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Optimal financing and operation strategy of fresh agricultural supply chain

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Increased market demand and expanded scales of production of fresh agricultural products by small and medium-sized enterprises (SMEs) have highlighted the challenge of funding sufficient infrastructure. Additional costs to improve the freshness of produce makes the optimal financial and operational policies different for these enterprises. On the basis of the characteristics of the fresh agricultural supply chain, this paper analyses the financing strategies adopted by SMEs and obtains optimal operational and financing strategies for SMEs in six different situations. The analysis shows that the optimal level of financing by SMEs is not only affected by the financing rate, but also negatively related to the freshness effort cost coefficient, and is positively related to the sensitivity coefficient of market freshness. Moreover, although the cost of improving the freshness level of the producte is only borne by the SME, the supply chain cannot maximise profit from the optimal financial strategies of SMEs. Shouldering the fresh effort cost also lessens the optimal financing requirement of the SME compared with that of the entire supply chain. The difference is affected by the fresh effort cost coefficient.

Key words: fresh agricultural product, supply chain management, joint production, financing decision.

1. Introduction

Supply chain management (SCM) is an integrated method to manage the flow of logistics, information and finance (Peng and Zhou 2019). However, financial and operational flows are often treated in isolation (Longinidis and Georgiadis 2011), despite the considerable number of studies that have focused on SCM. Nonetheless, financial constraint in most enterprises is a key factor that affects enterprises' decision-making. In fact, the empirical findings in Campello *et al*. (2010) suggest that in the aftermath of the 2008 financial crisis, constrained firms planned deeper cuts in technology spending, employment and capital spending. These results are also supported by a survey conducted by the European Central Bank (ECB 2014), which showed for SMEs in particular, access to capital is an even more pressing problem than finding customers.

Over the years, the definitions of SCM have changed and broadened in scope; however, these definitions are still limited to manufactured products

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and services with little attention being paid to agriculture. Post-harvest wastage is a major concern for fresh agricultural supply chain management. Ambler *et al*. (2018) used a questionnaire to report both complete loss and crop damage, as well as loss during harvest and transport, processing and storage, and they found that losses are spread across a much larger proportion of farmers. In developing or low-income countries, nearly two thirds of the food is usually lost in the pre- and post-harvest and processing levels (Chalak *et al.,* 2018). This post-harvest waste reduces the farmer's share in the final price and results in revenue loss. On the consumer side, post-harvest waste results in lesser availability and a higher price. Likewise, post-harvest wastage severely reduces the available product's quality and the options available for consumers (Shukla and Jharkharia 2013).

For a fresh agricultural supply chain, capital shortage results in limited production capacity and affects a distributor's effort to preserve product freshness, which has a significant effect on both the quality and quantity of the product delivered to market (Cai *et al*. 2013). Thus, small and medium-sized enterprises (SMEs) that deal with fresh agricultural products have urgent financing needs. In this process, the supply of orders to the core enterprises has been guaranteed, and the stability of the whole supply chain can be enhanced. Therefore, additional research addressing the financing and operational strategies of fresh agricultural supply chains can contribute to their enhanced performance.

Based on the characteristics of fresh agricultural product supply chain, this paper proposes the joint operation and financing decision models, and explores the effects of limited funds on SME decision-making and strategy of core enterprises in fresh agricultural products. The remainder of this article is organised as follows: Section 2 gives an overview of the existing literature. Section 3 introduces the notations and assumptions used and then presents mathematical models for different scenarios. Section 4 provides numerical examples to illustrate the proposed models. Section 5 concludes the article by summarising its main findings and providing suggestions for future research.

2. Review of literature

2.1 Fresh agricultural supply chain

This research focuses mainly on three aspects: optimal ordering strategy; optimal pricing strategy; and fresh agricultural supply chain coordination.

Optimal order strategy research focuses mainly on the impact of the product's perishable characteristics on inventory management. Based on a two-period model with capital-constrained retailer, Cao *et al*. (2017) studied the optimal pricing, ordering and advertising investment strategies. Wang and Yang (2016) established the ordering model under an option contract for the retailer with capital constraint and derived the optimal order of retailers with different risk aversion. By studying the supply chain consisting of a single supplier and a number of retailers, Duan and Liao (2013) found that under a predetermined maximal allowable shortage level, the old inventory ratio strategy based on the existing inventory ratio can reduce the expected system outdate rate considerably.

Many studies on optimal pricing strategy are based mainly on the assumption that the market demand is random, which is sensitive to the product's selling price freshness. Wang and Li (2012) designed the pricing mechanism of the product life cycle according to the dynamic observation of the information. By considering the uncertain market demand and gradual depletion of the quality and quantity of fresh produce, Cai *et al.* (2013) proposed a fresh-product supply chain with logistics outsourcing and derived the optimal decisions for three supply chain members, including the 3PL (third-party logistics) provider's transportation fee. Simultaneously, Qin *et al.* (2014) deliberated on the pricing and lot-sizing problem for products with quality and physical quantity deterioration. Cai and Guo (2018) developed mathematical models to determine the optimal fresh-keeping effort, retail and wholesale prices.

