A Thesis for the Degree of Ph.D. in Engineering

Flexible Operation Modes in Fresh Fruit Supply Chains with Cold Storages

January 2024

Graduate School of Science and Technology
Keio University

Bai Yue

Abstract

This dissertation explores flexible operation strategies in fresh fruit supply chains (FSCs) with cold storages. In traditional FSCs, growers usually sell fresh fruits with thin profit right after harvesting due to the perishability. In order to mitigate the deterioration of fresh fruits, cold storages, which are generally divided into the regular atmosphere storage (RAS) and the controlled atmosphere storage (CAS), are built accelerating in rural areas. Depending on the extension period of shelf life, we propose flexible operation modes in fresh FSCs with RAS and with CAS, respectively.

For RAS, we propose the flexible supply contract with put options (SCPO) for a rural fresh FSC with RAS, where the grower stores fresh fruits in RAS to extend the shelf life, which incurs extra storage costs that can be recovered by salvaging at a higher price later. The proposed model is analyzed from both the grower's and the buyer's perspectives. And the buyer's and the grower's profit functions are formulated. We derive the buyer's optimal policies for the initial order and put options as well as the grower's optimal policy for the planting quantity. The grower's optimal supply tariff can be obtained only numerically. In particular, we obtain closed-form formulae to determine the buyer's optimal order policy and the grower's optimal planting quantity in a special case. We show numerical experiments in which we examined the effectiveness of the proposed model and analyze how the parameters affect the performances of both the grower and the buyer.

For CAS, we consider a single-period, three-stage model in a rural fresh FSC with

CAS. With CAS, the grower produces fresh fruits and then sells them to a two-stage market, i.e., in-season and off-season, in sequence. We formulate the grower's profit function, propose the solution for the grower to make the optimal planting quantity and derive the optimal rental capacity of CAS. In particular, we study this model in a special case, and analyze numerically how the parameters influence the grower's behavior in such a supply chain.

Finally, the conclusions of this dissertation are presented and we explain the future direction of this research.

Content

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background and motivation

Fresh fruits are a major source of essential vitamins and minerals, such as vitamin A, vitamin C, and potassium, needed for human well-being (Brasil and Siddiqui, 2018). They are metabolically active, undergoing ripening and senescence processes that must be controlled to prolong postharvest quality. With the progress of food globalization, the amount of agri-foods that are traded has been increasing, and the distance transported and the duration have been extended (Fahmy and Nakano, 2016). Fresh fruits are perishable living products that require coordinated activity by growers, storage operators, processors, and retailers to maintain quality and reduce food loss and waste. Inadequate management of these processes can result in major losses in nutritional and quality attributes, outbreaks of food-borne pathogens, and financial loss for all players along the fresh fruit supply chains (FSCs), from growers to consumers (Siddiqui, 2017). Such inadequate management especially exists in developing countries.

As the largest developing country in the world, China is implementing the rural revitalization strategy in order to realize prosperous industry and rich life in rural areas. China is the world's largest fruit producer, and the fruit industry is one of the important industries for growers to increase their income (Liao and Li, 2023). In China, fresh FSCs include many channel participants, such as growers, agricultural enterprises, rural wholesalers, urban wholesalers, distributors, retailers and customers. Fruit planting areas are across cold, temperate, and tropical zones with large regional differences. Fruits are produced and sold all over the country. Consumers of fresh fruits are fussy about freshness and expect them to be year-round. Furthermore, the supply and procurement modes in fresh FSCs are diversified, such as multi-level wholesale market systems, and direct supply modes (for instance, e-commerce). Retailers can procure fruits through various channels, such as distributors, wholesaler markets, or directly from growers. Furthermore, a kind of fruit often faces competition with other similar fruits. On the other hand, growers also can sell fruits through various channels. Therefore, both planting area and demand of fresh FSCs have high uncertainty. Besides that, the output rate is random since it is largely affected by climate, and planting practices in each process, such as fertilizer spreading, mowing and thinning. A kind of fruit is popular and expensive this year and may be sold cheaply the next year. In addition, coupled with the problems of concentrated ripening and perishability, growers generally only can make limited profits in the supply chain.

In a traditional fresh FSC, the grower usually sells the fruits to the buyer right after harvesting because there are no cold storages to keep them fresh. When a large number of fruits mature, knowing the grower's eagerness to sell, the buyer may discount the wholesale price, which always results in low profits even huge losses for the grower. This is a serious problem in such supply chains in China. Consider the case of the kiwifruits supply chain in Pujiang County, Sichuan Province, China. The kiwifruit harvest season begins from July. After harvesting, most growers sell produce to buyers. Due to the perishability of kiwifruits and poor storage technology, growers are eager to sell all the produce as soon as possible, especially when a large number of kiwifruits has matured in a short time. Knowing the grower's eagerness to sell, buyers may discount the wholesale price. Thus, growers usually sell produce at a low price. With the development of rural e-commerce platforms, such as Taobao and TikTok, some growers start selling produce directly to customers at a higher price than before. However, poor storage technology makes it difficult to support the online sale of a large number of fresh fruits. Consequently, despite a large amount of labor and capital invested in a long planting season, growers usually gain only a thin profit or even loss. Similar cases can also be found in other fresh FSCs in rural China, such as cherry and lemon supply chains, which might be one of the reasons why some growers have a low enthusiasm for planting and living in poverty.

To solve such problems, China is developing the rural cold chain, especially by constructing cold storages which are effective and essential instruments to mitigate the quality decay and extend the life cycle of products. For example, Tongnan district in Chongqing is now planning to construct a controlled atmosphere storage with a capacity of two hundred thousand tons to improve the fresh-keeping ability mainly for lemons.

Two main types of cold storages are being constructed in rural areas, that is, regular atmosphere storage (RAS) and controlled atmosphere storage (CAS). RAS refers to a warehouse where temperature and humidity are constantly monitored and adjusted, whereas CAS refers to a gas-tight warehouse where the oxygen, carbon dioxide, and nitrogen levels are regulated along with temperature and humidity. The construction cost of CAS is higher than that of RAS, exceeding about 1,000 to 2,000 CNY per square meter. The lifetime of fresh fruits stored in CAS can be more than doubled than that in RAS, in the case of kiwifruits, up to 5-6 months. Moreover, in RAS, fruits can be stored, graded and taken out for sale based on markets. By contrast, in CAS, fruits only can be stored and taken out all one time, because a lot of oxygen entering again would accelerate the deterioration of fruits.

After introducing the cold storage into the traditional fresh FSC, the participants' bargaining power and the operation mode may be different. The grower's bargaining power may be enhanced because the cold storage can extend the shelf life of fruits. The buyer may also be favored because he needs not to take the risks associated with a large amount of inventory whereas to discount the price may become more difficult than before. For such a new fresh FSC, how to make full use of the cold storage to improve the grower’s profit and also the supply chain’s performance is an important subject. One can find various studies pertaining to freshness reagents, preservation packaging, fresh-keeping facilities and equipment, investment in preservation technologies, and so on. Here, the focus of our study is the operation mode associated with cold storages.

1.2 The proposed flexible operation mode

As mentioned before, regular atmosphere storage (RAS) and controlled atmosphere storage (CAS) are two main types of cold storages. Generally, RAS can keep fruits fresh for several weeks (for instance, 3 weeks for bananas) while CAS can keep them fresh for several months (for instance, 4 months for bananas), which provides more opportunities for participants in the supply chain and makes the operation mode to be more flexible rather than the traditional mode that selling right after harvesting. Depending on the extension period of shelf life, we propose flexible operation modes in fresh FSCs with RAS and CAS, respectively.

1.2.1 Flexible operation mode with RAS

For the case that RAS is available, growers can extend the lifetime of fruits. Their eagerness to sell in a short time right after harvesting may wane. Moreover, fruits not stored in cold storages may be sold at a higher price than before (Minten et al. 2014), due to a decrease in the quantity supplied at one time. For the buyer, it may become more difficult than before to discount the price, which may lead to a declined order quantity. On the other hand, the buyer may also be favored because he can transfer the overage risk to the grower when facing stochastic demand. Knowing this, the grower has an incentive to provide a flexible operation mode with downward adjustment in order to encourage the buyer to place a larger order before planting.

We introduce put options into the traditional supply contract, i.e., supply contract with put options (SCPO). Option contracts (real options) originate from financial options. Based on the adjustment direction, options can be divided into call, put, and bidirectional options. Put option gives the buyer the right, but not the obligation to respond to a coming or realized demand decrease by reducing the initial order, which is widely used in various industries. For example, a flexible contract with put options is introduced into a two-echelon container shipping service chain in order to enable carriers to give back the surplus empty containers to the leasing company (Liu et al., 2013). With a put option contract, the buyer purchases put options at a unit option price for each option, while can receive a corresponding full or partial refund for every exercised option. In this way, the grower shares a part of the buyer's demand decreasing risk, and encourages the buyer to place a larger order (Yang et al., 2017) .

In Chapter 3, we develop a single-period two-stage supply contract model with put options (SCPO), consisting of one grower and one buyer. The grower can rent RAS to extend the shelf life of fruits. The decision processes are as follows: at the beginning of the planning horizon, based on the supply tariff from the grower and the demand forecast, the buyer places an initial order and purchases options. With the buyer's order and the random output rate, the grower determines the planting quantity. During the planting season, the buyer updates the demand forecast. At the beginning of the selling season, the buyer exercises options if necessary. Then, the grower delivers the final order and stores surplus products in RAS to extend the shelf life, which incurs extra storage costs that can be recovered by salvaging at a higher price later. We try to examine whether SCPO can improve the performances of the grower and the buyer.

Some literature related to option contracts in fresh FSCs does not consider the random yield. Few studies include the supplier's decision on the supply tariff. In our study, under the condition of random yield, we investigate the grower's decision on both the planting quantity and the prices of the option contract.

1.2.2 Flexible operation mode with CAS

For CAS, the life cycle of products can be extended longer (Paam et al., 2022). For some growers who leave the marketing of their produce to buyers and other intermediaries, the operation of rural agri-food supply chains can be more flexible. A longer life cycle enables growers to engage in selling produce in the off-season rather than only in the in-season. Many fresh fruits, especially high-value and storable ones, stored in CAS can be sold in the off-season. For example, kiwifruits are harvested from July to early November. After stored in CAS, the selling season can be extended to April (of the next year). Moreover, the selling price in the off-season may be higher 2-3 times than that in the in-season.

In this case, at the beginning of the planting season, the stochastic demand faced by growers would change from single stage to two stages, i.e., in-season and off-season. In addition, the output rate is random since it is affected by planting conditions and practices. It would be complicated for the grower to make policies on planting, store and sale. If the output quantity is less than the total demand, the grower would incur shortage cost. On the contrary, the grower has to salvage the leftover at little or even no value due to the perishability. Moreover, after harvesting, the grower would rent CAS space for fruits to sell in the off-season. CAS is charged costly. If the fruits stored in CASs exceed the off-seasonal demand, the grower would not only lose high storage costs but also miss the chance to sell the leftover in season. Conversely, the grower would incur shortage costs, which may be caused by allocating more products for sale in season. We try to provide solutions and address the grower’s policies on planting, store and sale, i.e.,

- How many quantities to plant under random yield?
- How to utilize cold storages (e.g., rent or not; how large capacity to rent) under stochastic two-stage demand?
- How to make an effort to improve the profit?

In Chapter 4, we consider a single-period three-stage model in a fresh FSC with CAS which enables the grower to sell the fruits in the off-season. The grower produces fruits during the planting season at Stage 1 and sells them to a two-stage market, i.e., in-season and off-season, in sequence. The grower has two decision-making points. One is the planting quantity at the beginning of the planting season and the other is the rental capacity of CAS at the beginning of the selling season. The decision processes are as follows: At the beginning of the planting season (Stage 1), based on the random yield and the two-stage stochastic demand, the grower determines the planting quantity. During the planting season, the grower updates forecast information. At the beginning of the in-season (Stage 2), with the updated demand information, the grower determines the rental capacity of CAS to store full or part of fruits. The remained fruits are assigned to the in-season. At the beginning of the off-season (Stage 3), the grower sells products stored in CAS.

Most of the literature focuses on the planting policy or/and inventory policy. However, to the best of our knowledge, there is no literature to study the planting policy and the inventory policies considering two-stage demand, simultaneously. We provide solutions for the grower on planting, store and sale to in-season and off-season.

1.3 Dissertation structure

This research mainly relates to three fields in fresh FSCs, i.e., supply contracts, planting and inventory planning. Chapter 2 reviews the related research by classifying them into two categories: supply contracts for agri-food supply chains, planting and inventory planning in agri-food supply chains. In each category, we describe the related literature and explain the difference with our models.

Depending on the extension period of shelf life, we propose flexible operation modes in rural fresh FSCs with RAS in Chapter 3 and with CAS in Chapter 4, respectively.

In Chapter 3, we propose the flexible supply contract with put options (SCPO) for a rural fresh FSC with RAS, where the grower stores fresh fruits in RAS to extend the shelf life, which incurs extra storage costs that can be recovered by salvaging at a higher price later. The proposed model is analyzed from both the grower's and the buyer's perspectives. We formulate the buyer's and the grower's profit functions, and derive the buyer's optimal policies for the initial order and put options as well as the grower's optimal policy for the planting quantity. The grower's optimal supply tariff can be obtained only numerically. In particular, we obtain closed-form formulae to determine the buyer's optimal order policy and the grower's optimal planting quantity in a special case. We show numerical experiments and analyze how the parameters affect the performances of both the grower and the buyer.

In Chapter 4, we consider a single-period, three-stage model in a fresh fruit supply chain with CAS. With rural CAS, the grower produces fresh fruits and then sells them to a two-stage market, i.e., in-season and off-season, in sequence. We formulate the grower's profit function, propose the solution for the grower to make the optimal planting quantity and derive the optimal rental capacity of CAS. In particular, we study this model in a special case, and analyze numerically how the parameters influence the grower's behavior in such a supply chain.

Finally, the conclusions of this dissertation are presented in Chapter 5. Subsequently, we explain the future direction of this research.

Chapter 2

Literature Review

2.1 Introduction

This research mainly relates to two fields in fresh FSCs, i.e., supply contracts, planting and inventory planning. Cachon (2003) provides a general review of supply contracts, such as return policy, backup agreement, pay-to-delay contract, and so on. Zhao et al. (2016) present a review of the supply contracts with stochastic demand, especially for option contract models. The reviews of Ahumada and Villalobos (2009) and Takner and Bilgen (2021) cover the research on planting, harvest, production, inventory and distribution planning for agri-food supply chains. Furthermore, Nguyen et al. (2021) provide a similar review for fresh FSCs.

This chapter classifies the related literature into two categories: supply contracts for agri-food supply chains, planting and inventory planning in agri-food supply chains. In each category, after presenting pertinent studies, we review the most relevant literature to highlight the motivation of our study. Differences between these models and ours are also discussed.

2.2 Supply contracts for agri-food supply chains

To overcome the drawbacks of the wholesale contract in agri-food supply chains, many flexible supply contracts are proposed. The commonly studied supply contracts include revenue/cost sharing contracts, wholesale/quantity discount contracts (Cai et al., 2013; Zheng et al., 2019) and option contracts.

Many researchers study revenue/cost sharing contracts to coordinate agri-food supply chains. Sun and Li (2018) propose a secondary-income contract where the third-party organization buys the agri-foods from farmers at a fixed-purchase price lower than the unit wholesale price and then gives the farmers the chance of getting secondary income at a distribution ratio of the revenue. They derive the optimal production cost input of farmers. Considering the circulation loss of fresh agri-foods, Yan et al. (2020a) propose a revenue-sharing contract in a fresh agri-food supply chain based on radio frequency identification. Feng et al. (2021) develop cost-sharing and compensation strategies where the retailer takes the initiative to undertake the supplier's part of proportion of freshness preservation effort level. They obtain the optimal fresh-keeping effort level of the supplier. Shi and Wang (2022) present a revenue-sharing contract under weather-related uncertain yield where the retailer shares not only the yield risk by purchasing all the realized output but also shares a portion of his sales revenue with the supplier.

To further reduce supply chain risks, some researchers combine revenue and cost sharing contracts. Zhao and Wu (2011) design a revenue-sharing contract where a supplier delivers goods with a price lower than unit production cost to the retailer while the retailer returns part of its revenue to the supplier, and derive the supplier's optimal input quantity. Zhang et al. (2015) design a revenue sharing and cooperative investment contract where the manufacturer provides a subsidy proportion to the retailer's preservation technology investment and the retailer shares a portion of revenue. Ye et al. (2017) develop a revenue-sharing-and-production-cost-sharing contract of an agribusiness firm and multiple risk-averse farmers and analyze the farmer's optimal production quantity. Ma et al. (2019) propose a coordination contract based on cost and revenue sharing in a three-echelon supply chain where third-party logistics service providers (TPLSP) offer refrigeration services for a supplier and a retailer. The supplier shares a ratio of the TPLSP's freshness-keeping costs and the retailer shares a percentage of sales revenue with the TPLSP. Similar to Zhang et al. (2015), Moon et al. (2020) propose a revenue sharing coupled with investment cost sharing contract where the retailer invests in fresh-keeping technology. They further propose an incremental quantity discount contract where the manufacturer provides incremental discounts according to order quantity.

