solution exists.

Similarly, taking the second derivative of Eq. (12) with respect to w_2, we get $\frac{\partial^2\pi_{s2}}{\partial w_2^2} = -\delta\alpha T < 0$. Here, if π_{s2} is concave in w_2, the optimal solution also exists. Hence, by solving $\frac{\partial\pi_{s2}}{\partial w_2} = 0$ first, then substitute w_2 into $\frac{\partial\pi_{r2}}{\partial p_d} = 0$, $\frac{\partial\pi_{r2}}{\partial\tau_d} = 0$, we can develop the fresh-keeping cost-sharing contract. For any given fresh-keeping cost-sharing coefficient φ_1, the optimal retail price of the fresh product retailer is $p_d^* = \frac{9m(1-\varphi_1)(B_1+3\alpha c)+4B_2 c}{4(9(1-\varphi_1)\alpha m - B_2)}$ and the optimal fresh-keeping effort is $\tau_d^* = \frac{\delta\beta T\eta_0 k(B_1-3\alpha c)}{2(9(1-\varphi_1)\alpha m - B_2)}$.

Theorem 3 gives the optimal retail price and fresh-keeping effort for FPSC. Substituting p_d^* and τ_d^* into Eq. (11) and (12), we derive the optimal profit for both retailer and supplier respectively.

$$\pi_{r2}^* = \frac{\delta Tm(9(1-\varphi_1)^2\alpha m - 2B_2)(B_1 - 3\alpha c)^2}{16(9(1-\varphi_1)\alpha m - B_2)^2} \tag{13}$$

$$\pi_{s2}^* = \frac{\delta Tm(9(1-\varphi_1)^2\alpha m - \varphi_1 B_2)(B_1 - 3\alpha c)^2}{8(9(1-\varphi_1)\alpha m - B_2)^2} \tag{14}$$

In the cost sharing contract, the retailer has significant motivation to engage in fresh-keeping effort because part of cost is supposedly shared by the supplier. Let the optimal fresh-keeping effort is the same as in the centralized supply chain i.e., $\tau_d^* = \tau_c^*$. By comparing the optimal decisions under the fresh-keeping cost-sharing contract for the scenario of a centralized decision without a contract, we derive Proposition 2.

Proposition 2

When $\tau_d^* = \tau_c^*$, 1) $p_d^* > p_c^*$; 2) $\pi_{r2}^* + \pi_{s2}^* < \pi_c^*$.

Proof.

1) From $\tau_d^* = \dfrac{\delta\beta T\eta_0 k(B_1 - 3\alpha c)}{2(9(1-0.5)\alpha m - B_2)} = \dfrac{\delta\beta T\eta_0 k(B_1 - 3\alpha c)}{9\alpha m - 2B_2} = \tau_c^*$, we get $\varphi_1 = 0.5$.

Therefore, $p_d^* = \dfrac{9m(1-0.5)(B_1 + 3\alpha c) + 4B_2 c}{4(9(1-0.5)\alpha m - B_2)} > \dfrac{3m(3\alpha c + B_1) + 4B_2 c}{2(9\alpha m - 2B_2)} = p_c^*$. Hence, $p_d^* > p_c^*$.

2) Then, we can derive the total profit:

$$\pi_{r2}^* + \pi_{s2}^* = \frac{\delta Tm(9(1-0.5)^2\alpha m - 2B_2)(B_1 - 3\alpha c)^2}{16(9(1-0.5)\alpha m - B_2)^2} + \frac{\delta Tm(9(1-0.5)^2\alpha m - 0.5B_2)(B_1 - 3\alpha c)^2}{8(9(1-0.5)\alpha m - B_2)^2}$$

$$= \frac{\delta Tm(B_1 - 3\alpha c)^2(6.75\alpha m - 3B_2)}{16(4.5\alpha m - B_2)^2}$$

Therefore, $\frac{\pi_c^*}{\pi_{r2}^* + \pi_{s2}^*} > 1$. Hence, $\pi_{r2}^* + \pi_{s2}^* < \pi_c^*$.

Proposition 2 shows that the retail price under the fresh-keeping cost-sharing contract is higher than that in a centralized supply chain, and the total profit is lower than that without a contract. Therefore, it is useful for retailer to improve their fresh-keeping effort through fresh-keeping cost-sharing contracts; however, the FPSC cannot be coordinated under fresh-keeping cost-sharing contract. Thus, we must consider how to maximize profits by adding a revenue-sharing contract.