Coordinating the fresh agricultural supply chain relies on coordinated contracts, including wholesale-price-discount sharing, cost-sharing contracts and option contracts. Huang *et al.* (2011) studied lead-time coordination for supply chains with deteriorating products and found that a lead-time discount coordination strategy can maximise the profits of the entire supply chain by determining the appropriate optimal order quantity and lead time. Cai *et al.* (2013) studied lead time and considered logistics outsourcing and found that the presence of the third-party logistics provider in the supply chain has a significant effect on its performance. They developed an incentive scheme to coordinate the supply chain, which induced the three parties to act in a coordinated way. Anderson and Monjardino (2019) studied a new type of contract structure and showed how this can coordinate the supply chain and demonstrate the potential advantages of this contract form when producers are risk averse. Boyabatli *et al.* (2011) analyse the optimal procurement, processing and production decisions of a beef supply chain, and they found that higher variability (higher spot price variability, product market variability and correlation) increases the profits of the packer, but decreases the reliance on the contract market relative to the spot market. Li *et al.* (2013) designed coordination contracts for the cases of both deterministic and random demands find that an accept-all type of contract is required to coordinate the supply chain with random demand.

2.2 Operations-finance interface models

Operations and finance are two sides of one coin. Operations management sets the backbone of financial performance, and corporate finance supports real investment in operations.

Operations-finance interface models have identified three types of interdependence: (i) financial constraints on operations; (ii) correlation between operational and financial risks; and (iii) alternative risk mitigation (Zhao and Huchzermeier 2015). This paper focuses on the financial constraints on operations.

Financial constraints on operations refer to the bottlenecks in real investment. For instance, if the cost of borrowing is not that high, then capital-constrained newsvendor borrows funds to procure a less than ideal amount (Dada and Hu 2008). Boyabatli & Toktay (2011) analysed external loan financing and production technology decisions in imperfect capital markets. Our work is related to Babich's (2010) study, which modelled the relationship between the vendor's financial situation and capability to fulfil the buyer's order. Protopappa-Sieke and Seifert (2010) investigated the benefits of equally considering both operational and financial aspects in decision-making under working capital restrictions and payment delays. Li & Arreola-Risa (2017) demonstrated that optimal order quantity is independent of the supplier's random capacity but firm value is not.

3. Model development

3.1 Problem description and assumptions

Zhang *et al*. (2019) studied fresh food supply chains in China and provided evidence on the value of short supply chains. We have reason to believe this approach has good prospects, so our model is a short fresh agriculture supply chain. This paper is concerned with the joint operation and financing strategies in a two-stage single-supplier single-retailer supply chain, as shown in Figure 1, where in the supplier is SME of the fresh agricultural supply chain and the retailer is the core enterprise of the fresh agricultural supply chain. The process of supply chain decision is described as follows:

1. The SME (supplier) makes a commitment to freshness as θ;
2. The core enterprise (retailer) estimates the market demand according to the freshness θ of the supplier and determines order quantity q; and
3. The SME (supplier) produces according to the order quantity q. SME considers financing when orders exceed the maximum capacity of SME.

Some assumptions are used throughout the paper as follows:

1. The SME may be subject to financial constraints, whereas the core enterprise has sufficient capital to cover their desired purchasing costs fully;
2. The SME can change transport time and transportation conditions to affect products' freshness. When fresh agricultural products reach the core enterprise, the freshness is θ, where $\theta_0 \leq \theta \leq 1$ and θ_0 represents the minimum freshness that the customers can tolerate. In a certain range of freshness, the higher the freshness of fresh agricultural products, the

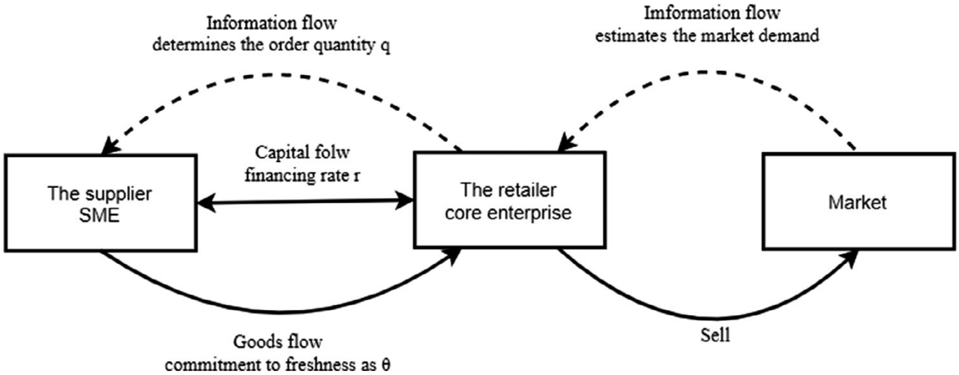

Figure 1 Base model of fresh agricultural supply chain.

greater the market demand (retail prices remain unchanged). During the sales process, the freshness of the product is reduced further, and the core enterprise quantifies the effects of the product's freshness on market demand through historical sales data as $y(p,\theta) = a - bp + k\theta$, where a represents basic demand, b represents the sensitivity of demand to price, and k represents the sensitivity of demand to freshness;

3. The market demand is stochastic considering the influence of external environment on fresh agricultural products. The market demand function is assumed as $D = y(p,\theta) + \eta$, where $y(p,\theta) = a - bp + k\theta$ represents the determining part of the market demand and η represents market stochastic factor that conforms to the negative exponential distribution, $f(\eta) = \lambda e^{-\lambda\eta}$, where, $\lambda > 0$;
4. The freshness effort cost of the SME in ensuring freshness is $c(\theta) = \frac{\sigma\theta^2}{2}$, (Cao *et al.,* 2018) where $\sigma > 0$ represents freshness effort coefficient, and $c'(\theta)>0$, $c''(\theta)>0$;
5. The unit financing cost r is constant, and the financing cost of the SME is proportional to the financing amount;
6. There is no salvage value, shortage cost and inventory cost;
7. The market determines product unit market prices, which remain unchanged; and
8. The financing rate is equal to the interest rate used by the bank when lending to the supplier. Financing rate is determined by bank and is exogenous in this model.