Different from the above literature, the option contract is a risk sharing mechanism by quantity flexibility, which is widely used in various industries, such as electricity (Oum et al., 2006), air cargo (Chen and Parlar, 2007) and container leasing (Liu et al., 2013). Some researchers study option contracts in agri-food supply chains where the products are perishable. Yang et al. (2017) develop call, put and bidirectional option contracts. They derive the supplier's optimal production quantity and the retailer's optimal initial order quantity and the optimal option quantity. They find that the initial order quantity with the put option contract is the highest. Wang and Chen (2018) investigate a newsvendor problem for fresh produce with put option contracts, and find that the newsvendor when using put option contracts can reduce the inventory risks that is caused by demand uncertainty and high circulation loss of fresh produce, while they do not consider the supplier's decision. Yan et al. (2020b) propose a call option contract combined with a cost sharing contract to coordinate the supply chain where fresh agri-foods are with two-period price due to the perishability. They obtain the farmer's optimal output quantity and the optimal order quantity for agri-foods trading company. Wan et al. (2021) propose a call option contract for a fresh agri-food supply chain when the production cost and the loss rate are disrupted, simultaneously. They derive the optimal quantity of options purchased by the distributor and find the supplier's optimal supply tariff numerically. Liao and Lu (2022) consider a three-level fresh agri-food supply chain and discuss a call option contract between the supplier and the retailer, and a wholesale price contract between the supplier and the producer. They obtain the optimal production input of the producer, and the optimal order quantity of the retailer.

Please observe that the characteristic of the supply chain in Chapter 3 is a fresh FSC with cold storages where the grower has an incentive to provide a put option contract for a larger order. Yang et al. (2017) and Wang and Chen (2018) are the closest to our model. However, different from them, we consider the random yield during production but they do not. Furthermore, we optimize the grower's supply tariff whereas they assume the contract prices are fixed parameters.

2.3 Planting and inventory planning in agri-food supply chains

2.3.1 Planting planning

A summary of the research related to planting planning is presented in Table 2.1, most of which focus on the fresh FSC. Many researchers consider planting planning models in multiple periods. In addition to the decision on planting quantity, decisions on varieties selection or/and planting time are also analyzed. Willis and Hanlon (1976) propose a temporal model to select an "optimum mix" of varieties of apples for planting over time, with the resources including storage capacity, capital and acres of orchard land. Darby-Dowman et al. (2000) present a recourse model for the problem of determining optimal planting plans involving the area, spacing and timing of planting the different varieties for a vegetable grower. Hester and Cacho (2003) build a bioeconomic model from planting to maturity utilizing dynamic simulation to find optimal thinning rates over the lifetime of the orchard by maximizing net present value. Cittadini et al. (2008) explore options for farm-scale strategic and tactical decision-making in farms in South Patagonia specialized in fruit production to maximize the profit and optimize the cumulative farm labor. Their main outcomes are the selected combinations of crop species and production techniques, the area of each combination assigned to specific land units and the timing of implementation of the orchard development plan. Tan and Çömden (2012) present a long-range planning methodology for a firm that purchases premium fruits or vegetables from farms and sells to retailers, and propose an approach to the optimal seeding time and area for each farm. Catalá et al. (2013) present a strategic planning model for pear and apple production and show optimal investment policy for the replacement of varieties under different scenarios.

Table 2.1: Summary of the research related to planting planning

Reference	Varieties of agri-foods	Planting policy			Considerations		
		Quantity	Variety	Time	Random yield	Stochastic demand	Cold storages
Willis and Hanlon (1976)	Apple	○	○	○			○
Hamer (1994)	Brussels sprout	○	○	○	○		○
Darby-Dowman et al. (2000)	Vegetable	○	○	○	○	○	
Hester and Cacho (2003)	Apple	○			○		
Kazaz（2004）	Olive	○			○	○	
Cittadini et al. (2008)	Cherry	○	○	○			
Tan and Çömden (2012)	Fruit and vegetable	○		○	○	○	
Catalá et al. (2013)	Pear and apple	○	○		○		
Golmohammadi and Hassini（2019）		○			○	○	
The model in Chapter 4	Fresh fruit	○			○	○	○

Some researchers consider single-period models. Hamer (1994) builds a decision support system for planting plans including variety selecting, sowing date and planting density for Brussels sprouts to meet the demand of different customers, and takes the cost of cooling and storage into consideration. Kazaz (2004) studies production planning for an olive oil producer who leases farm space from farmers to grow olives, and then determines the optimal amount of farm space to be leased and the optimal choices for olive oil production. Golmohammadi and Hassini (2019) study the problem of production planning, pricing and capacity planning of a farmer, and analyze the optimal size of the land to be planted and that to be rented in order to maximize the farmer’s profit. Similar to Kazaz (2004) and Golmohammadi and Hassini (2019), the model built in Chapters 4 focus on decision-making for planting quantity. However, we take cold storages into consideration whereas they do not.

2.3.2 Inventory planning

A summary of the research related to inventory planning is presented in Table 2.2. There are three main categories: economic order quantity (EOQ), inventory control and inventory allocation. The EOQ model is one of the oldest known models and a lot of work has been done on this model. Chen et al. (2016) provide a method to determine the optimal replenishment policy of a deteriorative agri-products supply chain including a supermarket and a facility agriculture enterprise. Singh (2016) builds an inventory model for perishable items with constant demand, for which the holding cost increases with time, such as the warehouse cost in cold storages, and provides the optimal solution for the inventory level and the order quantity. Some researchers focus on the inventory control problem. Masini et al. (2011) present a tactical planning model for a typical large company that operates several nodes of the fruit industry supply chain and provide the “production profiles” of packed fruit, concentrated juice and cider, which should be pursued to optimize the business profit, along with the required profiles of raw fruit and cold storage to feasibly operate throughout the fruit business cycle. Xu et al. (2019) propose a simulation-based optimization model of the three-level inventory system for fresh agri-foods, which consists of one manufacturer, multiple distributors, multiple retailers and one supplier. They provide the optimal inventory control policy.

Inventory allocation problem, widely concerned by researchers, can be divided into two types: allocation based on storages and allocation based on time. In the argi-food supply chain, many researchers focus on inventory allocation based on storages. Some literature considers three types of cold storage, i.e., RAS, CAS and smart-fresh CAS. Soto-Silva et al. (2017) develop a model combined purchasing and storage for an apple processing plant that purchases apples stored in different cold chambers divided by fresh keeping ability to minimize the storage cost. Based on Soto-Silva et al. (2017), Mateo-Fornés et al. (2021) explore the benefits of a two-stage stochastic programming model for purchase and storage decisions. Paam et al. (2019) propose inventory policies by optimizing the configuration of storage rooms for an apple industry in order to reduce apple loss.

Table 2.2: Summary of the research related to inventory planning

Reference	Varieties of agri-foods	Inventory policy			Considerations		
		EOQ	Inventory control	Inventory allocation*	Random yield	Stochastic demand	Cold storages
Masini et al. (2011)	Pear and apple		○				○
Chen et al. (2016)	Deteriorative agri-food	○				○	
Singh (2016)	Perishable items	○					○
Hou et al. (2017)	Fresh agri-food		○	T		○	○
Soto-Silva et al. (2017)	Apple			S			○
Liu et al. (2018)	Perishable agri-food			T		○	○
Paam et al. (2019)	Apple			S			○
Xu et al. (2019)	Fesh agri-food		○			○	
Pourmohammadi et al. (2020)	Wheat			S	○	○	
Mateo-Fornés et al. (2021)	Apple			S			○
Paam et al. (2022)	Fresh agri-food		○	S			○
The models in Chapter 4	Fresh fruit			T	○	○	○

* Inventory allocation according to storages (S) or time (T).

Pourmohammadi et al. (2020) propose a mixed-integer linear mathematical model for redesigning and planning of the wheat supply chain to address supplier selection, ordering, storing, transportation, and distribution problems considering long-term and short-term storage facilities. They determine the location and capacity of new storage facilities. Paam et al. (2022) solve multiple-period, multiple-product and multiple-warehouse inventory control and allocation problem where each warehouse has two modes (RAS and CAS). They provide the optimal number and mode of warehouses in each period.

Different from them, the model in Chapter 4 analyzes the inventory allocation problem based on time, that is, whether to allocate the fruits to be stored in CAS for a later off-season sale or not. Few researchers focus on inventory allocation based on time. Hou et al. (2017) build a multi-stage inventory control and allocation model for a wholesaler who sells fresh produce at a wholesale market and addresses display, disposal and order policies with cooling facilities. Liu et al. (2018) propose a single-product finite-stage inventory model for a wholesaler where warehouses are available. They address policies on the optimal purchase and inventory retrieval quantities. Both of them assume that sell fresh produce in the in-season, while our model in Chapter 4 focuses on the inventory allocation in a two-stage market, i.e., in-season for the first stage and off-season for the second stage, with relative independence and different retail prices.

2.3.3 Planting and inventory planning

After a long planting season, growers might proceed to participate in logistics, such as inventory, transportation and distribution. Some researchers integrate planting and inventory decisions. Ahumada and Villalobos (2011) present a tactical planning model for a large fresh produce grower to maximize revenues. The main decisions involve when and how much to plant of each crop, when to harvest and sell the crops and how much products to store. Based on Ahumad and Villalobos (2011), Ahumada et al. (2012) expand the model with the variability of weather and demand. Costa et al. (2014) study a vegetable crop rotation problem with demand constraints to decide what and when to produce given a set of lands. They analyze the inventory policy with the possibility of stocking harvested crops. Catalá et al.

(2016) propose a bi-objective optimization model for tactical planning in the pome fruit supply chain with CAS and RAS, and integrate production, distribution and inventory decisions. Fikry et al. (2021) presents an integrated strategic-tactical planning model for the sugar beet supply chain to optimally solve the production planning problem of when, where and how much to plant and the logistics problem involving transportation and inventory. Alemany et al. (2021) develop a set of models to analyze when and how much to plant and store of fresh tomatoes for multi-farmer supply chains under yield and demand uncertainties in different scenarios. They consider selling fresh products in in-season markets.

From Table 2.3, we can observe that the related literature studies the planting and inventory planning under a single-stage demand. However, the demand in our study has two stages. Among the researches, Ahumada et al. (2012) and Alemany et al. (2021) also consider both random yield and stochastic demand. Different from our models in Chapter 4 and 5, they do not study the effect of CAS on the supply chain.

2.4 Chapter summary

As this research mainly relates to three fields in fresh FSCs, i.e., supply contracts, planting and inventory planning, we classify the related literature into two categories: supply contracts for agri-food supply chains, planting and inventory planning in agri-food supply chains. In each category, after presenting pertinent studies, we review the most relevant literature to highlight the motivation of our study. Differences between these models and ours are also discussed.

Table 2.3: Summary of the research related to planting and inventory planning

Reference	Varieties of agri-foods	Planting policy			Inventory policy		Considerations			
		Quantity	Variety	Time	Inventory control	Inventory allocation	Random yield	Stochastic demand	Cold storages	Two/multi-stage demand
Ahumad and Villalobos (2011)	Fresh produce	○	○	○		○				
Ahumad et al. (2012)	Fresh produce	○	○	○		○	○	○		
Costa et al. (2014)	Vegetable	○	○	○		○		○		
Catalá et al. (2016)	Pear and apple	○	○		○				○	
Fikry et al. (2021)	Suger beet	○	○	○		○				
Alemany et al. (2021)	Tomato	○	○	○		○	○	○		
The model in Chapter 4	Fresh fruit	○				○	○	○	○	○

Chapter 3

Flexible Supply Contract with Put Options with Regular Atmosphere Storage

3.1 Introduction

This chapter studies the flexible supply contract with put options (SCPO) for a rural fresh FSC with RAS, where the grower stores fresh fruits in RAS to extend the shelf life, which incurs extra storage costs that can be recovered by salvaging at a higher price later. Our objective is to determine the grower's optimal planting policy and optimal supply tariff as well as the buyer's optimal order policies. We also analyze how the parameters affect the performances of both the grower and the buyer[1].

3.2 Model

[1]Partial content of this chapter has been published on the Journal of Japan Industrial Management Association, Vol.73, No.2E (Bai and Wang, 2022)

3.2.1 Notation and assumptions

Table 3.1 presents the parameters and decision variables used throughout this chapter. We consider a single-period, two-stage supply contract in a rural fresh FSC with random yield and stochastic demand. The buyer, who is far away from the grower and the spot market, orders fresh fruits from the grower and sells them to the market. The grower has one opportunity to plant one batch and is not allowed to be out of stock. When the output is less than the order, the grower replenishes the shortfall from the spot market where the number of products is sufficient. Note that the buyer cannot replenish inventory from the grower or the spot market because the market is very far, and the grower only accepts orders under her maximum production capacity. The RAS, as an external party with enough storage capacity, is available for the grower, which enables the grower to salvage the unsold fruits at a higher salvage price. All of the unsold products may be salvaged by both the grower and the buyer.

At the beginning of the planning horizon, the grower knows the output rate K ($K > 0$) with distribution function $\mathrm{T}(\cdot)$. The mean of K is $\bar{k}$. The values of n and m are based on experience but excluding extreme cases such as disasters resulted in no harvest. The buyer knows the demand D ($D \geq 0$) with distribution function $F(\cdot)$. After harvesting, the grower specifies K as a value k. Just before delivery, the buyer updates information and specifies the D as a value ξ.

Throughout the chapter, we assume the wholesale price and retail price are exogenously. We assume $\{w, g\} > c/\bar{k} > v_g$. Let $w > c/\bar{k}$ to ensure the grower to be possible to get marginal profit from planting. Let $g > c/\bar{k}$, otherwise the grower would purchase fruits from the spot market rather than planting. Let $c/\bar{k} > v_g$, otherwise the grower would earn infinite profit by salvaging products if she could plant infinite products. Furthermore, we assume $w > v_b$ as well.

Table 3.1: Notation throughout Chapter 3

Decision variables	
Q_{nvo}	Order quantity in NV model
Q_{nvp}	Planting quantity in NV model
Q_0	Quantity of initial order
q_0	Quantity of put options purchased
q_{ep}	Quantity of put options exercised
Q_{op}	Planting quantity in SCPO model
w_o	Unit price of put option
w_{ep}	Unit exercise price of put option
Parameters	
w	Unit wholesale price (including the shipping cost)
r	Unit retail price
p	Unit shortage cost
c	Unit planting cost
g	Unit spot market price
v_g	Unit salvage price of products stored in RAS for the grower
v_b	Unit salvage price for the buyer
K	The output rate (stochastic variable)
n	Minimum output rate during certain years
m	Maximum output rate during certain years
k	Determined value of K
$\tau(\cdot)$	Probability density function of K
$\mathrm{T}(\cdot)$	Cumulative density function of K
D	Demand for fresh fruits (stochastic variable)
ξ	Determined value of D
$f(\cdot)$	Probability density function (pdf) of D
$F(\cdot)$	Cumulative density function (cdf) of D

3.2.2 The traditional operation mode with RAS

This is a traditional operation mode of a fresh FSC with RAS, i.e., newsvendor (NV) model. The buyer places an order Q_{nvo} according to the demand forecast at the beginning of the planning horizon t_0, paying wholesale cost w for each unit. The grower plants the amount Q_{nvp} based on the buyer's order and the random output rate with unit planting cost c. At the beginning of the selling season t_1, the grower delivers products to the buyer and any order that cannot be met will be satisfied via the spot market. The grower's surplus products can be stored in RAS to extend their shelf life and they can be salvaged at v_g for each unit. During the selling season, the buyer earns revenues from each satisfied demand and incurs shortage cost p for any unsatisfied demand. At the end of the selling season, the buyer obtains an additional cash inflow from salvaging the unsold products. The model is graphically presented in Figure 3.1.