4.2 Fresh-keeping cost- and revenue-sharing contract

To achieve the optimal retail price and the same fresh-keeping effort as well as total profit as in the centralized supply chain, we consider a case in which a supplier offers a discount to a retailer (apart from sharing the fresh-keeping cost). In such a case, the retailer may be willing to reduce the price due to the lower procurement price, and it may also be willing to share some revenue with the supplier.

Fresh-keeping cost- and revenue-sharing contracts include three parameters. The first is the wholesale price w_3 that the retailer pays. The second is the cost share coefficient of the supplier, represented by φ_1 ($0 < \varphi_1 < 1$). The third is the revenue share coefficient of supplier, represented by φ_2 ($0 < \varphi_2 < 1$).

According to the above descriptions, we know that the profit function of the retailer is as follows:

$$\begin{aligned}\pi_{r3} &= \left(1-\varphi_2\right) p_d Q_d - w_3 Q_3 - \left(1-\varphi_1\right) c\left(\tau\right) \\ &= \left(\left(1-\varphi_2\right) p_d - w_3\right) \int_0^T \delta \left(1 - \alpha p_d + \beta \left(\theta_0 - \left(1-k\tau_d\right)\eta_0 \left(\frac{t}{T}\right)^{\frac{1}{2}}\right)\right) dt - \frac{1}{2}\left(1-\varphi_1\right) m\tau_d^2\end{aligned} \tag{15}$$

Then, the profit function of the supplier is:

$$\pi_{s3} = \varphi_2\, p_d\, Q_d + (w_3 - c)Q_d - \varphi_1\, c(\tau)$$
$$= (w_3 - c + \varphi_2\, p_d)\int_0^T \delta\left(1 - \alpha\, p_d + \beta\left(\theta_0 - (1 - k\,\tau_d)\eta_0\left(\frac{t}{T}\right)^{\frac{1}{2}}\right)\right)dt - \frac{1}{2}\varphi_1\, m\,\tau_d^2 \qquad (16)$$

Based on the above, we can derive Theorem 4.

Theorem 4 Under the fresh-keeping cost- and revenue-sharing contract, for any given wholesale price w_3, fresh-keeping cost-sharing coefficient φ_1 and revenue-sharing coefficient φ_2, the optimal retail price of a fresh product retailer is $p_d^*(\tau_d^*) = \dfrac{3(1-\varphi_2)(\beta\theta_0+1) - 2(1-\varphi_2)\beta\eta_0(1-k\tau_d) + 3w_3\alpha}{6(1-\varphi_2)\alpha}$ and the optimal fresh-keeping effort is $\tau_d^*(p_d^*) = \dfrac{2((1-\varphi_2)p_d^* - w_3)\beta\eta_0 T\delta k}{3(1-\varphi_1)m}$.

Proof.

Taking the second derivative of Eq. (15) with respect to p_d and τ_d, we have $\dfrac{\partial^2\pi_{r3}}{\partial\tau_d^2} = -(1-\varphi_1)m < 0$, $\dfrac{\partial^2\pi_{r3}}{\partial p_d^2} = -2(1-\varphi_2)\delta\alpha T < 0$. The Hessian matrix is $H = \begin{bmatrix} -2(1-\varphi_2)\alpha\delta T & \dfrac{2(1-\varphi_2)\eta_0\beta T\delta k}{3} \\ \dfrac{2(1-\varphi_2)\eta_0\beta T\delta k}{3} & -m(1-\varphi_1) \end{bmatrix}$. This shows that the Hessian matrix of π_{r3} returns a negative definite for all values of p_d and τ_d if $2\alpha\delta Tm(1-\varphi_1) - (\dfrac{2\eta_0\beta T\delta k}{3})^2 > 0$. Therefore, we find that π_{r2} is concave in p_d and τ_d, suggesting that the optimal solution exists.

Hence, solving $\dfrac{\partial\pi_{r3}}{\partial\tau_d} = 0$ and $\dfrac{\partial\pi_{r3}}{\partial p_d} = 0$, we can derive the optimal retail price $p_d^*(\tau_d^*) = \dfrac{3(1-\varphi_2)(\beta\theta_0+1) - 2(1-\varphi_2)\beta\eta_0(1-k\tau_d) + 3w_3\alpha}{6(1-\varphi_2)\alpha}$ and the optimal fresh-keeping effort $\tau_d^*(p_d^*) = \dfrac{2((1-\varphi_2)p_d^* - w_3)\beta\eta_0 T\delta k}{3(1-\varphi_1)m}$.

Let $p_d^* = p_c^*$ and $\tau_d^* = \tau_c^*$. It is then necessary to adjust the wholesale price w_3 to facilitate coordination, leading us to theorem 5.