Here is a special explanation of Assumption (8). As we all know, the retailer (core enterprise) is not a financial institution and is not good at setting interest rates. The retailer's low-cost way to determine the financing rate is to refer to the interest rate when it borrows from a bank. Therefore, r in Figure 1 is equal to the interest rate used by the bank when it loans to the retailer. From the perspective of the supplier, as a SME, it is more difficult for the supplier to obtain bank loans compared with large enterprises, because banks need to set higher thresholds for security reasons, and banks may set different loan interest rates based on factors such as the size of the company and its ability to repay. At this time, the financing provided by the retailer can reduce the cost of the supplier. This is one of the benefits of supply chain finance.

3.2 Notation

The following notation in Table 1 will be used in the paper.

3.3 Model development

3.3.1 Optimal operation strategy without capital constraints

When the product period begins, the core enterprise decides the order quantity. Given that a salvage value is non-existent, we can define the following profits of the core enterprise:

$$\pi_R = \begin{cases} pD - p_c q, & D \leq q \\ (p - p_c)q, & D > q \end{cases} \tag{1}$$

According to Assumption (3), we can determine the probability density function and calculate the expected profit as follows:

$$\begin{aligned} E(\pi_R) &= (pD - p_c q)P(D \leq q) + (p - p_c)qP(D > q) \\ &= \int_0^{q-y(p,\theta)} (pD - p_c q)f(D)dx + \int_{q-y(p,\theta)}^{\infty} (p - p_c)qf(D)dx \\ &= pq - p\int_0^{q-y(p,\theta)} F(x)dx - p_c q \end{aligned} \tag{2}$$

With $\frac{\partial^2 E(\pi_R)}{\partial q^2} = -f(q - y(p,\theta)) < 0$, let $\frac{\partial E(\pi_R)}{\partial q}=0$, and we can calculate the optimal order quantity q^* as follows:

Table 1 Meaning of notation

D	Fresh agricultural market demand
q	Order quantity of the core enterprise
q^*	Optimal order quantity of the core enterprise
q_2	Production quantities of the SME
N	Production capacity of the SME
θ	Freshness of fresh agricultural product when received by the core enterprise
θ^*	Optimal freshness of fresh agricultural product when received by the core enterprise
Q	Initial capital of the SME
Q_f	Financing amount of the SME
r	Financing rate of the SME
p	Retail price of unit product
p_c	Wholesale price between the SME and the core enterprise
c	The production cost of the SME

$$q^{*}=F^{-1}(\frac{p-p_c}{p})+a+k\theta-lp \tag{3}$$

Without capital constraints, the supplier can guarantee sufficient capacity to complete the orders of the core enterprise, and thus, the order quantity of the core enterprise is the production of the SME. We can define the profits of the SME as follows:

$$\pi_M=(p_c-c)q-\frac{\sigma\theta^2}{2} \tag{4}$$

With $\frac{\partial^2\pi_M}{\partial\theta^2}=-\sigma<0$, let $\frac{\partial\pi_M}{\partial\theta}=0$, and we can calculate the optimal freshness $\theta=\frac{(pc-c)}{\sigma}k$. According to Assumption (2), it satisfies the following inequality: $\theta_0<\theta<1$. Hence, we can obtain the optimal freshness θ shown in Table 2.

3.3.2 Optimal operation strategy with capital constraints

According to Assumption (1), the initial capital of the SME is constrained and cannot fully cover the cost of the optimal strategy without capital constraint:

$$Q\leq cq_N^{*}+\frac{1}{2}\sigma\theta_N^{*2} \tag{5}$$

Although the core enterprise has sufficient capital, the core enterprise still builds on the newsvendor model to determine the optimal order quantity according to market demand:

$$q_Y^{*}=F^{-1}(\frac{p-p_c}{p})+a+k\theta-lp \tag{6}$$

In the case of the capital constraints, the SME can use its initial capital Q for the production and freshness effort costs. When the SME commits to freshness, its production capacity is $N=\frac{Q-c(\theta)}{c}$, and its production quantity is $q_2=\min(q_Y^{*},N)$. Under the capital constraints assumption, the capacity of the SME must be less than or equal to the order quantity, $N\leq q_Y^{*}$. The remaining capital is obtained when the production capacity is greater than the order quantity, which contradicts the capital constraint assumption. Therefore, $q_2=N=\frac{Q-c(\theta)}{c}$, and the optimal operation strategy problem can be presented as follows:

Table 2 SME's optimal freshness without capital constraint

Different circumstances	$\frac{(p_c-c)k}{\sigma}<\theta_0$	$\theta_0\leq\frac{(p_c-c)k}{\sigma}\leq 1$	$\frac{(p_c-c)k}{\sigma}>1$
Optimal freshness θ_N^{*}	θ_0	$\frac{(p_c-c)k}{\sigma}$	1

$$\max_{\theta} \pi_M = \max_{\theta}(p_c - c)\,\frac{2Q-\sigma\theta^2}{2c} - \frac{\sigma\theta^2}{2}$$
$$s.t.\begin{cases} \frac{2Q-\sigma\theta^2}{2c} \le F^{-1}(\frac{p-p_c}{p}) + a + k\theta - lp \\ \theta_0 \le \theta \le 1 \end{cases} \tag{7}$$

We can calculate the optimal freshness and production quantity of the SME and the core enterprise's optimal order quantity. The results are shown in Table 3 where $t = F^{-1}(\frac{p-p_c}{p}) + a - lp$ represents the market demand expectation excluding the effect of freshness θ, and $Q_0 = \frac{\sigma^2\theta_0^2+2\sigma\theta_0 ck}{2\sigma} + ct$ represents the capital needed to meet the order quantity of the core enterprise while maintaining the lowest freshness level.

Further analysis of the results in Table 4 reveals the following:

1. As the initial capital of the SME is extremely scarce, $Q < Q_0$, it cannot cover fully the costs of production and freshness effort even at the lowest freshness level. Hence, the optimal strategy is to maintain the lowest freshness level θ_0 and place the remaining capital into production; and
2. As the initial capital of the SME is abundant, $Q \ge Q_0$, surplus capital occurs when the SME meets the order quantity of the core enterprise at the lowest freshness level. The optimal operation strategy of the SME is to improve the freshness level; thus, SMEs can improve market demand and increase income: $\theta_Y^* = \frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma}$.

In this condition, the SME can meet the orders of the core enterprise, but it cannot reach the optimal freshness level without capital constraints, thereby resulting in lower demand and lower profits for both SME and core enterprise.

3.3.3 Optimal operation and financing strategy with capital constraints

According to Assumption (1), the core enterprise has sufficient capital, and it does not need to finance. However, the capital constraint of the SME affects market supply and production quantity, resulting in profits below its expectations without constraints. Therefore, the core enterprise is willing to provide credit guarantee for the SME's loan to obtain additional financing amount. The optimal order quantity of the core enterprise remains constant as follow:

$$q_F^* = F^{-1}(\frac{p-p_c}{p}) + y(p,\theta) = F^{-1}(\frac{p-p_c}{p}) + a + k\theta - lp \tag{8}$$

Financing cost is paid on the maturity date of the loan, and hence, financing cost is considered only in the profit function and excluded in the cost

Table 3 Optimal operation strategy with capital constraints

Initial capital	$Q < Q_0$	$Q \geq Q_0$
Optimal freshness θ_Y^*	$\theta_Y^* = \theta_0$	$\theta_Y^* = \frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma}$
Optimal order quantity	$q_Y^* = F^{-1}\left(\frac{p-p_c}{p}\right) + a + k\theta_0 - lp$	$q_Y^* = F^{-1}\left(\frac{p-p_c}{p}\right) + a + k\frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma} - lp$
Optimal production quantity	$\frac{2Q-\sigma\theta_0^2}{2c}$	$q_2 = F^{-1}\left(\frac{p-p_c}{p}\right) + a + k\frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma} - lp$
Core enterprise's expected profit	$E(\pi_R) = (p-p_c)\frac{2Q-\sigma\theta^2}{2c} - p\int_0^{F^{-1}\left(\frac{p-p_c}{p}\right)} F(x)dx$	$E(\pi_R) = (p-p_c)\left[F^{-1}\left(\frac{p-p_c}{p}\right) + a + k\frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma} - lp\right] - p\int_0^{F^{-1}\left(\frac{p-p_c}{p}\right)} F(x)dx$
SME's profit	$\pi_M = (p_c - c)\frac{2Q-\sigma\theta_0^2}{2c} - \frac{1}{2}\sigma\theta_0^2$	$\pi_M = (p_c - c)\left[F^{-1}\left(\frac{p-p_c}{p}\right) + a + k\frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma} - lp\right] - \frac{c^2k^2+\sigma(Q-ct)-ck\sqrt{c^2k^2+2\sigma(Q-ct)}}{\sigma}$