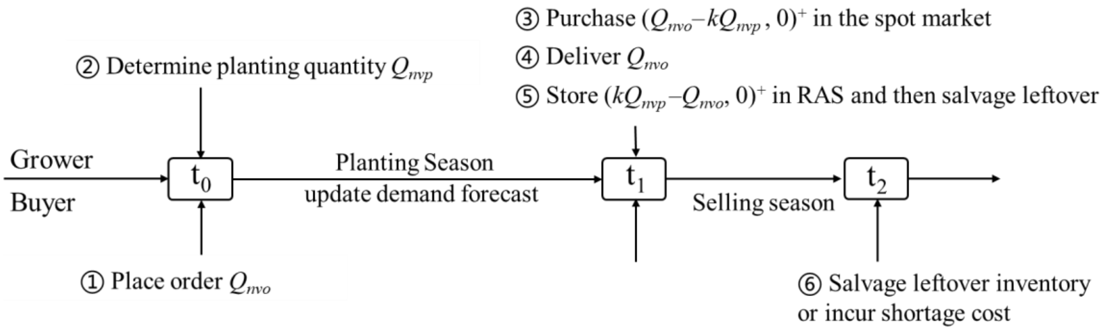

Figure 3.1: Graphical representation of the NV model

Based on the above description, the buyer's expected profit at t_0 is

$$PFT_{nvb}\left(Q_{nvo}\right) = -wQ_{nvo} + \int_{0}^{Q_{nvo}} \left[r\xi + v_b(Q_{nvo} - \xi)\right] f\left(\xi\right) d\xi$$
$$+ \int_{Q_{nvo}}^{\infty} \left[rQ_{nvo} - p(\xi - Q_{nvo})\right] f\left(\xi\right) d\xi$$

The first term represents the purchase cost. The second term is the revenues from selling and salvage when the buyer's order quantity meets the actual demand. The third term is the selling revenue and shortage cost when the buyer's order quantity does not satisfy the actual demand.

The buyer's problem is to maximize the profit by choosing the appropriate order quantity Q_{nvo} at the beginning of the planting season t_0.

$$\max PFT_{nvb}\left(Q_{nvo}\right)$$

$$\text{subject to } Q_{nvo} \geq 0$$

Taking the derivative of $PFT_{nvb}\left(Q_{nvo}\right)$ with respect to Q_{nvo} and equating it to zero, we get the following optimality condition:

$$F\left(Q_{nvo}\right)=\frac{r+p-w}{r+p-v_b} \tag{3.1}$$

If there exists a non-negative value of $Q_{nvo}^{'}$ which satisfies equation (3.1), then the optimal order quantity is $Q_{nvo}^{*}=Q_{nvo}^{'}$.

The grower's expected profit at t_0 is

$$PFT_{nvg}\left(Q_{nvp}\right)=-cQ_{nvp}+wQ_{nvo}-\int_{0}^{Q_{nvo}/Q_{nvp}} g\left(Q_{nvo}-kQ_{nvp}\right)\tau\left(k\right)dk$$
$$+\int_{Q_{nvo}/Q_{nvp}}^{\infty} v_g\left(kQ_{nvp}-Q_{nvo}\right)\tau\left(k\right)dk$$

The first term is the planting cost. The second term is the revenue received from the order. The third and fourth terms are the replenishment cost and the salvage revenue when the output quantity does not satisfy and meets the order, respectively.

The grower's problem is to maximize the profit by choosing the appropriate planting quantity Q_{nvp} at the beginning of the planting season t_0.

$$\max PFT_{nvg}\left(Q_{nvp}\right)$$

$$\text{subject to } Q_{nvp}>0$$

Proposition 1. There exists a non-negative value of $Q_{nvp}^{'}$ which satisfies equation (3.2), and the optimal planting quantity is $Q_{nvp}^{*}=Q_{nvp}^{'}$.

$$g\int_{0}^{Q_{nvo}/Q_{nvp}} k\tau\left(k\right)dk+v_g\int_{Q_{nvo}/Q_{nvp}}^{\infty} k\tau\left(k\right)dk=c \tag{3.2}$$

Proof: See Appendix A.1.

3.2.3 The flexible operation mode with RAS

This is a flexible operation mode with put options for a fresh FSC with RAS, i.e., SCPO model. At the beginning of the planting season $t_{0,1}$, the grower provides a supply tariff (i.e., wholesale price w (exogenous variable), option price w_o and exercise price w_{ep}.). With the supply tariff, the buyer determines the order policy (i.e., initial order Q_0 and put options q_0) based on the market demand forecast at $t_{0,2}$. After that, considering the buyer's order and random output rate, the grower determines the planting quantity Q_{op} at $t_{0,3}$. At the beginning of the selling season t_1, according to the updated information, the buyer can exercise options q_{ep} at the unit exercise price w_{ep} to adjust the initial order quantity downward if necessary. Then, the grower delivers the final order Q_0 - q_{ep} to the buyer and any unsatisfied order can be satisfied via the spot market. The grower's surplus products can be stored in RAS, which can be salvaged at v_g for each unit later. At the end of the selling season, the buyer obtains an additional cash inflow from salvaging unsold products or incurs a shortage cost. Graphical representation of SCPO model is presented in Figure 3.2.

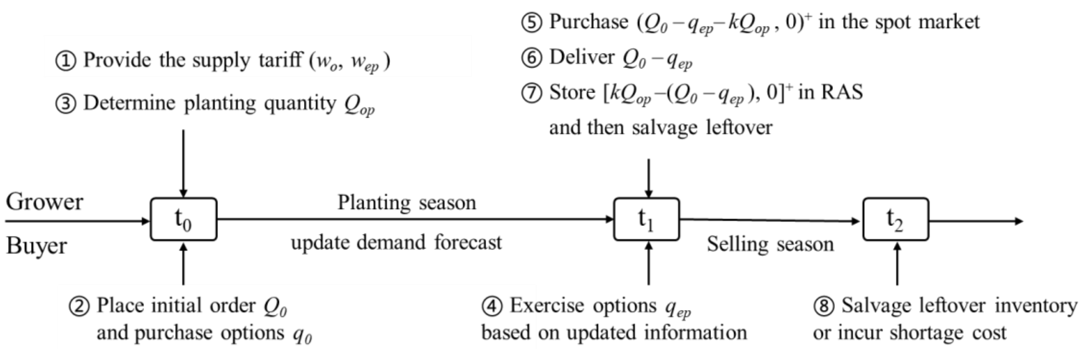

Figure 3.2: Graphical representation of the SCPO model

In this model, it is assumed that $w_{ep} \leq w$ to ensure that the buyer can get back a full or partial refund if exercising options, and that $v_b \leq w_{ep} - w_o$ to ensure that the options are profitable for the buyer to exercise. To ensure the buyer's incentive to purchase options, it is assumed $w_o \leq w$ and $r + p > w + w_o$. Let $v_g < w_{ep}$ ensure that the grower earns a profit from selling products rather than options.

The buyer's problem

The buyer's problem is to determine the optimal values of Q_0 and q_0 at $t_{0,2}$ and q_{ep} at t_1. In order to solve the buyer's problem at $t_{0,2}$, we first analyze the optimal policy at t_1. At the beginning of the selling season t_1, the buyer has placed an initial order Q_0 and purchased q_0 options. With $D=\xi$ observed, the buyer determines the quantity of options to be exercised q_{ep} in order to satisfy the demand during the selling season. Depending on the value of ξ, the buyer's optimal quantity of options to be exercised at time t_1 is

$$q_{ep}^{*}=\begin{cases} q_0 & if \quad \xi < Q_0 - q_0 \\ Q_0-\xi & if \quad Q_0 - q_0 \le \xi \le Q_0 \\ 0 & if \quad Q_0 < \xi \end{cases}$$

At t_0, the buyer's expected profit can be written as

$$PFT_{ob}\left(Q_0,q_0\right)=-wQ_0-w_oq_0+\int_0^{Q_0-q_0}\left[w_{ep}q_0+r\xi+v_b(Q_0-q_0-\xi)\right]f\left(\xi\right)d\xi$$
$$+\int_{Q_0-q_0}^{Q_0}\left[w_{ep}\left(Q_0-\xi\right)+r\xi\right]f\left(\xi\right)d\xi+\int_{Q_0}^{\infty}\left[rQ_0-p(\xi-Q_0)\right]f\left(\xi\right)d\xi$$

The first and second term represents the purchase costs of the initial order and put options. The third, fourth and fifth terms are the expected profits during the selling season when the actual demand ξ is in the intervals (0, Q_0 - q_0), [Q_0 - q_0, Q_0] and (Q_0, ∞), respectively. When ξ is in the interval (0, Q_0 - q_0), $\xi < Q_0 - q_0$ holds, i.e., even if the buyer exercises all options q_0, the demand is smaller than the final order quantity Q_0 - q_0. Thus, the buyer inevitably holds overage inventory. The fourth and fifth terms can be analyzed similarly.

The buyer's problem is to determine the number of the initial order Q_0 and the number of options purchased q_0 to maximize the profit function during the planning horizon.

$$\max PFT_{ob}\left(Q_0,q_0\right)$$

$$\text{subject to } Q_0 \geq 0, \quad q_0 \geq 0$$

Differentiating $PFT_{ob}(Q_0, q_0)$ with respect to Q_0 and q_0, respectively, and equating them to zero, we get the optimal solution at t_0 as described in Proposition 2.

Proposition 2. If there exist non-negative values of $Q_0^{'}$ and $q_0^{'}$ which satisfy

$$F(Q_0) = \frac{r + p - w - w_o}{r + p - w_{ep}} \tag{3.3}$$

and

$$F(Q_0 - q_0) = \frac{w_{ep} - v_b}{w_o} \tag{3.4}$$

then the optimal initial order is $Q_0^* = Q_0^{'}$ and the optimal number of put options purchased is $q_0^* = q_0^{'}$.

Proof: See Appendix A.2.

The grower's problem

The grower's problem is to determine the optimal values of w_o and w_{ep} at $t_{0,1}$, and then to determine the planting quantity Q_{op} at $t_{0,3}$. In order to solve the grower's problem at $t_{0,1}$, we first analyze the optimal planting quantity. At $t_{0,3}$, after receiving the order from the buyer, the grower determines the optimal planting quantity considering the random output rate. Depending on the values of the actual demand ξ and the output rate k at t_1, six cases can be derived in Table 3.2.

Table 3.2: Six cases for values of demand ξ and output rate k at t_1

No.	Intervals of ξ, k	Buyer's final order quantity	Overage inventory or shortage for the grower
1	$\left\{\xi, kQ_{op}\right\} \le Q_0 - q_0$	$Q_0 - q_0$	Shortage
2	$\xi \le Q_0 - q_0 < kQ_{op}$	$Q_0 - q_0$	Overage inventory
3	$\left\{Q_0 - q_0, kQ_{op}\right\} < \xi \le Q_0$	ξ	Shortage
4	$Q_0 - q_0 < \xi \le \left\{Q_0, kQ_{op}\right\}$	ξ	Overage inventory
5	$kQ_{op} \le Q_0 < \xi$	Q_0	Shortage
6	$Q_0 < \left\{\xi, kQ_{op}\right\}$	Q_0	Overage inventory

At $t_{0,3}$, the grower determines the planting quantity Q_{op} to maximize the profit function as below

$$\max PFT_{og}\left(Q_{op}\right)$$

$$= \max \left\{ \begin{array}{l} -cQ_{op} \\ + \int_0^{Q_0-q_0} \left\{ \begin{array}{l} -w_{ep}q_0 + \int_0^{(Q_0-q_0)/Q_{op}} \left[-g\left(Q_0 - q_0 - kQ_{op}\right)\right]\tau(k)\,dk \\ + \int_{(Q_0-q_0)/Q_{op}}^{\infty} v_g\left[kQ_{op} - \left(Q_0 - q_0\right)\right]\tau(k)\,dk \end{array} \right\} f(\xi)\,d\xi \\ + \int_{Q_0-q_0}^{Q_0} \left\{ \begin{array}{l} -w_{ep}(Q_0 - \xi) + \int_0^{\xi/Q_{op}} \left[-g\left(\xi - kQ_{op}\right)\right]\tau(k)\,dk \\ + \int_{\xi/Q_{op}}^{\infty} v_g\left(kQ_{op} - \xi\right)\tau(k)\,dk \end{array} \right\} f(\xi)\,d\xi \\ + \int_{Q_0}^{\infty} \left\{ \int_0^{Q_0/Q_{op}} \left[-g\left(Q_0 - kQ_{op}\right)\right]\tau(k)\,dk + \int_{Q_0/Q_{op}}^{\infty} v_g\left(kQ_{op} - Q_0\right)\tau(k)\,dk \right\} f(\xi)\,d\xi \end{array} \right\}$$

subject to $Q_{op} > 0$

Taking the derivative of $PFT_{og}\left(Q_{op}\right)$ with respect to Q_{op} and equating it to zero, we get the optimal planting quantity at $t_{0,3}$ as described in Proposition 3.

Proposition 3. There exists a non-negative value of $Q_{op}^{'}$ which satisfy the equation (3.5), and the optimal planting quantity is $Q_{op}^{*}=Q_{op}^{'}$.

$$v_g \int_{Q_0/Q_{op}}^{\infty} k\tau(k)dk + (g-v_g)\begin{bmatrix} F(Q_0-q_0)\int_{\xi/Q_{op}}^{(Q_0-q_0)/Q_{op}} k\tau(k)dk \\ +F(Q_0)\int_{Q_0/Q_{op}}^{\xi/Q_{op}} k\tau(k)dk \end{bmatrix} = c - g\int_0^{Q_0/Q_{op}} k\tau(k)dk \quad (3.5)$$

Proof: See Appendix A.3.

At $t_{0,1}$, the grower's problem is to find the optimal supply tariff by solving the optimization equation:

$$\max PFT_{og,t_0}(w_o,w_{ep}) = \max\left[wQ_0 + w_o q_0 + \Pi_{og}(Q_{op})\right]$$

$$\text{subject to } w_o > 0,\quad w_{ep} > 0$$

The closed-form solutions for w_o and w_{ep} are difficult to derive since Q_o and q_0 are functions of w_o and w_{ep}. Therefore, we use numerical experiments to analyze the optimal supply tariff.

To obtain closed-form solutions of the buyer's order policy and the grower's planting quantity, we demonstrate the above two models in a case of uniformly distributed demand and output rate below.

3.3 Justification of the proposed model

In this section, we analyze a special case where demand and output rate are both uniformly distributed. At t_0, the grower knows the output rate K follow uniform distribution over interval [n, m]. And the buyer knows that demand D is uniformly distributed over [$\gamma-\beta,\gamma+\beta$]. After harvesting, the grower specifies K as a value k. Just before delivery, the buyer specifies the D as a value ξ with the updated demand information. The pdf and cdf of ξ and K are as follows.

$$f(\xi)=\frac{1}{2\beta} \qquad \xi\in[\gamma-\beta,\gamma+\beta],$$

$$F(\xi)=\frac{\xi-\gamma+\beta}{2\beta} \qquad \xi\in[\gamma-\beta,\gamma+\beta],$$

$$\tau(k)=\frac{1}{m-n} \qquad k\in[n,m],$$

$$\mathrm{T}(k)=\frac{k-n}{m-n} \qquad k\in[n,m].$$

In this model, considering the grower neither holds overage inventory nor is out of stock absolutely, we have $\frac{Q_{nvo}}{m}\le Q_{nvp}\le\frac{Q_{nvo}}{n}$ in NV model and $\frac{Q_0-q_0}{m}\le Q_{op}\le\frac{Q_0}{n}$ in SCPO model.

3.3.1 The traditional operation mode with RAS

At t_0, the buyer's problem is to maximize the profit function $SPFT_{nvb}(Q_{nvo})$ by choosing the appropriate order quantity Q_{nvo}.

$$\max SPFT_{nvb}(Q_{nvo})=\max\left\{\begin{array}{l}-wQ_{nvo}+\int_{\gamma-\beta}^{Q_{nvo}}\left[r\xi+v_b(Q_{nvo}-\xi)\right]f(\xi)d\xi\\ +\int_{Q_{nvo}}^{\gamma+\beta}\left[rQ_{nvo}-p(\xi-Q_{nvo})\right]f(\xi)d\xi\end{array}\right\}$$

Taking the derivative of $SPFT_{nvb}(Q_{nvo})$ with respect to Q_{nvo}, the buyer's optimal order quantity is obtained:

$$Q_{nvo}^{*}=\gamma+\beta-\frac{2\beta(w-v_b)}{r+p-v_b} \tag{3.6}$$

At t_0, the grower's problem is to maximize the profit function $SPFT_{nvg}(Q_{nvp})$ by choosing the appropriate planting quantity Q_{nvp}.

$$\max SPFT_{nvg}\left(Q_{nvp}\right)=\max\left\{\begin{array}{l}-cQ_{nvp}+wQ_{nvo}-\int_{n}^{Q_{nvo}/Q_{nvp}} g\left(Q_{nvo}-kQ_{nvp}\right)\tau\left(k\right)dk \\ +\int_{Q_{nvo}/Q_{nvp}}^{m} v_g\left(kQ_{nvp}-Q_{nvo}\right)\tau\left(k\right)dk\end{array}\right\}$$

Taking the derivative of $SPFT_{nvg}\left(Q_{nvp}\right)$ with respect to Q_{nvp}, the grower's optimal planting quantity is described in Proposition 4.