Theorem 5 If the fresh-keeping cost- and revenue-sharing contract $(\varphi_1, \varphi_2, w_3)$ is satisfied by $\varphi_1 = \varphi_2$, $w_3 = (1-\varphi_2)c$ and $\dfrac{9\alpha m(9\alpha m - 2B_2)}{2(9\alpha m - B_2)^2} \le \varphi_2 \le 1 - \dfrac{(9\alpha m - 2B_2)^2}{4(9\alpha m - B_2)^2}$, then $\pi_{r3}^* + \pi_{s3}^* = \pi_c^*$ is achieved, and the FPSC can be coordinated.

Proof.

Let $p_d^* = p_c^*$; that is $\dfrac{w_3}{2(1-\varphi_2)} = \dfrac{c}{2}$. Thus, we obtain $w_3 = c(1-\varphi_2)$.

Similarly, let $\tau_d^* = \tau_c^*$; thus, we obtain $\dfrac{(1-\varphi_2)p_d^* - w_3}{1-\varphi_1} = p_c^* - c$. That is, $(1-\varphi_2)(p_d^* - c) = (1-\varphi_1)(p_c^* - c)$; therefore, $\varphi_1 = \varphi_2$.

Substituting $\varphi_1 = \varphi_2$, $w_3 = c(1-\varphi_2)$ and p_c^* and τ_c^* into Eq. (15) and Eq. (16), we derive the optimal total profit of the retailer as follows:

$$\pi_{r3}^* = \frac{(1-\varphi_2)\delta Tm(B_1 - 3\alpha c)^2}{4(9\alpha m - 2B_2)} \tag{17}$$

The optimal total profit of supplier is:

$$\pi_{s3}^* = \frac{\varphi_2 \delta Tm(B_1 - 3\alpha c)^2}{4(9\alpha m - 2B_2)} \tag{18}$$

Comparing Eq. (17) and Eq. (18) with Eq. (9) and Eq. (10), we get $\dfrac{9\alpha m(9\alpha m - 2B_2)}{2(9\alpha m - B_2)^2} \le \varphi_2 \le 1 - \dfrac{(9\alpha m - 2B_2)^2}{4(9\alpha m - B_2)^2}$.

Then, the total profit under the fresh-keeping cost- and revenue-sharing contract is:

$$\pi_3^* = \pi_{r3}^* + \pi_{s3}^* = \frac{(1-\varphi_2)\delta Tm(B_1-3\alpha c)^2}{4(9\alpha m-2B_2)} + \frac{\varphi_2 \delta Tm(B_1-3\alpha c)^2}{4(9\alpha m-2B_2)} = \frac{\delta Tm(B_1-3\alpha c)^2}{4(9\alpha m-2B_2)} \quad (19)$$

It is equal to the total profit π_c^* in the centralized FPSC. Thus, $\pi_{r3}^* + \pi_{s3}^* = \pi_c^*$, and the fresh-keeping cost- and revenue-sharing contract makes sense.

Comparing the retailer's profit under cost- and revenue- sharing contract with the case in decentralized FPSC, we get

$$\pi_{r3}^* - \pi_{r1}^* = \frac{(1-\varphi_1)\delta Tm(B_1-3\alpha c)^2}{4(9\alpha m-2B_2)} - \frac{\delta Tm(9\alpha m-2B_2)(B_1-3\alpha c)^2}{16(9\alpha m-B_2)^2}$$
$$= \delta Tm(B_1-3\alpha c)^2\left[\frac{(1-\varphi_1)}{4(9\alpha m-2B_2)} - \frac{(9\alpha m-2B_2)}{16(9\alpha m-B_2)^2}\right]$$

Because of $\varphi_1 \in \left[\frac{9\alpha m(9\alpha m-2B_2)}{2(9\alpha m-B_2)^2},\ 1-\frac{(9\alpha m-2B_2)^2}{4(9\alpha m-B_2)^2}\right]$, $1-\varphi_1 \ge \frac{(9\alpha m-2B_2)^2}{4(9\alpha m-B_2)^2}$. Therefore, $\pi_{r3}^* - \pi_{r1}^* \ge 0$. That is the retailer under cost- and revenue- sharing contract can earn more profit than the case in decentralized FPSC.