Table 4 Optimal operation and financing strategy with capital constraints

Initial capital	Financing rate	Optimal financing amount	optimal freshness	Optimal order quantity	Production quantity
$Q \geq Q_0$	$r > \frac{p_c k}{\sqrt{c^2k^2+2\sigma(Q-ct)}} - 1$	0	$\frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma}$	$k\frac{\sqrt{c^2k^2+2\sigma(Q-ct)}-ck}{\sigma} + t$	$q_2 = q_F^*$
	$r \leq \frac{p_c k}{\sqrt{c^2k^2+2\sigma(Q-ct)}} - 1$	$\frac{p_c^2k^2-c^2k^2(1+r)^2}{2\sigma(1+r)^2} - Q + ct$	$\frac{p_c k-ck(1+r)}{\sigma(1+r)}$	$k\frac{p_c-ck(1+r)}{\sigma(1+r)} + t$	$q_2 = q_F^*$
$Q < Q_0$	$r > \frac{(p_c-c)}{c}$	0	θ_0	$k\theta_0 + t$	$\frac{2Q-\sigma\theta_0^2}{2c}$
	$\frac{p_c k}{\sqrt{c^2k^2+\sigma^2\theta_0^2+2\sigma\theta_0 ck}} - 1 < r \leq \frac{(p_c-c)}{c}$	$Q_0 - Q$	θ_0	$k\theta_0 + t$	$q_2 = q_F^*$
	$r \leq \frac{p_c k}{\sqrt{c^2k^2+\sigma^2\theta_0^2+2\sigma\theta_0 ck}} - 1$	$\frac{p_c^2k^2-c^2k^2(1+r)^2}{2\sigma(1+r)^2} - Q + ct$	$\frac{p_c k-ck(1+r)}{\sigma(1+r)}$	$k\frac{p_c-ck(1+r)}{\sigma(1+r)} + t$	$q_2 = q_F^*$

constraint. We can calculate the SME's profit as follows:

$$\pi_M = (p_c - c)q_2 - \frac{1}{2}\sigma\theta^2 - rQ_f \tag{9}$$

The optimal operation and financing strategy problem of the SME can be presented as follows:

$$\begin{aligned}&\max_{\theta,Q_f}\{\pi_M\} = \max_{\theta,Q_f}(p_c - c)q_2 - \tfrac{1}{2}\sigma\theta^2 - rQ_f\\ &s.t.\begin{cases} cq_2 + \frac{1}{2}\sigma\theta^2 \le Q + Q_f \\ q_2 = \min\{q^*, N\} \\ \theta_0 \le \theta \le 1 \\ Q_f \ge 0 \end{cases}\end{aligned} \tag{10}$$

In the decision problem, the decision variables of the SME are financing amount Q_f and freshness level θ. According to these variables, the problem-solving process can be divided into two steps:

First step: make a decision on optimal financing amount Q_f^* of the SME.

Second step: make a decision on the optimal promised freshness level according to the optimal financing amount Q_f^* obtained in the first step.

The financing amount cannot be infinite because of the existence of financing cost. The financing amount must satisfy the constraint $Q + Q_f \le cq_N^* + \frac{1}{2}\sigma\theta_N^{*2}$. Thus, the second step is the solution to the problem discussed in Section 3.3.2. Referring to the conclusion in Section 3.3.2, we can calculate the optimal freshness level $\theta_F^*(Q_f)$ in the case of financing amount Q_f. We can also calculate the optimal financing amount Q_f^* using the optimal promise freshness $\theta_F^*(Q_f)$. The results are shown in Table 4.

Further analyses of the results in Table 4 reveal the following:

1. When the initial capital of the SME is abundant, $Q \ge Q_0$.

Although financing is considered, the optimal operation strategy of the SME is to maintain higher freshness level $\theta_Y \ge \theta_0$ and meet the optimal order quantity of the core enterprise under this freshness.

Given the capital constraint, the optimal freshness level is lower without capital constraint, $\theta_Y \le \theta_N$. Therefore, the SME considers financing to improve its freshness level and expand its production capacity. We can calculate the marginal revenue of financing $MR = \frac{p_c k}{\sqrt{c^2k^2 + 2\sigma(Q + Q_f - ct)}} - 1$, whereas the marginal cost of financing is financing rate r. From the formula, we can see that as the financing amount increases, the marginal revenue decreases. The feature of marginal revenue results from the further improvement in freshness level becoming increasingly difficult as the cost increases. Hence, to maximise profits, the SME decides on the financing amount after comparison of the financing cost r and MR.

When financing rate r is greater than marginal revenue MR, $r > \frac{p_c k}{\sqrt{c^2k^2+2\sigma(Q-ct)}} - 1$, the SME does not carry out financing, the optimal financing amount $Q_f^* = 0$.

When financing rate r is less than or equal to marginal revenue MR, $r \leq \frac{p_c k}{\sqrt{c^2k^2+2\sigma(Q-ct)}} - 1$, the SME carries out financing. As the marginal revenue of the financing diminishes, calculating the marginal value of the financing is possible when the marginal rate of return is equal to financing cost. Thus, we can calculate the optimal financing amount $Q_f^* = \frac{p_c^2k^2 - c^2k^2(1+r)^2}{2\sigma(1+r)^2} - Q + ct$.

2. When the initial capital of the SME is extremely scarce, $Q < Q_0$.

When financing is unavailable, the optimal operation of the SME is to maintain the lowest freshness level θ_0 and placing the remaining capital to production. However, because of the financial constraint, the SME cannot meet the order quantity of the core enterprise. In the considered scenario, improving promised freshness cannot lead to high profit. Therefore, because the financing amount $Q_f \leq Q_0 - Q$, the SME will place the financing capital to production to meet the core enterprise's order quantity, and the marginal revenue of financing $MR_1 = \frac{p_c - c}{c}$. If the SME continues to finance until the financing amount satisfied it $Q_f > Q_0 - Q$, extra capital is needed after meeting the core enterprise's order quantity. The SME also considers improving the freshness level and production capacity, and by citing the previous results, the marginal revenue of extra financing is $MR_2 = \frac{p_c k}{\sqrt{c^2k^2+2\sigma(Q+Q_f-ct)}} - 1$. Therefore, the marginal revenue decreases because of additional freshness effort costs, $\frac{p_c k}{\sqrt{c^2k^2+2\sigma(Q+Q_f-ct)}} - 1 < \frac{p_c - c}{c}$. Hence, to maximise the profits, the SME decides on the financing amount by comparing financing cost r with the marginal revenue that the financing amount brings.