Proposition 4. The grower's optimal planting quantity is defined as

$$Q_{nvp}^{*}=\begin{cases}\dfrac{Q_{nvo}}{m} & if\ \ Q_{nvp1}<\dfrac{Q_{nvo}}{m} \\ Q_{nvp1} & if\ \ \dfrac{Q_{nvo}}{m}\le Q_{nvp1}\le\dfrac{Q_{nvo}}{n} \\ \dfrac{Q_{nvo}}{n} & if\ \ \dfrac{Q_{nvo}}{n}<Q_{nvp1}\end{cases}$$

where

$$Q_{nvp1}=Q_{nvo}\sqrt{\frac{g-v_g}{gn^2-v_g m^2+2(m-n)c}}$$

Proof: See Appendix A.4.

3.3.2 The flexible operation mode with RAS

The buyer's problem

Based on the description in Section 3.2.3, the buyer's expected profit at $t_{0,2}$, can be written as

$$\begin{aligned}SPFT_{ob}\left(Q_0,q_0\right)=&-wQ_0-w_o q_0+\int_{\gamma-\beta}^{Q_0-q_0}\left[w_{ep}q_0+r\xi+v_b(Q_0-q_0-\xi)\right]f\left(\xi\right)d\xi \\ &+\int_{Q_0-q_0}^{Q_0}\left[w_{ep}\left(Q_0-\xi\right)+r\xi\right]f\left(\xi\right)d\xi+\int_{Q_0}^{\gamma+\beta}\left[rQ_0-p(\xi-Q_0)\right]f\left(\xi\right)d\xi\end{aligned}$$

The buyer's problem is to determine the number of the initial order Q_0 and the number of options purchased q_0 to maximize the profit function during the planning horizon. Differentiating $SPFT_{ob}\left(Q_0, q_0\right)$ with respect to Q_0 and q_0, respectively, and equating them to zero, we derive the optimization conditions as

$$Q_0 = \gamma + \beta - \frac{2\beta(w + w_o - w_{ep})}{p + r - w_{ep}} \tag{3.7}$$

$$q_0 = \frac{2\beta(p + r - w - w_o)}{p + r - w_{ep}} + \frac{2\beta w_o}{\left(v_b - w_{ep}\right)} \tag{3.8}$$

It can be readily proved that $Q_0 > 0$. On the other hand, to obtain $q_0 > 0$, we need the following inequality

$$w_o < \frac{(w_{ep} - v_b)(p + r - w)}{p + r - v_b} \tag{3.9}$$

If the inequality (3.9) holds, the optimal initial quantity Q_0^* and the optimal quantity of put options purchased q_0^* follow the equation (3.7) and equation (3.8), respectively.

Otherwise, the optimal $q_0^* = 0$ and $Q_0^* = Q_{nvo}^*$ as in the equation (3.6).

Proposition 5. The buyer's optimal policy for Q_0 and q_0 satisfies the following properties:

(i) Q_0 increases with w_{ep} and p, and decreases with w_o.

(ii) q_0 increases with w_{ep}, β and p, and decreases with w_o and v_b.

Proof: See Appendix A.5.

The grower's problem

At $t_{0,3}$, after receiving the order from the buyer, the grower determines the optimal planting quantity. Depending on the values of Q_0 and q_0, four planting plans are derived as follows.

Plan 1. $Q_0 - q_0 \le nQ_{op} < mQ_{op} \le Q_0$.

In this case, the output quantity cannot fulfill the initial order but can satisfy the firm order quantity (Q_0 - q_0) from the buyer. Here, depending on the values of the actual demand ξ and the output rate k at t_1, six cases can be derived as shown in Table 3.3.

Table 3.3: Six cases for values of demand ξ and output rate *k* at t_1 in plan 1

No.	Intervals of ξ, k	Buyer's final order quantity	Overage inventory or Shortage for the grower
1	$\xi \le Q_0 - q_0 < kQ_{op}$	Q_0-q_0	Overage inventory
2	$Q_0 - q_0 < \xi < nQ_{op} \le Q_0$	ξ	Overage inventory
3	$Q_0 - q_0 < kQ_{op} < \xi \le Q_0$	ξ	Shortage
4	$Q_0 - q_0 < \xi \le kQ_{op} \le Q_0$	ξ	Overage inventory
5	$mQ_{op} < \xi \le Q_0$	ξ	Shortage
6	$kQ_{op} \le Q_0 < \xi$	Q_0	Shortage

The grower determines the optimal planting quantity Q_{op} to maximize the profit function

$$\max SPFT_{og}^{1}\left(Q_{op}\right)$$

$$= \max \left\{ \begin{aligned} & -cQ_{op} + \int_{\gamma-\beta}^{Q_0-q_0} \left\{ -w_{ep} q_0 + \int_n^m v_g \left[kQ_{op} - \left(Q_0 - q_0\right) \right] \tau(k)\, dk \right\} f(\xi)\, d\xi \\ & + \int_{Q_0-q_0}^{nQ_{op}} \left\{ -w_{ep}(Q_0 - \xi) + \int_n^m v_g (kQ_{op} - \xi) \tau(k)\, dk \right\} f(\xi)\, d\xi \\ & + \int_{nQ_{op}}^{mQ_{op}} \left\{ -w_{ep}(Q_0 - \xi) + \int_n^{\xi/Q_{op}} \left[-g\left(\xi - kQ_{op}\right) \right] \tau(k)\, dk + \int_{\xi/Q_{op}}^{m} v_g (kQ_{op} - \xi) \tau(k)\, dk \right\} f(\xi)\, d\xi \\ & + \int_{mQ_{op}}^{Q_0} \left\{ -w_{ep}(Q_0 - \xi) + \int_n^m \left[-g\left(\xi - kQ_{op}\right) \right] \tau(k)\, dk \right\} f(\xi)\, d\xi \\ & + \int_{Q_0}^{\gamma+\beta} \left\{ \int_n^m \left[-g\left(Q_0 - kQ_{op}\right) \right] \tau(k)\, dk \right\} f(\xi)\, d\xi \end{aligned} \right\}$$

subject to $\dfrac{Q_0 - q_0}{n} \le Q_{op} \le \dfrac{Q_0}{m}$

Plan 2. $nQ_{op} \le Q_0 - q_0 < Q_0 \le mQ_{op}$.

Here, the maximum output quantity is higher than the initial order whereas the minimum output quantity is lower than the firm order (Q_0 - q_0). Six cases can be derived as shown in Table 3.2.

The grower determines the optimal planting quantity Q_{op} to maximize the expected profit function

$$\max SPFT_{og}^{2}\left(Q_{op}\right)$$

$$= \max \left\{ \begin{array}{l} -cQ_{op} + \int_{\gamma-\beta}^{Q_0-q_0} \left\{ \begin{array}{l} -w_{ep}q_0 + \int_{n}^{(Q_0-q_0)/Q_{op}} \left[-g\left(Q_0 - q_0 - kQ_{op}\right)\right]\tau(k)\,dk \\ + \int_{(Q_0-q_0)/Q_{op}}^{m} v_g\left[kQ_{op} - \left(Q_0 - q_0\right)\right]\tau(k)\,dk \end{array} \right\} f(\xi)\,d\xi \\ + \int_{Q_0-q_0}^{Q_0} \left\{ \begin{array}{l} -w_{ep}(Q_0 - \xi) + \int_{n}^{\xi/Q_{op}} \left[-g\left(\xi - kQ_{op}\right)\right]\tau(k)\,dk \\ + \int_{\xi/Q_{op}}^{m} v_g\left(kQ_{op} - \xi\right)\tau(k)\,dk \end{array} \right\} f(\xi)\,d\xi \\ + \int_{Q_0}^{\gamma+\beta} \left\{ \int_{n}^{Q_0/Q_{op}} \left[-g\left(Q_0 - kQ_{op}\right)\right]\tau(k)\,dk + \int_{Q_0/Q_{op}}^{m} v_g\left(kQ_{op} - Q_0\right)\tau(k)\,dk \right\} f(\xi)\,d\xi \end{array} \right\}$$

subject to $\dfrac{Q_0}{m} \le Q_{op} \le \dfrac{Q_0 - q_0}{n}$

Plan 3. $nQ_{op} \le Q_0 - q_0 \le mQ_{op} \le Q_0$.

In this plan, the initial order is higher than the maximum output quantity while the minimum output quantity is lower than the firm order. Here, six cases can be derived as shown in Table 3.4.

Table 3.4: Six cases for values of demand ξ and output rate k at t_1 in plan 3

No.	Intervals of ξ, k	Buyer's final order quantity	Overage inventory or shortage for the grower
1	$\{\xi, kQ_{op}\} \le Q_0 - q_0$	$Q_0 - q_0$	Shortage
2	$\xi \le Q_0 - q_0 < kQ_{op}$	$Q_0 - q_0$	Overage inventory
3	$\{Q_0 - q_0, kQ_{op}\} < \xi < mQ_{op}$	ξ	Shortage
4	$Q_0 - q_0 < \xi \le kQ_{op}$	ξ	Overage inventory
5	$mQ_{op} < \xi \le Q_0$	ξ	Shortage
6	$kQ_{op} \le Q_0 < \xi$	Q_0	Shortage

The grower determines the optimal planting quantity Q_{op} to maximize the profit function

$$
\max SPFT_{og}^{3}\left(Q_{op}\right)
$$

$$
= \max \left\{ \begin{array}{l}
-cQ_{op} + \int\limits_{\gamma-\beta}^{Q_0-q_0} \left\{ \begin{array}{l} -w_{ep} q_0 + \int\limits_{n}^{(Q_0-q_0)/Q_{op}} \left[-g\left(Q_0 - q_0 - kQ_{op}\right) \right] \tau(k)\, dk \\ + \int\limits_{(Q_0-q_0)/Q_{op}}^{m} v_g \left[kQ_{op} - \left(Q_0 - q_0\right) \right] \tau(k)\, dk \end{array} \right\} f(\xi)\, d\xi \\
+ \int\limits_{Q_0-q_0}^{mQ_{op}} \left\{ \begin{array}{l} -w_{ep}\left(Q_0 - \xi\right) + \int\limits_{n}^{\xi/Q_{op}} \left[-g\left(\xi - kQ_{op}\right) \right] \tau(k)\, dk \\ + \int\limits_{\xi/Q_{op}}^{m} v_g \left(kQ_{op} - \xi\right) \tau(k)\, dk \end{array} \right\} f(\xi)\, d\xi \\
+ \int\limits_{mQ_{op}}^{Q_0} \left\{ -w_{ep}\left(Q_0 - \xi\right) + \int\limits_{n}^{m} \left[-g\left(\xi - kQ_{op}\right) \right] \tau(k)\, dk \right\} f(\xi)\, d\xi \\
+ \int\limits_{Q_0}^{\gamma+\beta} \left\{ \int\limits_{n}^{m} \left[-g\left(Q_0 - kQ_{op}\right) \right] \tau(k)\, dk \right\} f(\xi)\, d\xi
\end{array} \right\}
$$

$$
\text{subject to } \frac{Q_0 - q_0}{m} \le Q_{op} \le \left\{ \frac{Q_0 - q_0}{n}, \frac{Q_0}{m} \right\}
$$

Plan 4. $Q_0 - q_0 \le nQ_{op} \le Q_0 \le mQ_{op}$.

In this case, the maximum output quantity is higher than the initial order while the firm order is lower than the minimum output quantity. Six cases can be derived in Table 3.5.

Table 3.5: Six cases for values of demand ξ and output rate k at t_1 in plan 4

No.	Intervals of ξ, k	Buyer's final order quantity	Overage inventory or shortage for the grower
1	$\xi \le Q_0 - q_0 < kQ_{op}$	Q_0-q_0	Overage inventory
2	$Q_0 - q_0 < \xi \le nQ_{op} \le Q_0$	ξ	Overage inventory
3	$Q_0 - q_0 < kQ_{op} < \xi \le Q_0$	ξ	Shortage
4	$Q_0 - q_0 < \xi \le \left\{Q_0, kQ_{op}\right\}$	ξ	Overage inventory
5	$kQ_{op} \le Q_0 < \xi$	Q_0	Shortage
6	$Q_0 < \left\{\xi, kQ_{op}\right\}$	Q_0	Overage inventory

The grower determines the optimal planting quantity Q_{op} to maximize the profit function

$$\max SPFT_{og}^{4}\left(Q_{op}\right)$$

$$= \max \left\{ \begin{array}{l} -cQ_{op} + \int_{\gamma-\beta}^{Q_0 - q_0} \left\{ -w_{ep} q_0 + \int_{n}^{m} v_g \left[kQ_{op} - \left(Q_0 - q_0\right) \right] \tau(k)\, dk \right\} f(\xi)\, d\xi \\ + \int_{Q_0 - q_0}^{nQ_{op}} \left\{ -w_{ep}\left(Q_0 - \xi\right) + \int_{n}^{m} v_g \left(kQ_{op} - \xi\right) \tau(k)\, dk \right\} f(\xi)\, d\xi \\ + \int_{nQ_{op}}^{Q_0} \left\{ \begin{array}{l} -w_{ep}\left(Q_0 - \xi\right) + \int_{n}^{\xi/Q_{op}} \left[-g\left(\xi - kQ_{op}\right) \right] \tau(k)\, dk \\ + \int_{\xi/Q_{op}}^{m} v_g \left(kQ_{op} - \xi\right) \tau(k)\, dk \end{array} \right\} f(\xi)\, d\xi \\ + \int_{Q_0}^{\gamma+\beta} \left\{ \int_{n}^{Q_0/Q_{op}} \left[-g\left(Q_0 - kQ_{op}\right) \right] \tau(k)\, dk + \int_{Q_0/Q_{op}}^{m} v_g \left(kQ_{op} - Q_0\right) \tau(k)\, dk \right\} f(\xi)\, d\xi \end{array} \right\}$$

subject to $\left\{\frac{Q_0 - q_0}{n}, \frac{Q_0}{m}\right\} \le Q_{op} \le \frac{Q_0}{n}$

Taking the derivative of $SPFT_{og}^{j}\left(Q_{op}\right)$ with respect to Q_{op} in plan j (j = 1,2,3,4), the grower's optimal planting quantity $Q_{op,j}^{*}$ is described in Proposition 6.

Proposition 6. The grower's optimal planting quantity $Q_{op,j}^{*}$ in plan j is defined as below.

(i) In plan 1, the optimal planting quantity is

$$Q_{op,1}^{*} = \begin{cases} \frac{Q_0 - q_0}{n} & if \;\; Q_{op,1} < \frac{Q_0 - q_0}{n} \\ Q_{op,1} & if \;\; \frac{Q_0 - q_0}{n} \le Q_{op,1} \le \frac{Q_0}{m} \\ \frac{Q_0}{m} & if \;\; \frac{Q_0}{m} < Q_{op,1} \end{cases}$$

where

$$Q_{op,1} = \frac{3(n+m)\left[\gamma(g - v_g) + \beta(g + v_g)\right] - 12c\beta}{2\left(n^2 + m^2 + nm\right)(g - v_g)}$$

(ii) In plan 2, the optimal planting quantity is

$$Q_{op,2}^{*} = \begin{cases} \frac{Q_0}{m} & if \;\; Q_{op,2} < \frac{Q_0}{m} \\ Q_{op,2} & if \;\; \frac{Q_0}{m} \le Q_{op,2} \le \frac{Q_0 - q_0}{n} \\ \frac{Q_0 - q_0}{n} & if \;\; \frac{Q_0 - q_0}{n} < Q_{op,2} \end{cases}$$

where

$$Q_{op,2} = \sqrt{\frac{\left(v_g - g\right)\left[2q_0^3 + 6\left(q_0 - \beta\right)Q_0^2 - 6\left(\gamma - \beta + q_0\right)Q_0 q_0 + 3\left(\gamma - \beta\right)q_0^2\right]}{6\beta\left[gn^2 - v_g m^2 + 2c\left(m - n\right)\right]}}$$

(iii) In plan 3, the optimal planting quantity is

$$Q_{op3}^* = \begin{cases} \dfrac{Q_0 - q_0}{m} & if \quad Q_{op,3} < \dfrac{Q_0 - q_0}{m} \\ Q_{op,3} & if \quad \dfrac{Q_0 - q_0}{m} \le Q_{op,3} \le \left\{\dfrac{Q_0 - q_0}{n}, \dfrac{Q_0}{m}\right\} \\ \min\left(\dfrac{Q_0 - q_0}{n}, \dfrac{Q_0}{m}\right) & if \quad Q_{op,3} > \left\{\dfrac{Q_0 - q_0}{n}, \dfrac{Q_0}{m}\right\} \end{cases}$$

where

$$Q_{op,i} = E_i^{\frac{1}{3}} + \frac{B_i}{3A_i} + \frac{B_i^2}{9A_i^2 E_i^{\frac{1}{3}}}, \ (i = 3, 4) \tag{3.10}$$

$$A_3 = 2(g - v_g)m^3$$

$$B_3 = 3\gamma(g - v_g)m^2 + 3\beta\left[(g + v_g)m^2 - 2gn^2 - 4c(m - n)\right]$$

$$C_3 = \left(g - v_g\right)\left(Q_0 - q_0\right)^2\left(3\gamma - 3\beta - 2Q_0 + 2q_0\right)$$

$$A_4 = 2(g - v_g)n^3$$

$$B_4 = 3\gamma(g - v_g)n^2 + 3\beta\left[(g + v_g)n^2 - 2v_g m^2 + 4c(m - n)\right]$$

$$C_4 = \left(g - v_g\right)Q_0^2\left(3\gamma - 2Q_0 + 3\beta\right)$$

(iv) In plan 4, the optimal planting quantity is

$$Q_{op,4}^{*}=\begin{cases}\max\left(\dfrac{Q_0-q_0}{n},\dfrac{Q_0}{m}\right) & if \quad Q_{op,4}<\left\{\dfrac{Q_0-q_0}{n},\dfrac{Q_0}{m}\right\}\\ Q_{op,4} & if \quad \left\{\dfrac{Q_0-q_0}{n},\dfrac{Q_0}{m}\right\}\le Q_{op,4}\le\dfrac{Q_0}{n}\\ \dfrac{Q_0}{n} & if \quad Q_{op,4}>\dfrac{Q_0}{n}\end{cases}$$

where $Q_{op,4}$ can be found in equation (3.10).