Similarly, $\pi_{s3}^* - \pi_{s1}^* = \frac{\varphi_2 \delta Tm(B_1-3\alpha c)^2}{4(9\alpha m-2B_2)} - \frac{9\alpha\delta Tm(B_1-3\alpha c)^2}{8(9\alpha m-B_2)^2}$

$$= \delta Tm(B_1-3\alpha c)^2\left[\frac{\varphi_2}{4(9\alpha m-2B_2)} - \frac{9\alpha}{8(9\alpha m-B_2)^2}\right]$$

Because of $\varphi_2 \in \left[\frac{9\alpha m(9\alpha m-2B_2)}{2(9\alpha m-B_2)^2},\ 1-\frac{(9\alpha m-2B_2)^2}{4(9\alpha m-B_2)^2}\right]$, $\varphi_2 \ge \frac{9\alpha m(9\alpha m-2B_2)}{2(9\alpha m-B_2)^2}$. Hence, $\pi_{s3}^* - \pi_{s1}^* \ge 0$. That is the supplier under cost- and revenue- sharing contract can earn more profit than the case in decentralized FPSC.

Theorem 5 indicates that when the cost-sharing coefficient φ_1 is equal to the revenue-sharing coefficient φ_2, and they are all in the range of $\left[\frac{9\alpha m(9\alpha m-2B_2)}{2(9\alpha m-B_2)^2},\ 1-\frac{(9\alpha m-2B_2)^2}{4(9\alpha m-B_2)^2}\right]$, the FPSC can be coordinated by the fresh-keeping cost- and revenue-sharing contract and that a win-win situation between the fresh product retailer and supplier can be achieved. A comparison of the FPSC profits shows that all parties incur higher profits in the cost- and revenue-sharing contract in comparison to the decentralized case. Consequently, the retailer and the supplier have enough motivation to accept cost- and revenue- sharing contract.

We now discuss how the cost- and revenue- sharing contract can be implemented in practice.

The supplier and the retailer first agree on cost- and revenue- sharing contract $(\varphi_1, \varphi_2, w_3)$, the supplier can observe the optimal retail price and the optimal fresh-keeping effort which determined by retailer. As for Q, the supplier can conduct a check of the ordering quantity when the contract is reached. The wholesale price can then be determined by $w_3 = (1-\varphi_2)c$. According to the contract, the fresh-keeping cost sharing proportion of supplier is φ_1, the retailer's proportion is $(1-\varphi_1)$; the revenue sharing proportion of supplier is φ_2, the retailer's proportion is $(1-\varphi_2)$; where $\varphi_1 = \varphi_2$, they are in the range of $\left[\frac{9\alpha m(9\alpha m-2B_2)}{2(9\alpha m-B_2)^2}, 1-\frac{(9\alpha m-2B_2)^2}{4(9\alpha m-B_2)^2}\right]$.

Corollary 1 Under the fresh-keeping cost- and revenue-sharing contract $(\varphi_1, \varphi_2, w_3)$, if consumers' sensitivity to the price of product α is greater, the FPSC will be difficult to coordinate. However if consumers' sensitivity to the freshness of product β is greater, the FPSC will be easy to coordinate.

Proof.

According to Theorem 5 $\varphi_2 \in [\frac{9\alpha m(9\alpha m-2B_2)}{2(9\alpha m-B_2)^2}, 1-\frac{(9\alpha m-2B_2)^2}{4(9\alpha m-B_2)^2}]$, denoting as $\varphi_2 \in [\varphi_{2min}, \varphi_{2max}]$. Taking the first derivative of φ_{2min} with respect to α, we get

$\frac{\partial \varphi_{2min}}{\partial \alpha} = \frac{9mB_2^2}{(9\alpha m - B_2)^3} > 0$; that is, φ_{2min} is positively related to α. Taking the first derivative of φ_{2max} with respect to α, we get $\frac{\partial \varphi_{2max}}{\partial \alpha} = -\frac{9(9\alpha m - 2B_2)mB_2}{2(9\alpha m - B_2)^3} < 0$; that is φ_{2max} is negatively correlated to α. Therefore, the range of φ_2 is decreasing with an increasing α when $\varphi_2 \in [\varphi_{2min}, \varphi_{2max}]$. In other words, the revenue-sharing coefficient of the fresh product supplier is negatively correlated with consumers' sensitivity to price, making the supplier unwilling to accept the contract and the FPSC difficult to coordinate.

Similarly, $\frac{\partial \varphi_{2min}}{\partial \beta} = -\frac{18\alpha m B_2^2}{\beta(9\alpha m - B_2)^3} < 0$, $\frac{\partial \varphi_{2max}}{\partial \beta} = \frac{9\alpha m(9\alpha m - 2B_2)B_2}{\beta(9\alpha m - B_2)^3} > 0$. Therefore, the range of φ_2 is increasing with the increasing β when $\varphi_2 \in [\varphi_{2min}, \varphi_{2max}]$. In other words, the revenue-sharing coefficient of the fresh product supplier is positively related to consumers' sensitivity to freshness, making the supplier willing to accept the contract and the FPSC easy to coordinate.