Financing rate r is greater than marginal revenue MR_1, $r > \frac{(p_c - c)}{c}$, and thus, the SME does not conduct financing, and the optimal financing amount is $Q_f^* = 0$.

Financing rate r is between marginal revenue MR_1 and MR_2, $\frac{p_c k}{\sqrt{c^2k^2+\sigma^2\theta_0^2+2\sigma\theta_0 ck}} - 1 < r \leq \frac{(p_c - c)}{c}$, and thus, the SME conducts financing. We can calculate the optimal financing amount $Q_f^* = Q_0 - Q$.

Financing rate r is less than marginal revenue MR_2, $r \leq \frac{p_c k}{\sqrt{c^2k^2+\sigma^2\theta_0^2+2\sigma\theta_0 ck}} - 1$, and with the marginal revenue of the financing diminishing, calculating the marginal value of the financing is possible when the marginal revenue is equal to the financing cost. Thus, we can calculate the optimal financing amount $Q_f^* = \frac{p_c^2k^2 - c^2k^2(1+r)^2}{2\sigma(1+r)^2} - Q + ct$.

4. Numerical analysis

This section presents numerical examples to illustrate the behaviour of the developed models. We first introduce a set of parameters to define a base scenario and then present various important model parameters to study how: (i) the financing rate influences the optimal financing amount; (ii) the financing amount influences the SME's optimal freshness level; and (iii) the financing amount influences the profits of the SMEs and core enterprises.

Consider an SME–core enterprise system with the following parameters: $Q = 1,800,000$, $r = 6\%$, $p_c = 11.2$, $c = 9.0$, $\sigma = 150,000$, $a = 800,000$, $k = 40,000$, $l = 35,000$, $p = 17.0$, $\theta_0 = 0.3$ and $\lambda = 0.0001$.

When financing is unavailable, $Q_f = 0$, the optimal operation strategy is shown in Table 5, where $\Delta\pi_M$ represents the increment of the SME's profit from no financing to a certain financing amount, and $\Delta E(\pi_R)$ represents the core enterprise's expected profit increment.

Keeping lowest freshness level $\theta_0 = 0.3$, we can calculate the optimal order quantity $q_0 = F^{-1}\left(\frac{p-p_c}{p}\right) + a + k\theta_0 - lp = 221,170$ of the core enterprise, and the SME's capital needs to meet the core enterprise's order quantity $Q_0 = cq + \frac{1}{2}\sigma\theta_0^2 = 1,997,310 > Q$. Combining the results in Table 4, we can calculate the optimal financing amount $Q_f^* = \frac{p_c^2k^2 - c^2k^2(1+r)^2}{2\sigma(1+r)^2} - Q + ct = 245,980$. Table 5 shows the optimal operation strategies of the SMEs and the core enterprises under the optimal financing amount. Moreover, to analyse the effects of the financing amount, Table 5 compares the optimal operation strategies with different financing amounts. In the case of $Q_f = 150,000 < Q_f^*$, $Q_f = 197,310 = Q_0 - Q$, $Q_f = 319,570 = cq_N^* + \frac{1}{2}\sigma(\theta_N^*)^2$ and $Q_f = 400,000 > cq_N^* + \frac{1}{2}\sigma(\theta_N^*)^2$, the parameters related to core enterprises and SMEs are calculated. In order to highlight the changes brought by financing, the expected profit increment of core enterprises and the SME is given.

Q_f^* represents the optimal financing amount of the SME; π_M represents the profits of the SME; and $E(\pi_R)$ represents the expect profits of the retailer. Based on the result in Section 3.3.3, we can draw the curve of profit

Table 5 Optimal operation strategies with different financing amounts

Q_f^*	θ^*	q^*	q_2	π_M	$E(\pi_R)$	$\Delta\pi_M$	$\Delta E(\pi_R)$
0	0.30	221,170	199,250	431,600	1,155,700	0	0
150,000	0.30	221,170	215,920	459,270	1,252,300	27,670	96,600
197,310	0.30	221,170	221,170	467,990	1,282,800	36,390	127,100
245,980	0.42	225,970	225,970	469,150	1,310,600	37,550	154,900
319,570	0.59	232,770	232,770	466,810	1,350,100	35,210	194,400
400,000	0.59	232,770	232,770	461,990	1,350,100	30,390	194,400