Proof: See Appendix A.6.

At $t_{0,3}$, the grower's optimal planting quantity Q_{op}^{*} is defined as following:

(i) When $m(Q_0-q_0)<nQ_0$, Q_{op}^{*} takes one of $Q_{op,1}^{*}$, $Q_{op,3}^{*}$ and $Q_{op,4}^{*}$ that maximizes the grower's expected profit.

(ii) When $m(Q_0-q_0)\ge nQ_0$, Q_{op}^{*} takes one of $Q_{op,2}^{*}$, $Q_{op,3}^{*}$ and $Q_{op,4}^{*}$ that maximizes the grower's expected profit.

At $t_{0,1}$, the grower's problem is to find the optimal supply tariff to maximize the following formula,

$$\max SPFT_{og,t_0}^{j}\left(w_o,w_{ep}\right)=\max\left[wQ_0+w_oq_0+G_{og}^{j}\left(Q_{op}\right)\right]$$

subject to $w_o>0,\quad w_{ep}>0$

Let $\left(w_{o,j}^{*},w_{ep,j}^{*}\right)$ denote the optimal supply tariff for the grower in plan *j*. The optimal supply tariff $\left(w_o^{*},w_{ep}^{*}\right)$ takes one of value among $\left(w_{o,1}^{*},w_{ep,1}^{*}\right)$, $\left(w_{o,2}^{*},w_{ep,2}^{*}\right)$, $\left(w_{o,3}^{*},w_{ep,3}^{*}\right)$ and $\left(w_{o,4}^{*},w_{ep,4}^{*}\right)$ that maximizes the grower's expected profit. Similarly, we analyze the optimal supply tariff in numerical experiments.

3.4 Numerical experiments

In this section, we first examine the effectiveness of the proposed model, and then analyze to what extent, the SCPO model under various parameters and also the RAS can improve the profits for the grower and also for the buyer. The parameter settings are as follows: c = 30, n = 0.4, m = 1, g = 85, v_g = 20, w =80, r = 150, p = 150, v_b = 0, γ = 1000 and β = 500. When analyzing a parameter, the values of the others are kept at the initial setting as shown above. For each parameter set, the optimal solution and the corresponding expected profit are calculated. What's more, to evaluate the improvement when using SCPO for the grower and the buyer, respectively, we compute the two ratios,

$$\Delta_B = \frac{\Delta Buyer's\ \ profit}{Buyer's\ \ profit_{NV}} \text{ and } \Delta_G = \frac{\Delta Grower's\ \ profit}{Grower's\ \ profit_{NV}}$$

where

$$\Delta Buyer's\ \ profit = Buyer's\ \ profit_{SCPO} - Buyer's\ \ profit_{NV}$$

$$\Delta Grower's\ \ profit = Grower's\ \ profit_{SCPO} - Grower's\ \ profit_{NV}$$

3.4.1 Performance comparison for models

We propose the SCPO model with three conditions: random yield, optimal supply tariff and RAS. To prove the effectiveness of the proposed model, we use the traditional operation mode under the same conditions as a benchmark and compare participants' performances for SCPO model with only two of these three conditions as below.

(i) SCPO model without considering random yield.

In this case, the grower's optimal planting quantity is Q_p = 1318 (See Appendix A.7 for the formula) while the optimal planting quantity in our model is equal to 1518.

(ii) SCPO model without considering the supply tariff as decision variables.

In this case, we set the supply tariff (w_o, w_{ep}) to (4, 22) while the optimal supply tariff obtained in our model is (5, 21).

(iii) SCPO model without considering RAS.

In this case, we set the salvage price of unsold products to 0 (v_g = 0) while the salvage price of unsold products stored in RAS may be increased to 20 (v_g = 20).

Figure 3.3 presents expected profits of the grower and the buyer for different models with various conditions, and Figure 3.4 shows the grower's optimal planting quantity and the buyer's optimal order policy in the proposed and the traditional models. From Figure 3.3, we find that the grower's performance of the proposed SCPO model is better than that of the traditional operation mode and also than that of SCPO model with other conditions, from which we can conclude that the proposed SCPO model is effective for the grower. And with rural cold storages, the grower can get affluent. Moreover, compared with traditional operation mode, the proposed SCPO model enhances both the grower's and the buyer's profits. Interestingly, in the proposed SCPO model, the grower's profit may be higher than the buyer's profit. From Figure 3.4, we observe that the grower receives a larger order from the buyer while plants less fruits. Obviously, the proposed SCPO model is more beneficial to the grower, which protects the grower's profit.

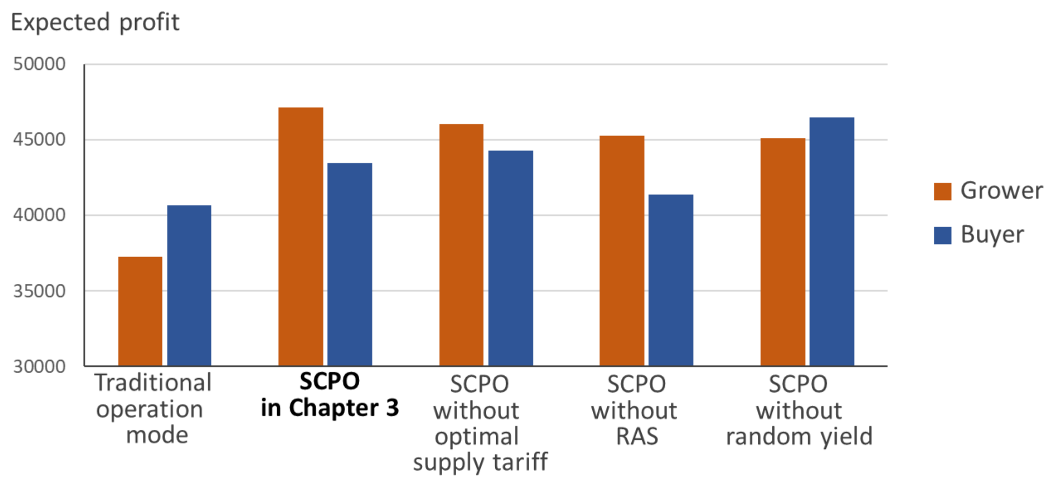

Figure 3.3: Expected profit vs. supply contracts

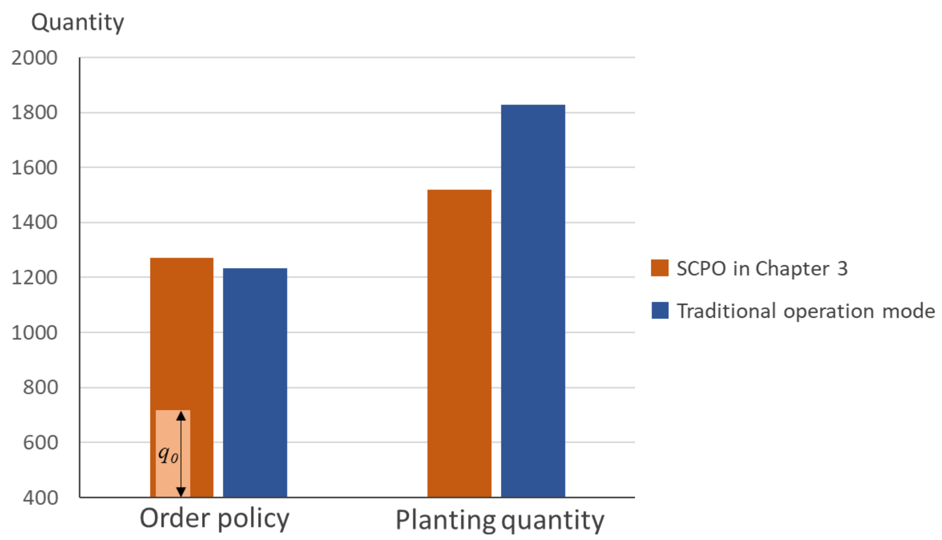

Figure 3.4: Solutions of SCPO and traditional models

3.4.2 Sensitivity analysis

Effect of the salvage price of products stored in RAS v_g

Figure 3.5, Table 3.6 and Figure 3.6 present the optimal quantities, optimal supply tariff and corresponding expected profits under various values of v_g, respectively.

The corresponding ratios △ under different values of v_g are plotted in Figure 3.7. We vary v_g from 0 to 25, which satisfies the assumption $c/\bar{k} > v_g$ in Section 3.2.1.

From Figure 3.5, we observe that with the SCPO model, as v_g increases, the grower's loss from salvage decreases. The grower tends to increase the planting quantity Q_{op} because the loss from overage inventory decreases. However, the increasing risk related to overage inventory makes the grower increase the option price w_o, as shown in Table 3.6, to compensate for the planting cost. At the same time, to keep the options attractive, the exercise price of the put option w_{ep} also increases, which enables the buyer to obtain a larger refund when exercising the options. As a result, the buyer increases the initial order Q_0. However, the variation of the option quantity q_0 is unclear because q_0 is decreasing in w_o and increasing in w_{ep}, according to Proposition 5. Moreover, a higher salvage value v_g means a higher preservation level of RAS. We observe that the preservation level enhances the grower's enthusiasm for planting.

The corresponding expected profit increases as shown in Figure 3.6. The grower's profit increases because of the high salvage value v_g and the possible high order quantity from the buyer. Two conflicting effects affect the buyer's profit. One is that the increase in w_{ep} enables the buyer to have more flexibility to respond to uncertain demand, hence the profit increases. Another effect is the higher option purchase cost due to the increasing w_o. As a result, the buyer's profit increases. Moreover, in Figure 3.7, we can see that the SPCO model is more beneficial to the grower. Using SCPO model, the improvements for the grower $\triangle_G$ and the buyer $\triangle_B$ can be up to 29% (when $v_g = 0$) and 7.5% (when $v_g = 25$), respectively.

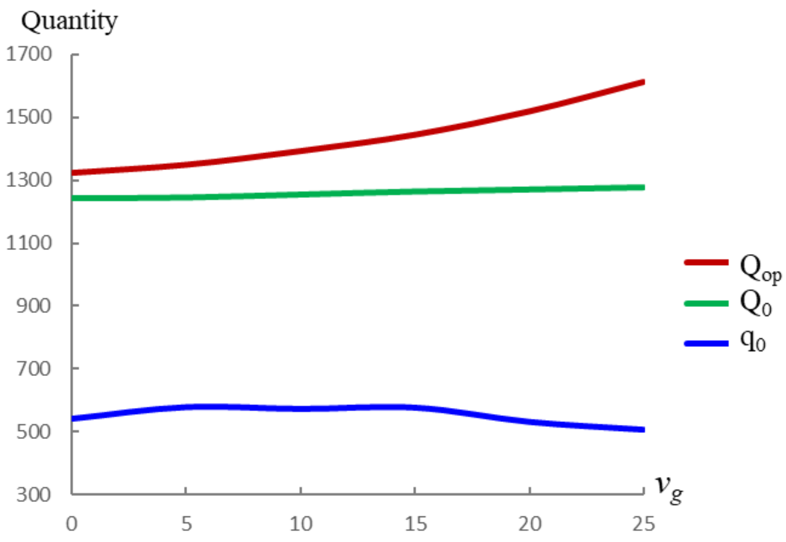

Figure 3.5: Variation of optimal policy function of v_g

Table 3.6: Effect of v_g on the grower's optimal supply tariff

v_g	0	5	10	15	20	25
w_o	1	1	2	3	5	7
w_{ep}	5	6	11	16	21	26

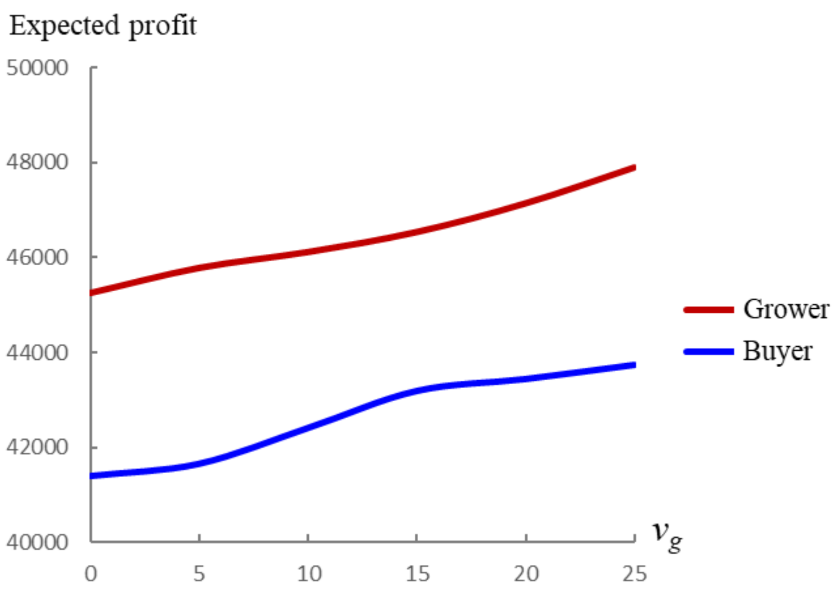

Figure 3.6: Variation of expected profit function of v_g

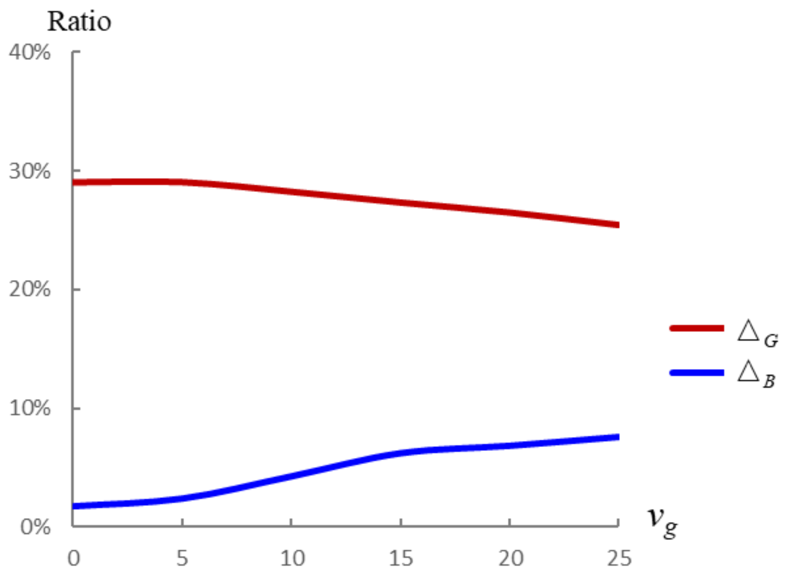

Figure 3.7: Variation of the ratio function of v_g

Effect of the spot market price *g*

Figure 3.8, Table 3.7 and Figure 3.9 present the optimal quantities, optimal supply tariff and corresponding expected profits under various values of g, respectively. The corresponding ratios $\triangle$ under different values of g are plotted in Figure 3.10. We vary g from 80 to 105, which satisfies the assumption $g > c/\bar{k}$ in Section 3.2.1.