From Theorem 5 and Corollary 1, we know that it is necessary to choose the proper conditions when negotiating a contract. The total FPSC profit is positively related with consumers' sensitivity to product price and negatively correlated with consumers' sensitivity to product freshness.

5 Numerical analysis

In the above sections, we theoretically discuss how to coordinate the FPSC under a contract situation and a non-contract contract situation and then explore the differences between the centralized FPSC and the decentralized FPSC. To illustrate the theoretical results, we present some numerical examples in this section. The parameters are summarized in Table 1.

Insert Table 1 Parameters

Using the parameters in Table 1, we apply them into previously analysed scenarios.

Insert Figure 3 Optimal decisions under different preferences without a contract

The results in Figure 3 verify Theorems 1 and 2 and Proposition 1. They show the optimal retail price and the optimal fresh-keeping effort between the centralized FPSC and the decentralized FPSC. Figure 3.1 & 3.4 indicate that the optimal fresh-keeping effort in a centralized supply chain is higher than that in a decentralized supply chain. Figure 3.2 & 3.5 illustrate that that the optimal retail price in a centralized supply chain is lower than that in a decentralized supply chain. Figure 3.3 & 3.6 demonstrate that the optimal total profit in a centralized supply chain is greater than that in a decentralized supply chain. In sum, the optimal decisions in the centralized FPSC are better than those in the decentralized FPSC.

Insert Figure 4 Optimal decisions and profits under the fresh-keeping cost-sharing contract

From Figure 4, we can see that the optimal fresh-keeping effort under the fresh-keeping cost-sharing contract is the same as that found in the centralized FPSC (Figure 4.1 & 4.4). However, the retailer price is higher than that in the centralized FPSC (Figure 4.2 & 4.5); and the total profit is lower (Figure 4.3 & 4.6). Therefore, the FPSC cannot be coordinated via a fresh-keeping cost-sharing contract.

Insert Figure 5 Optimal decisions and profits under the fresh-keeping cost- and revenue-sharing contract

Figure 5 reveals the optimal decisions and profits under the fresh-keeping cost- and revenue-sharing contract. These findings confirm Theorems 4 and 5. By comparing the results in Figure 3.1 & 3.4 with Figure 5.1 & 5.4, and Figure 3.2 & 3.5 with Figure 5.2 & 5.5, it becomes clear that the optimal fresh-keeping effort and retail price under the fresh-keeping cost- and revenue-sharing contract achieve the level of the centralized FPSC; the individual profit is higher than those in other two scenarios. Moreover, from Figure 5.3 & 5.6, it can be seen that the total profit is the same as that in the centralized supply chain.

Insert Figure 6. The effects of consumers' sensitivity to price and freshness on profit

Based on Corollary 1, we can illustrate the effects of consumers' sensitivity to price and freshness on profit, which is depicted in Figure 6. We know that the optimal profit that under the fresh-keeping cost- and revenue-sharing contract achieve the level of the centralized FPSC. From Figure 6, it is clear that the FPSC profit increases with the increasing of consumers' sensitivity to product freshness, and it decreases with the increasing of consumers' sensitivity to product price.

Our analysis thus reveals that from the product's fresh-keeping perspective, cost- and revenue- sharing contract offered by the retailer or obtained through negotiation leads to a higher fresh-keeping effort in FPSC, brings more profit to both supplier and retailer. The results explain the reason why supplier and retailer would prefer cost- and revenue- sharing contract under fresh-keeping effort, and would cooperate with supply chain partners in order to benefit from the fresh-keeping initiatives.

6 Conclusion and future research

One of the specific challenges in food supply chain is that freshness of food is one of the keys for customers purchasing decision. This leads to two important questions: first, how much effort and resources are needed among FPSC members in order to keep the product refresh. Second, how to motivate and coordinate PFSC members through contract mechanism. This paper strives to answer these questions.

In this paper, we have examined the coordination of FPSC with a fresh-keeping effort. We focus on the coordination of the FPSC through different contracts when the fresh-keeping effort is considered in the model. Two cases are considered: a fresh-keeping cost-sharing contract and a fresh-keeping cost- and revenue-sharing contract. In each case, we determine the optimal retail price, the optimal wholesale price and the optimal fresh-keeping effort. The result suggests that the fresh-keeping cost- and revenue-sharing contract is more effective for coordinating the FPSC.