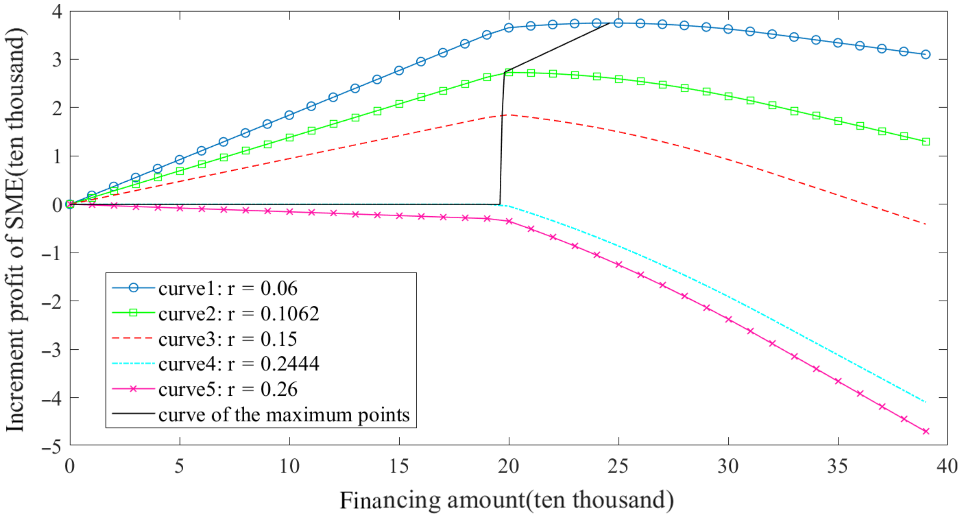

Figure 2 Optimal financing amount of SMEs with different financing rates. [Colour figure can be viewed at wileyonlinelibrary.com]

increment of the SME with the financing amount. Figure 2 shows the comparison of the curves under different financing rates. The maximum point of each profit increment curve in the graph is marked (with multiple maximum points given, the last maximum point is taken as the marked point). The curve of the marked points shows how financing rate affects optimal financing amount. When the financing rate is $r < 10.65\%$, the optimal financing amount decreases when financing rate increases. When the financing rate is $10.65\% \leq r \leq 24.44\%$, the optimal financing amount does not change when financing rate increases, $Q_f^* = Q_0 - Q$. When the financing rate is $r > 24.44\%$, the SME does not carry out financing.

Figure 3 analyses the change in optimal freshness level of SMEs with different financing amounts. When the financing amount is less than 197,310, the optimal freshness level is unchanged when the financing amount increases. With a financing amount between 197,310 and 245,980, the optimal freshness level increases when the financing amount increases, and the SME's profit increases. With a financing amount between 245,980 and 319,570, the optimal freshness level increases when the financing amount increases, but the SME's profit decreases. With a financing amount over 319,570, the optimal freshness level does not change when the financing amount increases, and the SME's profit decreases rapidly. With a financing amount between 197,310 and 319,670, the change in profit increment caused by the change in financing amount is significantly smaller than that between 0 and 197,310 or between 319,770 and 400,000.

Based on the result in Section 3.3.3, we can draw the curves of the expected increment profit of the core enterprise, the SME's increment profit and the entire supply chain's expected increment profit with the financing amount. In

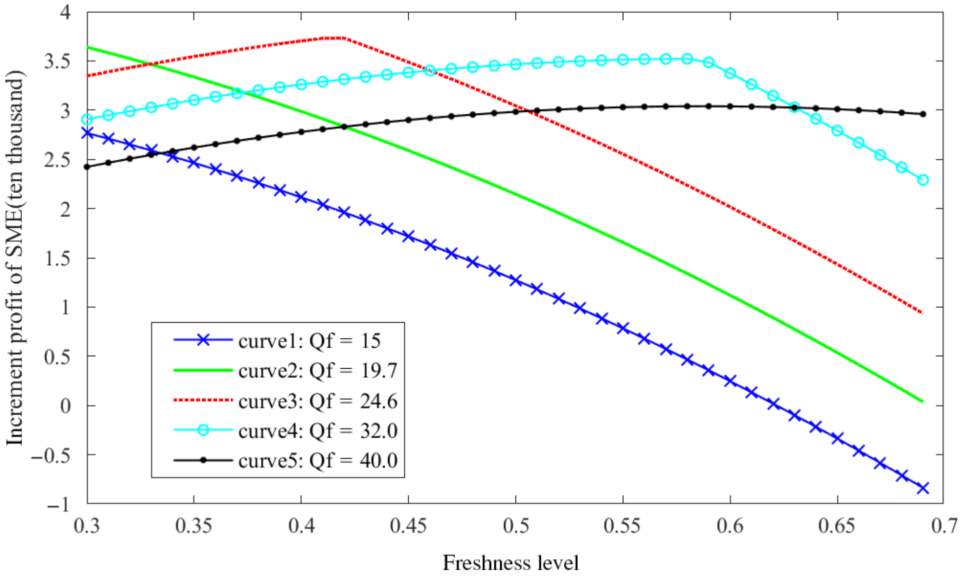

Figure 3 Optimal freshness level of SMEs with different financing amounts. [Colour figure can be viewed at wileyonlinelibrary.com]