From Figure 3.8, we observe that with the SCPO model, as g increases, the grower's purchase cost in the spot market increases. The grower tends to increase the planting quantity Q_{op} because the purchase cost in the spot market increases. To avoid the risks associated with the increased planting quantity, the grower keeps the exercise price of the put option w_{ep} at the lowest value, i.e., $w_{ep} = v_g + 1 = 21$ and also keeps the option price w_o unchanged to attract the buyer to purchase options as shown in Table 3.7. As a result, both the initial order Q_0 and the number of purchased options q_0 also keep unchanged. The corresponding expected profit changes as shown in Figure 3.9. The grower's profit decreases because of the high spot market g while the buyer's expected profit is not affected. Moreover, in Figure 3.10, we can see that when using SCPO model, the improvement for the grower $\triangle_G$ and that for the buyer $\triangle_B$ can be up to 28% (when g = 65) and 7%, respectively.

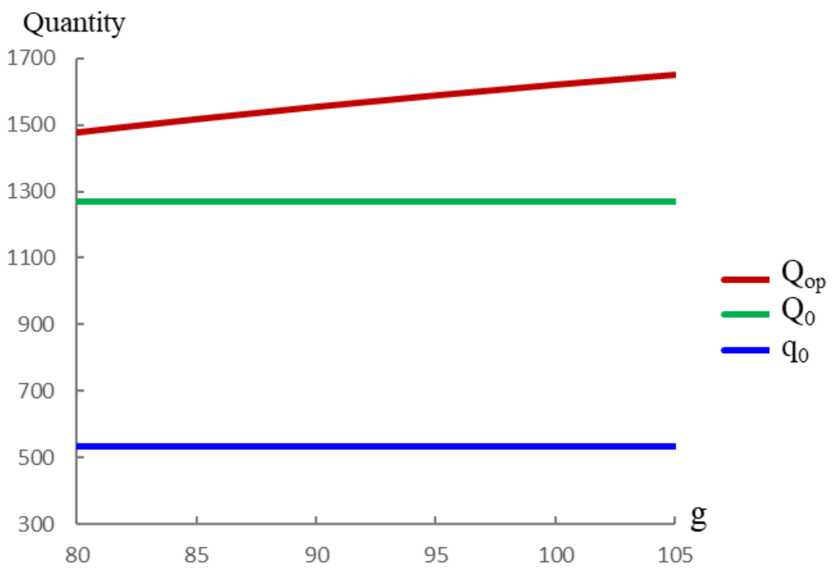

Figure 3.8: Variation of optimal policy function of g

Table 3.7: Effect of g on the grower's optimal supply tariff

g	80	85	90	95	100	105
w_o	5	5	5	5	5	5
w_{ep}	21	21	21	21	21	21

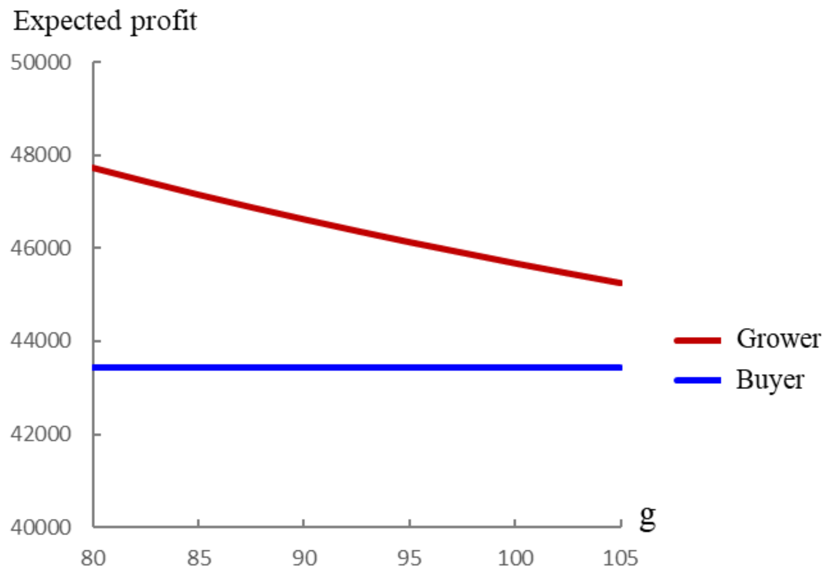

Figure 3.9: Variation of expected profit function of *g*

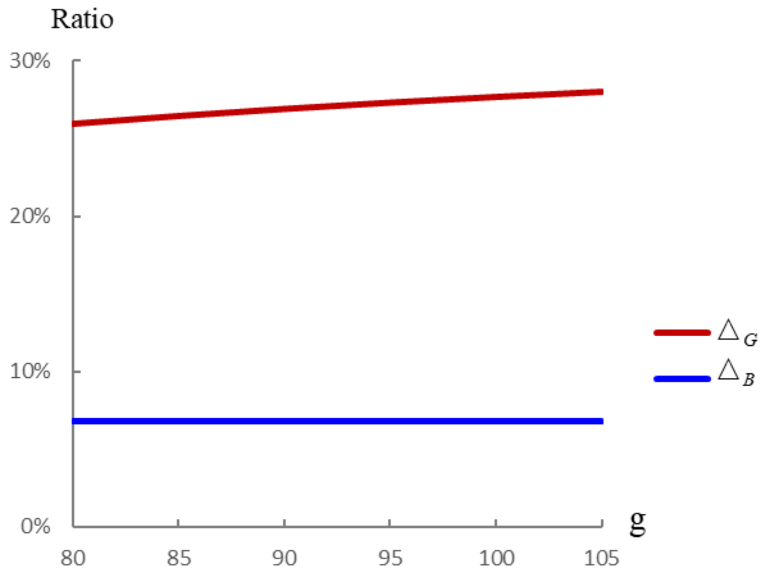

Figure 3.10: Variation of the ratio function of *g*

Effect of the shortage cost *p*

Figure 3.11, Table 3.8 and Figure 3.12 present the optimal quantities, optimal supply tariff and corresponding expected profits under various values of *p*, respectively. The corresponding ratios △ under different values of p are plotted in Figure 3.13. We vary p from 50 to 550.

From Figure 3.11, we observe that with the SCPO model, as p increases, the shortage cost of the buyer increases. As p increases 50 to 550, the buyer tends to increase the initial order Q_0 to avoid the expensive shortage cost and increase the number of purchased options q_0 to decrease the overage risk. Knowing this, the grower keeps the exercise price of the put option w_{ep} at the lowest value, i.e., $w_{ep} = v_g + 1 = 21$ and increases the option price w_o to prevent the buyer from over-purchasing options that may be realized as shown in Table 3.8. The increase in the planting quantity Q_{op} is due to receiving a larger order. It is worth noting that when the shortage cost is low, i.e., p = 50, the options are less attractive to the buyer. The grower would set the exercise price of the put option w_{ep} at the highest value, i.e., $w_{ep} = w = 80$. Also, the grower increases the option price w_o to transfer more risk to the buyer. As a result, the buyer increases the firm order quantity (Q_0 - q_0), and then the grower increases the planting quantity Q_{op}.

The corresponding expected profit changes as shown in Figure 3.12. The buyer's expected profit decreases because of the increasing shortage cost while the grower's expected profit increases because of receiving a larger order. Furthermore, the grower's expected profit may be higher than that of the buyer when the shortage cost p is high. We can conclude that the grower benefits from the buyer's risk aversion. In Figure 3.13, we can see that when p = 550, the improvement in SCPO model for the grower $\triangle_G$ and that for the buyer $\triangle_B$ can be up to 31% and 10%, respectively. We can conclude that the higher the shortage cost, the more beneficial the SCPO model is for supply chain participants.

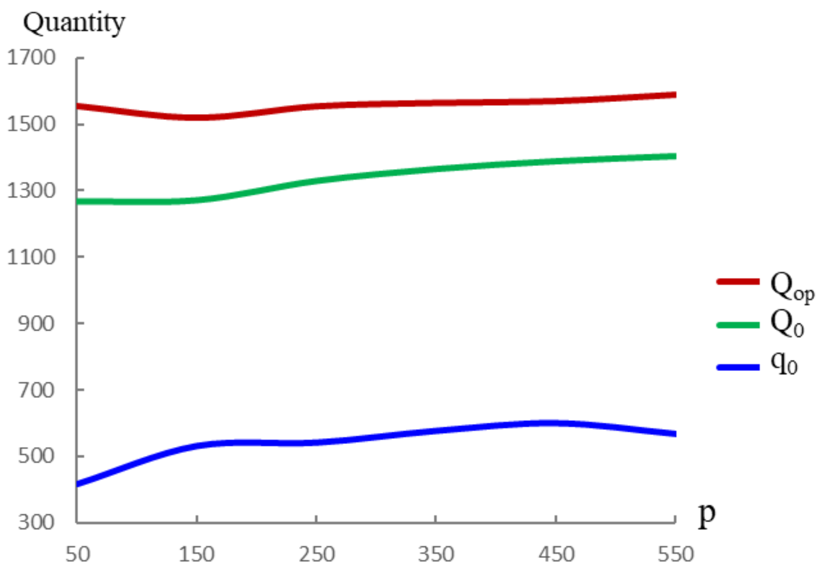

Figure 3.11: Variation of optimal policy function of *p*

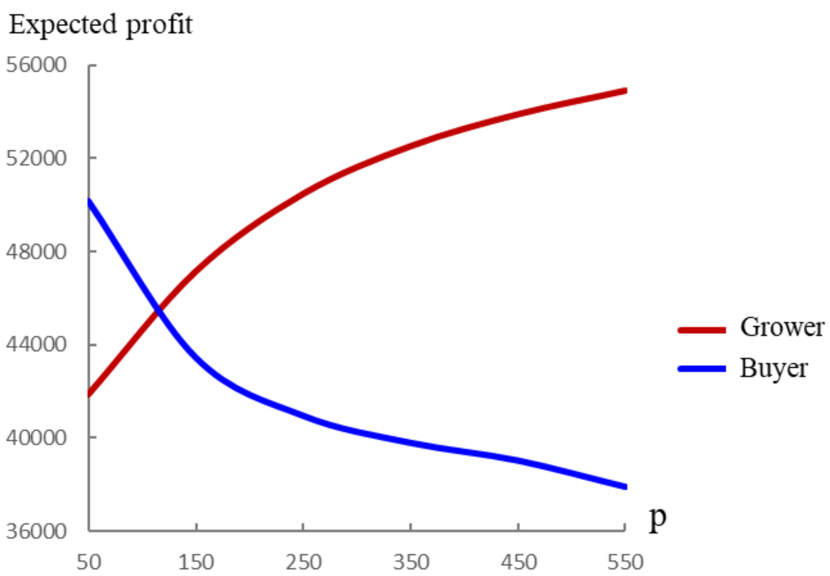

Figure 3.12: Variation of expected profit function of *p*

Table 3.8: Effect of *p* on the grower's optimal supply tariff

p	**50**	**150**	**250**	**350**	**450**	**550**
w_o	28	5	6	6	6	7
w_{ep}	80	21	21	21	21	21

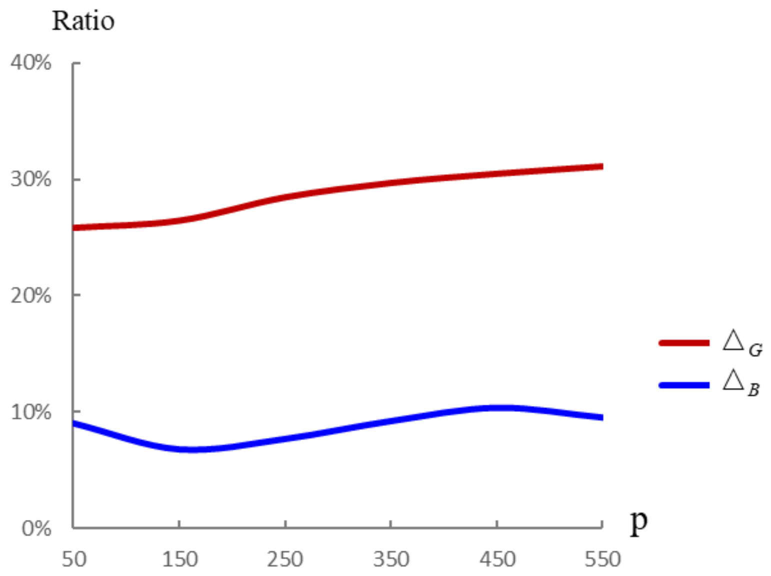

Figure 3.13: Variation of the ratio function of p

Effect of uncertainties of the yield and the demand

Figure 3.14, Table 3.9 and Figure 3.15 present the optimal quantities, optimal supply tariff and corresponding expected profits under different yield and demand uncertainties, respectively. The uncertainty is set to three levels, i.e., L_y: Low, M_y: Medium and H_y: High (y = K, β). The output rate K is uniformly distributed with mean 0.7. The yield uncertainty denoted as (n, m) decreases from (0.2, 1.2) to (0.6, 0.8) by a step of 0.2 for both n and m. The demand uncertainty denoted as β increases from 100 to 900 by a step of 400.

As the yield uncertainty decreases, i.e., from H_K to L_K, we notice that in Figure 3.14, the grower would increase the planting quantity Q_{op}. The grower increases the option price w_o to transfer the risk of planting to the buyer and keeps the exercise price of the put option w_{ep} at the lowest value, i.e., $w_{ep} = v_g + 1 = 21$ as shown in Table 3.9. As a result, the buyer decreases the number of purchased options q_0. The corresponding expected profits are shown in Figure 3.15. The grower's expected profit increases due to the low yield uncertainty while the buyer's expected profit decreases because he has less flexibility to respond to uncertain demand. We can conclude that with high yield uncertainty, the grower provides more flexibility. It is worth noting that with low yield uncertainty and medium/high demand uncertainty (Cases: $M_{\beta}L_{K}$ and $H_{\beta}L_{K}$), the grower would prefer *Plan 1* ($Q_0 - q_0 < nQ_{op} < mQ_{op} \le Q_0$) in Section 3.2.2 where the output quantity cannot fulfill the initial order Q_0 but can satisfy the firm order quantity (Q_0 - q_0) from the buyer, whereas prefer *Plan 2* ($nQ_{op} \le Q_0 - q_0 < Q_0 < mQ_{op}$) in other cases.

As the demand uncertainty increases, i.e., from L_{β} to H_{β}, we observe that in Figure 3.14, the buyer tends to increase the initial order Q_0 to avoid the expensive shortage cost, and to increase the number of purchased options q_0 to decrease the overage risk. Knowing this, the grower keeps the exercise price of the put option w_{ep} at the lowest value, i.e., $w_{ep} = v_g + 1 = 21$ and increases the option price w_o to prevent the buyer from over-purchasing options that may be realized as shown in Table 3.9. However, when the demand uncertainty is high and the yield uncertainty is medium (Case $H_{\beta}M_{K}$ in Table 3.9), the grower would increase the exercise price of the put option w_{ep} to keep options attractive. As a result, the buyer increases both the initial order quantity and the number of put options. From Figure 3.15, we can see that the buyer's expected profit decreases because of the increasing demand uncertainty while the grower's expected profit increases because of receiving a larger order. We can conclude that the higher the demand uncertainty, the more attractive the SCPO is to the buyer.

From Table 3.9, we observe that with low demand uncertainty and high yield uncertainty (Case $L_\beta H_K$), the grower tends to provide more flexibility by decreasing the price of put option. And in Figure 3.15, the grower gets a high profit when the yield uncertainty is low and demand uncertainty is high (Case $H_\beta L_K$) while the buyer gets a high profit when the yield uncertainty is high and demand uncertainty is low (Case $H_\beta L_K$). We can conclude that participants benefit from each other's risk aversion. Moreover, the improvement in SCPO model for the grower $\triangle_G$ can be up to 53% and that of the buyer $\triangle_B$ can be up to 29% when both the yield and the demand uncertainties are high (Case $H_\beta H_K$). We can conclude that the higher the uncertainties of the yield and demand, the more beneficial the SCPO model is for supply chain participants.