We find that, in negotiating the contract, it is necessary to carefully consider the conditions to maximize total profit without scarifying individual profit. It is worth noting that the profit of the FPSC is negatively correlated with consumers' sensitivity to product price, while it is positively related to consumers' sensitivity to product freshness.

There are several topics that merit further research. In this paper, we assume that the fresh-keeping cost is paid by the fresh product retailer in a centralized supply chain. A natural extension is to examine a setting in which the fresh-keeping cost is paid by the fresh product supplier. Since, in this research, the consumer arrival rate at any time is assumed to be constant, another interesting possibility is to examine a situation in which the rate is stochastic. Finally, we will extend our model to consider how to coordinate the FPSC through cost- and revenue-sharing contracts when two retailers compete by studying the coordination mechanisms of the FPSC when one retailer has the priority to make its decision first.

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Table 1 Parameters

k	m	c	δ	T	θ_0	η_0
0.20	100	0.50	100	10	0.90	0.80

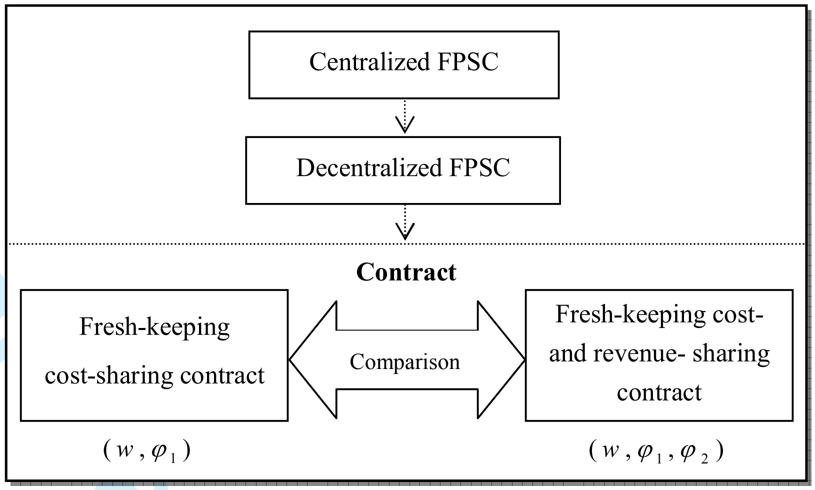

Figure 1 Research Framework for a FPSC

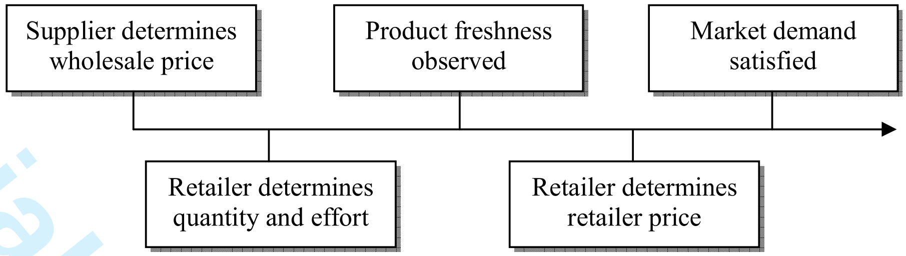

Figure 2 Relationships of Events under Consideration

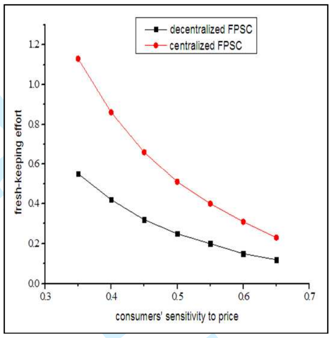

Figure 3.1 The effect of consumers' sensitivity to price on fresh-keeping effort

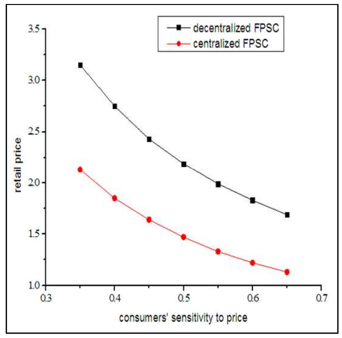

Figure 3.2 The effect of consumers' sensitivity to price on retail price

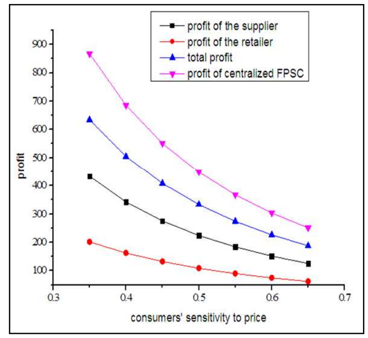

Figure 3.3 The effect of consumers' sensitivity to price on profit

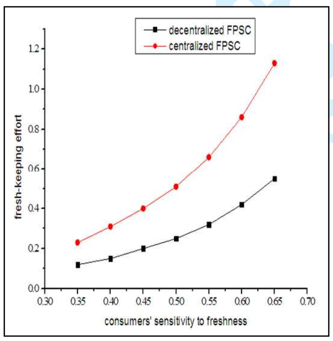

Figure 3.4 The effect of consumers' sensitivity to freshness on fresh-keeping effort