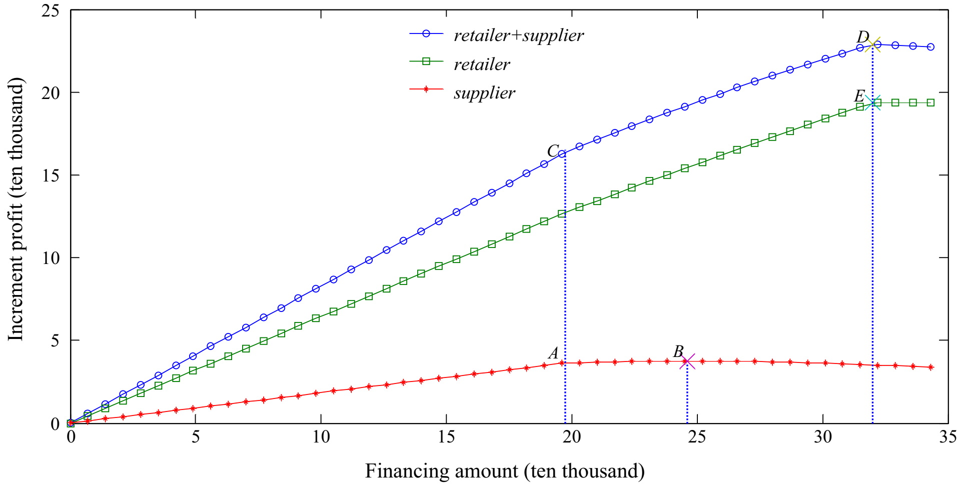

Figure 4 SME's and core enterprise's profits with financing amount. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 4B,D,E represent the maximum profit points of the SME, the core enterprise and the whole supply chain, respectively, and A and C represent the turning points of their curves.

The figure shows that the entire supply chain's expected increment profit increases linearly to C point when the financing amount increases. Subsequently, as the increase in increment profits of the SME slows down, the overall increase in supply chain increment profits also slows down. At point B, the

Table 6 Influence of freshness maintaining effort coefficient on optimal financing amount

σ	90,000	120,000	150,000	180,000	210,000
Q_f^*	354,920	286,830	245,980	218,740	200,010
$Q_{f,s}^*$	477,580	378,830	319,570	280,070	251,860
$\Delta Q_f = Q_{f,s}^* - Q_f^*$	122,659	92,000	73,590	61,330	51,850
loss of overall profit of supply chain	61,583	46,187	36,947	30,791	25,994

SME's profit reaches the maximum, but the supply chain's overall profit continues to increase as the financing amount increases, and the maximum profit is obtained at point D. Therefore, when the supply chain enterprises take decentralised decision-making and the supplier makes financing decisions independently, after the SME decides the optimal financing amount (point A), the core enterprises still cannot achieve the maximum profit under the condition that the SME has no capital constraint. The SME's optimal financing amount is less than that of the entire supply chain.

Table 6 shows that we can calculate the supply chain's optimal financing amount $Q_{f,s}^* = 319,670$, $\Delta Q_f = Q_{f,s}^* - Q_f^* = 73,590$, which leads to the loss in the supply chain's overall profit.

$Q_{f,s}^*$ represents the optimal financing amount of the whole supply chain. As can be seen from Figure 4, the optimal financing amount of the whole supply chain is determined by the function of the total profits of the supplier and the retailer. Further analysis shows that the difference in financing amount is susceptible to the effects of the freshness effort coefficient. The reduction in the freshness effort coefficient will expand the difference between the optimal financing amounts of the SME and the supply chain, and the loss of the supply chain's overall profit will increase, thereby suggesting that the lower the freshness effort coefficient is, more attention the retailer, as a supply chain leader, will pay to supply chain coordination issues and encourage the SME to decide on a considerable financing amount to obtain higher overall supply chain profits.

5. Conclusions

This paper focused on an agricultural supply chain model for a situation where the SME's initial capital is constrained and cannot fully cover the cost of the optimal operation strategy without a capital constraint. Therefore, the SME must decide on the level of financing and an operations strategy.

The models developed in this paper divided the SME's initial capital into two cases: (i) the initial capital cannot fully cover the production cost and freshness effort cost even with the lowest freshness level. Without financing, the SME's optimal operation strategy is to maintain the lowest freshness level and place the remaining capital to production. (ii) Surplus capital is present when the SME can meet the order quantity of the core enterprise at the lowest freshness level. Without financing, the SME's optimal operation strategy is to improve freshness and guarantee the capacity to meet the order quantity.

Given the freshness effort cost, the marginal revenue of financing under the condition of improving freshness to obtain more demand is less than that under the condition of maintaining the lowest freshness level. Therefore, the SME must balance the marginal revenue and financing rate separately in two situations to determine the optimal financing amount.

This paper shows that the optimal financing amount of SMEs is not only affected by the financing rate, but also negatively related to the freshness effort cost coefficient. It is also positively related to the sensitivity coefficient of market freshness.

In a decentralised setting, when the SME bears the entire freshness effort cost, the optimal financing amount is less than that of the supply chain. Moreover, the smaller the freshness effort cost (i.e. the greater the freshness maintaining effort coefficient), the greater the difference in the financing amount, and the greater overall profit loss of the supply chain.

A possible extension of this work is to consider efficient cost-sharing mechanisms that induce cooperation between different members in the supply chain even under decentralised decision-making. In a decentralised setting, establishing incentives for cooperation is necessary, especially when one of the supply chain actors experiences reduced profits to obtain the supply chain's maximum profit. In short, the financing of supply chain is a difficult problem. The research in this paper is useful for enterprises seeking to accurately define their business problem and implement remedial strategies.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

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