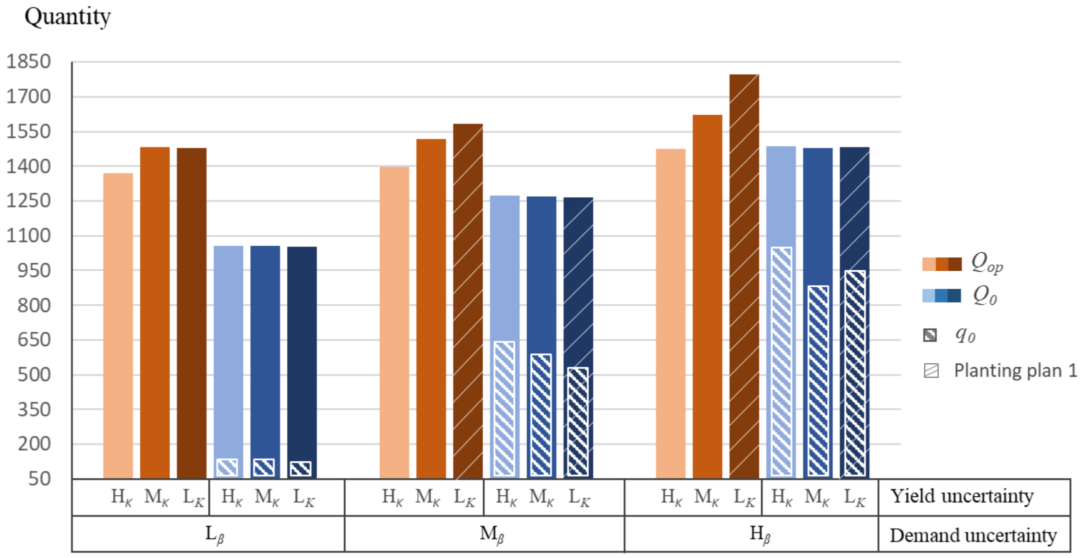

Figure 3.14: Optimal policy vs. yield and demand uncertainties

Table 3.9: Effect of yield and demand uncertainties on the grower's optimal supply tariff

Demand uncertainty level / (w_o, w_{ep}) / Yield uncertainty level (n, m)	L_β $\beta = 100$	M_β $\beta = 500$	H_β $\beta = 900$
H_K (0.2, 1.2)	(4, 21)	(4, 21)	(5, 21)
M_K (0.4, 1)	(4, 21)	(5, 21)	(7, 22)
L_K (0.6, 0.8)	(5, 21)	(6, 21) *	(6, 21) *

* In this case, the grower would prefer *Plan 1*.

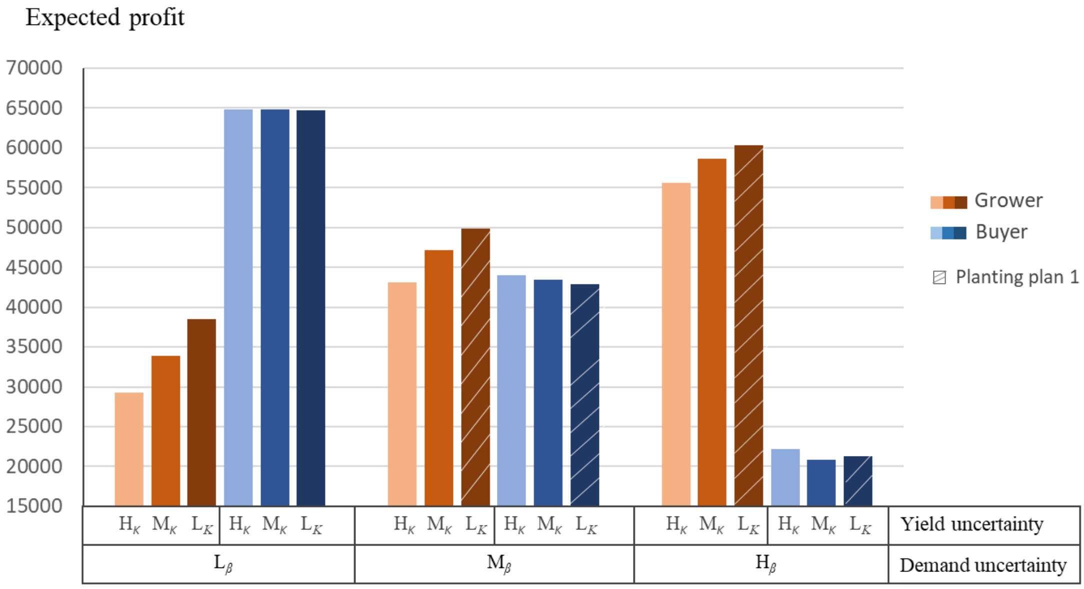

Figure 3.15: Variation of expected profit function vs. yield and demand uncertainties

The grower's profit sensitivity analysis

This section is to examine in an example how parameters affect the grower's profit, which parameter may affect the profit the most largely and which is valuable for the grower to invest if SCPO has been adopted. We set the basic parameters as follows: c = 30, n = 0.4, m = 1, g = 85, v_g = 10, w =80, r = 150, p = 50, v_b = 0, γ = 1000 and β = 500.

We compare how the grower's salvage price v_g, the spot market price g, the shortage cost for the buyer p and the variation of the output rate affect the supplier's expected profit, respectively. And we do the comparison by increasing v_g, p, m-n and decreasing g by 6 steps from 10%~60% with a step of 10%, respectively. The values of m and n are changed to keep the mean of K (i.e., $\frac{m-n}{2}$) constant. The corresponding profits are shown in Figure 3.16. From Figure 3.16, we observed that the most influential parameter on profit is the spot market price g. For all the parameters, the effect order is the spot market price, the yield uncertainty, the shortage cost for the buyer and the grower's salvage price. We can conclude that the grower should reduce the purchase cost in the spot market and invest to improve the planting technology and management in order to keep the output rate in a small range.

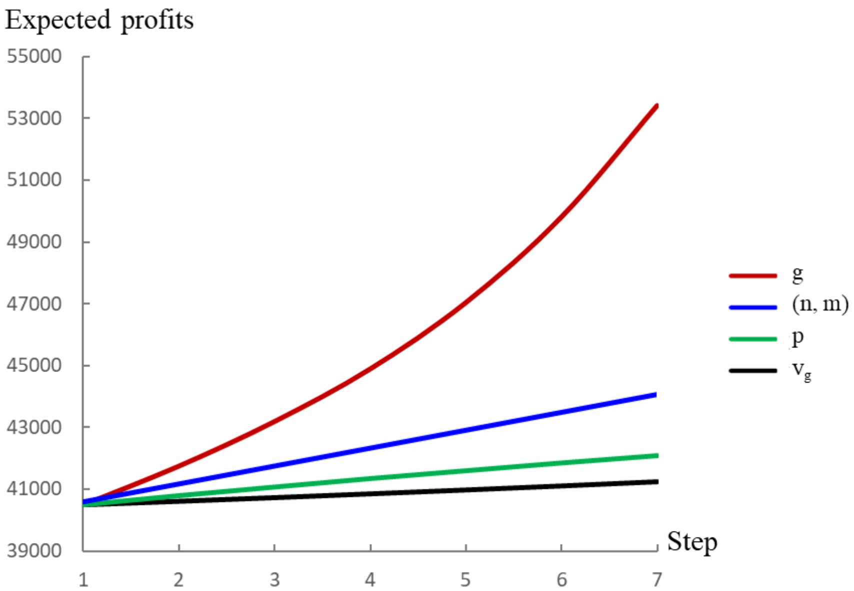

Figure 3.16: The grower's expected profit vs. parameters

3.5 Chapter summary

In this chapter, we modeled a single-period, two-stage contract with put options (SCPO) in a fresh fruit supply chain (FSC) with regular atmosphere storages (RAS). Put options give the buyer the right, but not the obligation, to decrease the initial order, one for each option. At the beginning of the planning horizon, the buyer places an initial order and purchases put options with a preliminary demand forecast. Considering the buyer's order and the random yield, the grower determines the planting quantity. During the planting season, the buyer updates the demand forecast. At the beginning of the selling season, the buyer exercises put options if necessary. Then, the grower delivers the final order and stores surplus products in RAS to extend their shelf life, which incurs extra storage costs that can be recovered by salvaging at a higher price later.

The proposed model was analyzed from both the grower's and buyer's perspectives. And the buyer's and the grower's profit functions were formulated, which were then used to derive the buyer's optimal policies for the initial order and put options as well as the grower's optimal policy for the planting quantity. The grower's optimal supply tariff can be obtained only numerically. In particular, we obtained closed-form formulae to determine the buyer's optimal order policy and the grower's optimal planting quantity in a special case. We showed numerical experiments in which we examined the effectiveness of the proposed model and analyzed how the parameters v_g, g, p and uncertainties of the yield and the demand influence the optimal policies and expected profits in such a supply chain.

In the numerical analysis, some managerial insights in SCPO have been observed:

1. The grower's performance of the proposed SCPO model is better than that of

SCPO model with other conditions. Compared to the traditional operational mode, the proposed SCPO model can improve the grower's and buyer's performances, simultaneously. And the proposed SCPO model is more beneficial to the grower, which protects the grower's profit.

2. With rural cold storages, the grower can get affluent. A higher preservation level of RAS and a low yield uncertainty enhances a grower's enthusiasm for planting.
3. Supply chain participants benefit from each other's risk aversion.
4. The higher the demand uncertainty, the more beneficial the SCPO model is for supply chain participants. With high uncertainties of the yield and the demand, the grower's and buyer's profits can be enhanced up to 53% and 29%, respectively.
5. With SCPO model, comparing parameters' effect on expected profit, the spot market price may affect the grower's profit most largely.

Chapter 4

Flexible Operation Mode with Controlled Atmosphere Storage

4.1 Introduction

In Chapter 3, we prove that the SCPO contract can improve the grower's profit in a fresh FSC with RAS. This chapter tries to provide a solution for the grower on how to plant, store and sell in a fresh FSC with CAS. The grower produces fresh fruits during planting season and sells them to a two-stage market, i.e., in-season and off-season. Our objective is to determine the grower's optimal planting policy and optimal rental capacity of CAS. We also analyze how the parameters affect the behaviors and outcomes[2].

4.2 Model

---

[2]Partial content of this chapter has been accepted by Asian Journal of Management Science and Applications, 2023

4.2.1 Notation and assumptions

Table 4.1 presents the parameters and decision variables throughout this chapter. we consider a single-period three-stage model in a fresh FSC with CAS under random yield and stochastic demand. The grower produces fresh fruits at Stage 1 and then sells them to markets. Since CAS can mitigate the deterioration of fruits for several months, the selling season can be divided into two stages, i.e., selling season A (In-season, Stage 2) and selling season B (Off-season, Stage 3). The selling season A is to sell the fruits right after harvesting and the selling season B is to sell after storage. After harvesting, the grower rents capacity of CAS and divides the fruits into two groups, one group for the selling season A, and the other for the selling season B. Any unsold fruits for each stage may be salvaged by the grower. Note that the leftover at the end of the selling season A cannot be handed over to the selling season B due to the perishability. And CAS, as an external party, with enough storage capacity is available for the grower.

Let K ($K > 0$) represent the random output rate in the planting season. The mean of K is $\bar{k}$. The values of n and m are based on experience but excluding extreme cases such as disasters resulted in no harvest. Let D_i ($D_i \geq 0$) represent the stochastic demand in the selling season i (i=A, B). At the beginning of the planting season, the grower knows the demand D_A with distribution function $G_{DA}(\cdot)$ and the demand D_B with distribution function $F_{DB|XB}(\cdot)$. The X_B ($X_B \geq 0$) with distribution function $F_{XB}(\cdot)$ is a location parameter of the conditional demand distribution of D_B. For the output rate K, the grower knows its distribution function $\mathrm{T}(\cdot)$. After harvesting, with the updated demand information, the grower specifies K, the demand D_A and the location parameter X_B as a value k, ξ_A and x_B, respectively. The updated parameter x_B is with distribution function $F_{DB|xB}(\cdot)$.

Table 4.1: Notation throughout Chapter 4

Decision variables	
Q_p	Planting quantity in the FSC with CAS
Q_r	Rental capacity of CAS
Q_{np}	Planting quantity in the FSC with CAS for in-season
Parameters	
r_i	Unit retail price in the selling season i (i=A, B)
p_i	Unit shortage cost in the selling season i
v_i	Unit salvage price in the selling season i
c_0	Unit planting cost
c_1	Unit rental cost of CAS
K	The output rate (stochastic variable)
n	Minimum output rate during certain years
m	Maximum output rate during certain years
k	Determined value of K
$\tau(\cdot)$	Probability density function (pdf) of K
$\mathrm{T}(\cdot)$	Cumulative density function (cdf) of K
D_i	Demand in the selling season i (stochastic variable)
ξ_i	Determined value of D_i
$g_{DA}(\cdot)$	pdf of D_A
$G_{DA}(\cdot)$	cdf of D_A
X_B	Location parameter of D_B
$f_{XB}(\cdot)$	pdf of X_B
$F_{XB}(\cdot)$	cdf of X_B
$f_{DB|xB}(\cdot)$	Conditional pdf of D_B for $X_B = x_B$
$F_{DB|xB}(\cdot)$	Conditional cdf of D_B for $X_B = x_B$

The graphical representation of the model in the FSC with CAS is shown in Figure 4.1. At the beginning of the planting season t_0, considering the random output rate and the forecasted two-stage demand in the selling season, the grower determines the planting quantity Q_p at unit planting cost c_0. During the planting season, the grower collects more demand information to update the two-stage demand forecast. At the beginning of the selling season t_1, the grower determines the rental capacity for CAS at unit rental cost c_1 to store part of the fruits based on the updated demand information. Then, the remained fruits are assigned to the selling season A. At t_2, the beginning of the selling season B, the grower sells fruits stored in CAS. At the end of each stage in the selling season, the grower may salvage the unsold fruits or incur shortage cost.

Throughout the paper, we assume r_B - c_1 > r_A > $c_0/\bar{k}$ to ensure that the sale after storage is profitable and that the grower has an incentive to plant, and let p_B > p_A because the loss of the margin on the sale after storage is larger than that right after harvesting. Let $c_0/\bar{k}$ > {v_A, v_B - c_1} to ensure the loss from overage inventory.

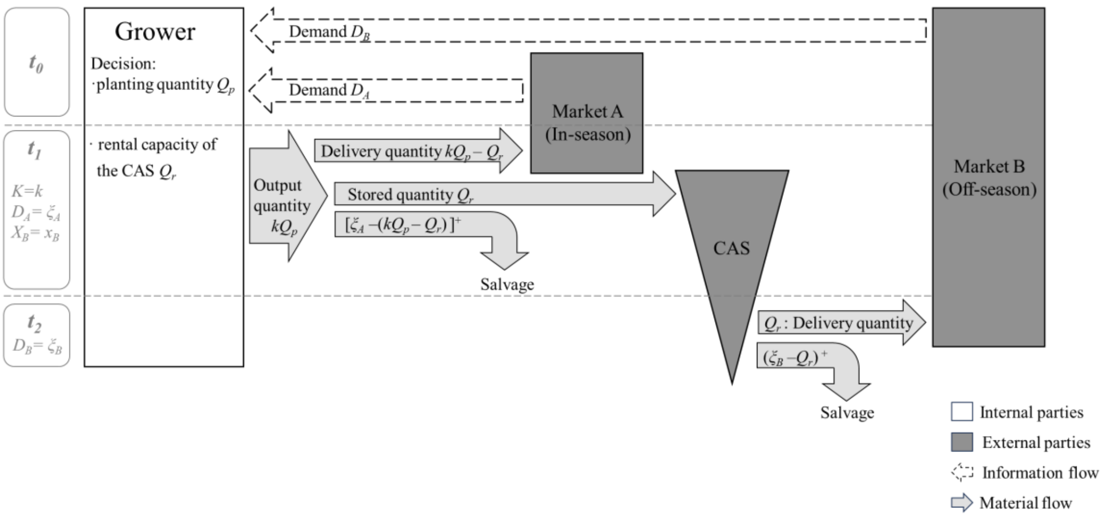

Figure 4.1: Graphical representation of the model in Chapter 4

4.2.2 Formulation

The costs are imposed two times. The first is at t_0 when planting and the second is at t_1 when renting capacity of CAS. We first formulate the profit function at t_1.

At t_1, the grower's profit function denoted by $PFT_{t_1}\left(Q_p, Q_r \left| k, \xi_A, x_B\right.\right)$, which is the sum of the profit during the selling season A and the expected profit during the selling season B, can be formulated as,

$$\begin{aligned} PFT_{t_1}\left(Q_r \left| k, \xi_A, x_B\right.\right) &= r_A \min\left(kQ_p - Q_r, \xi_A\right) + v_A\left(kQ_p - Q_r - \xi_A\right)^+ \\ &\quad - p_A\left[\xi_A - \left(kQ_p - Q_r\right)\right]^+ + \mathrm{E}\left[PFT_{t_2B}\left(Q_r \left| x_B\right.\right)\right] \end{aligned} \tag{4.1}$$

where

$$\mathrm{E}\left[PFT_{t_2B}\left(Q_r \left| x_B\right.\right)\right] = E\left[r_B \min\left(Q_r, D_B\right) + v_B\left(Q_r - D_B\right)^+ - p_B\left(D_B - Q_r\right)^+ \left| x_B\right.\right] - c_1 Q_r$$

and

$$\left(Z\right)^+ = \max\left\{0, Z\right\}$$

In equation (4.1), the first two terms are the revenues in the selling season A from sold and salvaged products, the third term represents the shortage cost in the selling season A, and the fourth term represents the expected profit in the selling season B which is the expected revenues of the grower coming from sold and salvaged products subtracting the expected shortage cost and the rental cost of CAS.