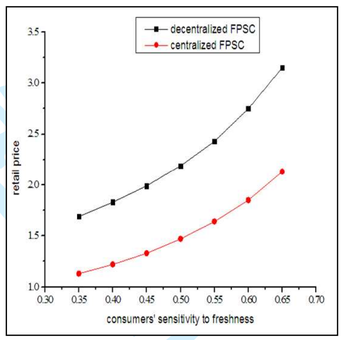

Figure 3.5 The effect of consumers' sensitivity to freshness on retail price

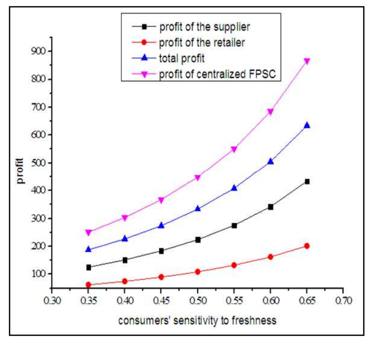

Figure 3.6 The effect of consumers' sensitivity to freshness on profit

Figure 3 Optimal decisions under different preferences without a contract

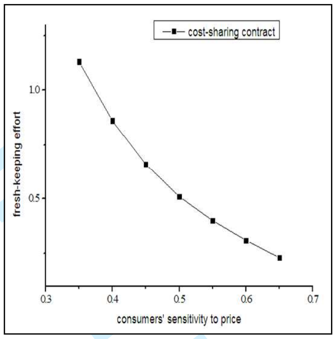

Figure 4.1 The effect of consumers' sensitivity to price on fresh-keeping effort

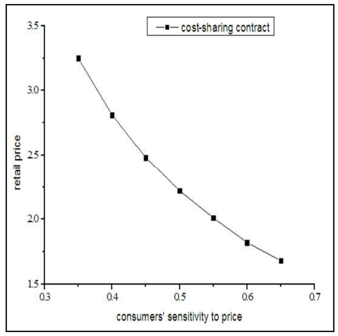

Figure 4.2 The effect of consumers' sensitivity to price on retail price

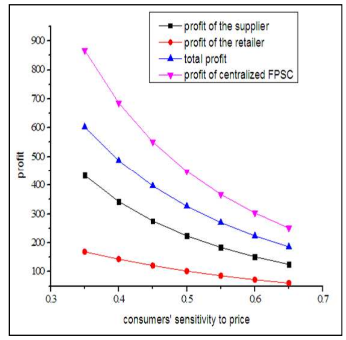

Figure 4.3 The effect of consumers' sensitivity to price on profit

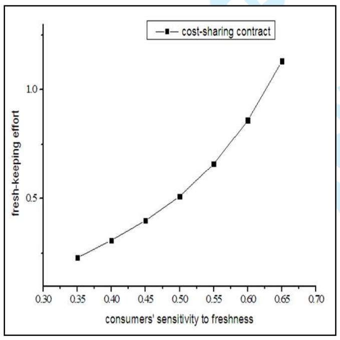

Figure 4.4 The effect of consumers' sensitivity to freshness on fresh-keeping effort

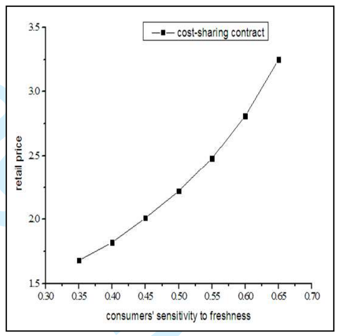

Figure 4.5 The effect of consumers' sensitivity to freshness on retail price

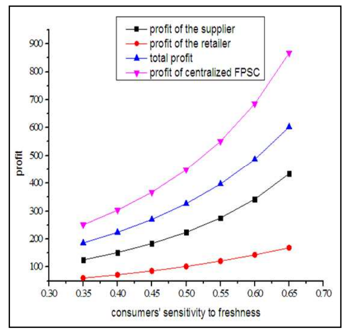

Figure 4.6 The effect of consumers' sensitivity to freshness on profit

Figure 4 Optimal decisions and profits under the fresh-keeping cost-sharing contract

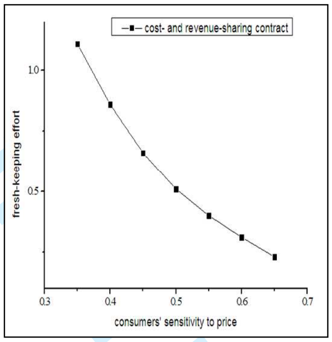

Figure 5.1 The effect of consumers' sensitivity to price on fresh-keeping effort

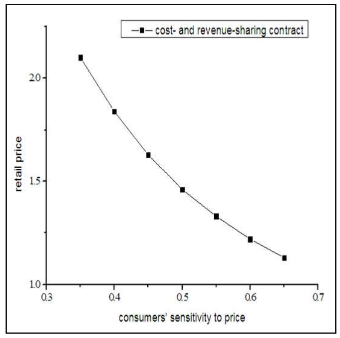

Figure 5.2 The effect of consumers' sensitivity to price on retail price

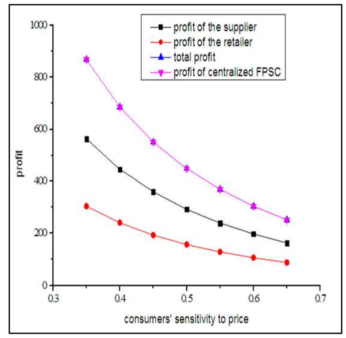

Figure 5.3 The effect of consumers' sensitivity to price on profit

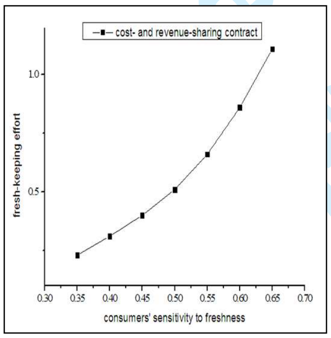

Figure 5.4 The effect of consumers' sensitivity to freshness on fresh-keeping effort

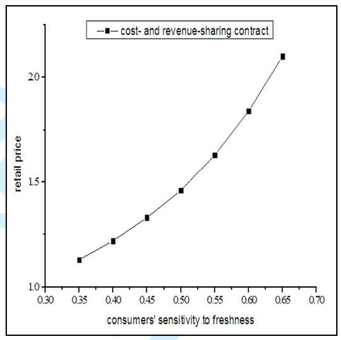

Figure 5.5 The effect of consumers' sensitivity to freshness on retail price

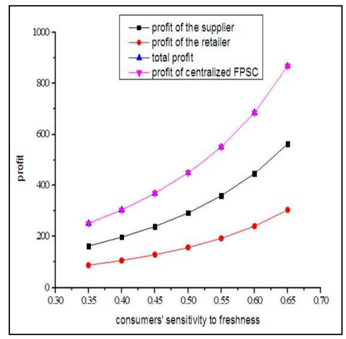

Figure 5.6 The effect of consumers' sensitivity to freshness on profit

Figure 5 Optimal decisions and profits under the fresh-keeping cost- and revenue-sharing contract

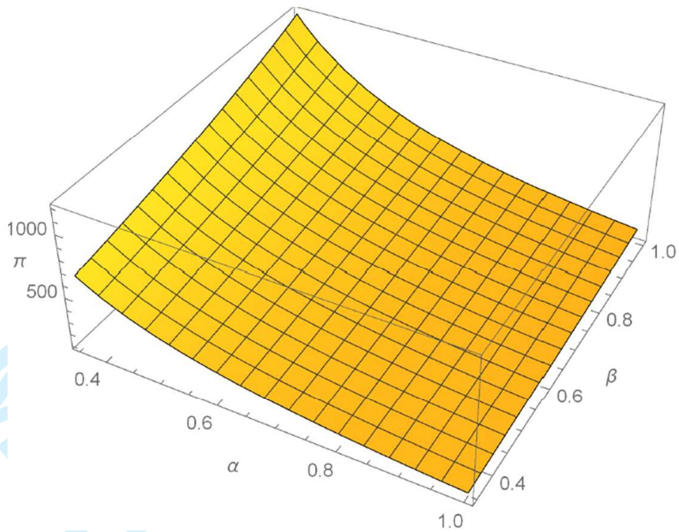

Figure 6 The effects of consumers' sensitivity to price and freshness on profit