At t_0, the expected profit over the planning horizon can be expressed as

$$PFT_{t_0}\left(Q_p\right) = -c_0 Q_p + E\left[PFT_{t_1}\left(Q_r \left| K, D_A, X_B\right.\right)\right]$$

The grower's purpose is to maximize the expected profit, that is,

$$\max PFT_{t_0}\left(Q_p\right)$$

$$\text{subject to } Q_p \geq 0$$

4.2.3 Optimal solution at t_1

At the beginning of the selling season t_1, the grower knows the output quantity kQ_p. With $D_A = \xi_A$ and $X_B = x_B$ observed, the grower's problem is to find the optimal rental capacity of CAS Q_r to maximize the profit function $PFT_{t_1}\left(Q_r \left| k, \xi_A, x_B\right.\right)$ during the selling season. According to the specified values of k, ξ_A and x_B, two cases are derived as below.

Case 1. $\xi_A > kQ_p$.

In this case, the demand ξ_A is larger than the output quantity kQ_p. Therefore, shortage occurs in the selling season A. The grower's problem can be written as below,

$$\max PFT_{t_1}^{1}\left(Q_r \left| k, \xi_A, x_B\right.\right) = \max\left\{r_A\left(kQ_p - Q_r\right) - p_A\left[\xi_A - \left(kQ_p - Q_r\right)\right] + \mathrm{E}\left[PFT_{t_2 B}\left(Q_r \left| x_B\right.\right)\right]\right\}$$

Case 2. $\xi_A \leq kQ_p$.

In this case, whether the grower is in shortage or overage in the selling season A depends on the supply quantity reserved for the selling season B, which equals to the rental capacity of CAS. The grower's problem can be written as below,

$$\max PFT_{t_1}^{3}\left(Q_r \left|k,\xi_A,x_B\right.\right)=\begin{cases}\max PFT_{t_1}^{1}\left(Q_r \left|k,\xi_A,x_B\right.\right) & if\ Q_r \geq kQ_p-\xi_A \\ \max PFT_{t_1}^{2}\left(Q_r \left|k,\xi_A,x_B\right.\right) & if\ Q_r < kQ_p-\xi_A\end{cases}$$

where

$$PFT_{t_1}^{2}\left(Q_r \left|k,\xi_A,x_B\right.\right)=r_A\xi_A+v_A\left(kQ_p-Q_r-\xi_A\right)+\mathrm{E}\left[PFT_{t_2B}\left(Q_r \left|x_B\right.\right)\right]$$

Noting that $PFT_{t_1}^{1}\left(kQ_p-\xi_A \left|k,\xi_A,x_B\right.\right)=PFT_{t_1}^{2}\left(kQ_p-\xi_A \left|k,\xi_A,x_B\right.\right)$, we know that the function $PFT_{t_1}^{3}\left(Q_r \left|k,\xi_A,x_B\right.\right)$ is continuous.

By solving the grower's problem for the two cases, we derive the optimal solution which can be shown as below.

Proposition 1. At t_1, the optimal rental capacity of CAS Q_r^* is defined as following:

(i) When $\xi_A > kQ_p$,

$$Q_r^*=\begin{cases}kQ_p & if\ \ kQ_p < s_1\left(x_B\right) \\ s_1\left(x_B\right) & if\ \ 0\leq s_1\left(x_B\right)\leq kQ_p \\ 0 & if\ \ s_1\left(x_B\right)<0\end{cases}$$

(ii) When $\xi_A \leq kQ_p$,

$$Q_r^*=\begin{cases}kQ_p & if\ \ kQ_p < s_1\left(x_B\right) \\ s_1\left(x_B\right) & if\ \ kQ_p-\xi_A < s_1\left(x_B\right)\leq kQ_p \\ kQ_p-\xi_A & if\ \ s_1\left(x_B\right)\leq kQ_p-\xi_A\leq s_2\left(x_B\right) \\ s_2\left(x_B\right) & if\ \ 0\leq s_2\left(x_B\right)< kQ_p-\xi_A \\ 0 & if\ \ s_2\left(x_B\right)<0\end{cases}$$

where

$s_j\left(x_B\right)$ (j = 1, 2) is characterized by $F_{D_B|x_B}\left[s_j\left(x_B\right)\right]=\rho_j$.

$$\rho_1 = \frac{r_B + p_B - c_1 - (r_A + p_A)}{r_B + p_B - v_B}$$

$$\rho_2 = \frac{r_B + p_B - c_1 - v_A}{r_B + p_B - v_B}$$

$$s_1(x_B) < s_2(x_B)$$

Proof: See Appendix B.1.

The corresponding maximum profit functions at *t1* are described as following:

(i) When $\xi_A > kQ_p$,

$$PFT_{t_1}^{1*}(Q_r | k, \xi_A, x_B) = \begin{cases} PFT_{t_1}^1(kQ_p | k, \xi_A, x_B) & if \quad kQ_p < s_1(x_B) \\ PFT_{t_1}^1(s_1(x_B) | k, \xi_A, x_B) & if \quad 0 \le s_1(x_B) \le kQ_p \\ PFT_{t_1}^1(0 | k, \xi_A, x_B) & if \quad s_1(x_B) < 0 \end{cases} \quad (4.2)$$

(ii) When $\xi_A \le kQ_p$,

$$PFT_{t_1}^{3*}(Q_r | k, \xi_A, x_B)$$
$$= \begin{cases} PFT_{t_1}^1(kQ_p | k, \xi_A, x_B) & if \quad kQ_p < s_1(x_B) \\ PFT_{t_1}^1(s_1(x_B) | k, \xi_A, x_B) & if \quad kQ_p - \xi_A < s_1(x_B) \le kQ_p \\ PFT_{t_1}^3(kQ_p - \xi_A | k, \xi_A, x_B) & if \quad s_1(x_B) \le kQ_p - \xi_A \le s_2(x_B) \\ PFT_{t_1}^2(s_2(x_B) | k, \xi_A, x_B) & if \quad 0 \le s_2(x_B) < kQ_p - \xi_A \\ PFT_{t_1}^2(0 | k, \xi_A, x_B) & if \quad s_2(x_B) < 0 \end{cases} \quad (4.3)$$

4.2.4 Optimal solution at *t0*

At *t0*, the grower's problem is to determine the optimal planting quantity to maximize the total expected profit over the planning horizon.

$$\max PFT_{t_0}(Q_p) = \max\left\{-c_0 Q_p + E\left[PFT_{t_1}^{1*}(Q_r | K, D_A, X_B) + PFT_{t_1}^{3*}(Q_r | K, D_A, X_B)\right]\right\}$$

subject to $Q_p \geq 0$

To obtain the expected function at t_1, with respect to the random variable X_B, we get the equation (4.4) as below through mathematical manipulations (Wang and Tsao, 2006).

$$s_j\left(x_B\right)=s_j\left(0\right)+x_B \tag{4.4}$$

Substituting (4.2) and (4.3) by (4.4) and noting $x_B \geqslant 0$, we have the maximum profit functions at t_1 after deformation as following:

(i) When $\xi_A > kQ_p$,

$$PFT_{t_1}^{1*}\left(Q_r\left|k,\xi_A,x_B\right.\right)=\begin{cases} PFT_{t_1}^{1}\left(kQ_p\left|k,\xi_A,x_B\right.\right) & if \quad kQ_p-s_1\left(0\right)<x_B \\ PFT_{t_1}^{1}\left(s_1\left(x_B\right)\left|k,\xi_A,x_B\right.\right) & if \quad -s_1\left(0\right)\leq x_B\leq kQ_p-s_1\left(0\right) \\ PFT_{t_1}^{1}\left(0\left|k,\xi_A,x_B\right.\right) & if \quad 0\leq x_B<-s_1\left(0\right) \end{cases}$$

(ii) When $\xi_A \leq kQ_p$,

$$PFT_{t_1}^{3*}\left(Q_r\left|k,\xi_A,x_B\right.\right)$$
$$=\begin{cases} PFT_{t_1}^{1}\left(kQ_p\left|k,\xi_A,x_B\right.\right) & if \quad kQ_p-s_1\left(0\right)<x_B \\ PFT_{t_1}^{1}\left(s_1\left(x_B\right)\left|k,\xi_A,x_B\right.\right) & if \quad kQ_p-\xi_A-s_1\left(0\right)<x_B\leq kQ_p-s_1\left(0\right) \\ PFT_{t_1}^{3}\left(kQ_p-\xi_A\left|k,\xi_A,x_B\right.\right) & if \quad kQ_p-\xi_A-s_2\left(0\right)\leq x_B\leq kQ_p-\xi_A-s_1\left(0\right) \\ PFT_{t_1}^{2}\left(s_2\left(x_B\right)\left|k,\xi_A,x_B\right.\right) & if \quad -s_2\left(0\right)\leq x_B<kQ_p-\xi_A-s_2\left(0\right) \\ PFT_{t_1}^{2}\left(0\left|k,\xi_A,x_B\right.\right) & if \quad 0\leq x_B<-s_2\left(0\right) \end{cases}$$

Then the expected function at t_1 with respect to the random variables K, D_A and X_B is obtained as follows:

$$E_{D_B}\left[\Pi_{t_1}^{1*}\left(Q_r\left|K,D_A,X_B\right.\right)+\Pi_{t_1}^{3*}\left(Q_r\left|K,D_A,X_B\right.\right)\right]$$

$$=\int_0^{\infty}\left\{\begin{array}{l}\int_{kQ_p}^{\infty}\left[\begin{array}{l}\int_0^{-s_1(0)}\Pi_{t_1}^1\left(0\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\+\int_{-s_1(0)}^{kQ_p-s_1(0)}\Pi_{t_1}^1\left(s_1\left(x_B\right)\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\+\int_{kQ_p-s_1(0)}^{\infty}\Pi_{t_1}^1\left(kQ_p\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\end{array}\right]g_{DA}(\xi_A)d\xi_A\\+\int_0^{kQ_p}\left[\begin{array}{l}\int_0^{-s_2(0)}\Pi_{t_1}^2\left(0\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\+\int_{-s_2(0)}^{kQ_p-\xi_A-s_2(0)}\Pi_{t_1}^2\left(s_2\left(x_B\right)\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)\,dx_B\\+\int_{kQ_p-\xi_A-s_2(0)}^{kQ_p-\xi_A-s_1(0)}\Pi_{t_1}^3\left(kQ_p-\xi_A\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\+\int_{kQ_p-\xi_A-s_1(0)}^{kQ_p-s_1(0)}\Pi_{t_1}^1\left(s_1\left(x_B\right)\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\+\int_{kQ_p-s_1(0)}^{\infty}\Pi_{t_1}^1\left(kQ_p\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\end{array}\right]g_{DA}(\xi_A)d\xi_A\end{array}\right\}\tau\left(k\right)dk$$

To describe the grower's behavior, we analyze the grower's optimal policy in a specific case below.

4.3 Justification of the proposed model

In this section, we analyze a specific case for justification of the proposed model. At t_0, the grower knows that the demand D_A follows normal distribution with the mean μ_A and the standard deviation σ_A, and that the demand D_B follows uniform distribution over the interval $[X_B - \alpha, X_B + \alpha]$, where the average demand during the selling season B, the X_B is unknown but uniformly distributed over $[\mu_B - b, \mu_B + b]$.

The output rate K is known as uniform distribution over the interval $[n, m]$. During the planting season (from t_0 to t_1), the grower updates the demand forecast. At t_1, the grower specifies the K as a value k. And based on the forecast update, the grower specifies the D_A and the X_B as a value ξ_A and value x_B, respectively. We assume that $\mu_B \geq \alpha + b$ to ensure $D_B \geq 0$. The pdf of D_A, the pdf and cdf of X_B and D_B given $X_B = x_B$ and K are as follows:

$$
\begin{aligned}
g_{DA}(\xi_A) &= \frac{1}{\sqrt{2\pi}\sigma_A} e^{\left(-\frac{(\xi_A-\mu_A)^2}{2\sigma_A^2}\right)} && \xi_A \in [0, +\infty], \\
f_{X_B}(x_B) &= \frac{1}{2b} && x_B \in [\mu_B - b, \mu_B + b], \\
F_{X_B}(x_B) &= \frac{1}{2b}(x_B - \mu_B + b) && x_B \in [\mu_B - b, \mu_B + b], \\
f_{DB|xB}(\xi_B) &= \frac{1}{2\alpha} && \xi_B \in [x_B - \alpha, x_B + \alpha], \\
F_{DB|xB}(\xi_B) &= \frac{1}{2\alpha}(\xi_B - x_B + \alpha) && \xi_B \in [x_B - \alpha, x_B + \alpha], \\
\tau(k) &= \frac{1}{m-n} && k \in [n, m], \\
\mathrm{T}(k) &= \frac{1}{m-n}(k-n) && k \in [n, m].
\end{aligned}
$$

4.3.1 Optimal solution at t_1

Depending on the value of the location parameter X_B, we derive two cases as below.

Case 1. $kQ_p < x_B - \alpha$ (i.e., $x_B > kQ_p + \alpha$).

In this case, the maximum rental capacity of CAS for the grower is kQ_p. Even if the grower rents capacity kQ_p, the supply quantity in the selling season B cannot meet the possible demand D_B. The grower inevitably incurs shortage cost both in selling season B and selling season A. The profit function can be written as

$$SPFT_{t_1}^{1}\left(Q_r \left|k,\xi_A,x_B\right.\right)=-c_1Q_r+r_A\left(kQ_p-Q_r\right)-p_A\left[\xi_A-\left(kQ_p-Q_r\right)\right]$$
$$+\int_{x_B-\alpha}^{x_B+\alpha}\left[r_BQ_r-p_B\left(\xi_B-Q_r\right)\right]f\left(\xi_B\right)d\xi_B$$

Obviously, the optimal rental quantity of CAS is $Q_r^*=kQ_p$ and the maximum profit function is

$$SPFT_{t_1}^{1*}\left(kQ_p \left|k,\xi_A,x_B\right.\right)=-c_1kQ_p-p_A\xi_A+\int_{x_B-\alpha}^{x_B+\alpha}\left[r_BkQ_p-p_B\left(\xi_B-kQ_p\right)\right]f\left(\xi_B\right)d\xi_B$$

Case 2. $kQ_p \geq x_B-\alpha$ (i.e., $x_B \leq kQ_p+\alpha$).

In this case, either overage or shortage inventory in the selling season B may occur. Depending on the values of the output rate K and the demand D_A, we can derive two cases as below.

Case 2-1. $\xi_A > kQ_p$.

In this case, shortage occurs in the selling season A. The profit function is

$$SPFT_{t_1}^{2}\left(Q_r \left|k,\xi_A,x_B\right.\right)=-c_1Q_r+r_A\left(kQ_p-Q_r\right)-p_A\left[\xi_A-\left(kQ_p-Q_r\right)\right]$$
$$+\int_{x_B-\alpha}^{Q_r}\left[r_B\xi_B+v_B\left(Q_r-\xi_B\right)\right]f\left(\xi_B\right)d\xi_B$$
$$+\int_{Q_r}^{x_B+\alpha}\left[r_BQ_r-p_B\left(\xi_B-Q_r\right)\right]f\left(\xi_B\right)d\xi_B$$

The optimal rental capacity Q_r^* for the case 2-1 is given by

$$Q_r^*=\begin{cases} kQ_p & if \quad kQ_p-y\left(p_A+r_A\right)<x_B\leq kQ_p+\alpha \\ x_B+y\left(p_A+r_A\right) & if \quad \mu_B-b\leq x_B\leq kQ_p-y\left(p_A+r_A\right) \end{cases}$$

where

$$y(z) = \alpha - \frac{2\alpha(z + c_1 - v_B)}{r_B + p_B - v_B}$$

Then, the maximum profit function for the case 2-1 can be written as

$$SPFT_{t_1}^{2*}\left(Q_r \left| k, \xi_A, x_B\right.\right) = \begin{cases} SPFT_{t_1}^{2}\left(kQ_p \left| k, \xi_A, x_B\right.\right) & if \;\; kQ_p - y\left(p_A + r_A\right) < x_B \le kQ_p + \alpha \\ SPFT_{t_1}^{2}\left(x_B + y\left(p_A + r_A\right) \left| k, \xi_A, x_B\right.\right) & if \;\; \mu_B - b \le x_B \le kQ_p - y\left(p_A + r_A\right) \end{cases}$$

Case 2-2. $\xi_A \le kQ_p$.

In this case, whether the grower results in shortage or overage in the selling season A depends on the supply quantity reserved for the selling season B, which equals to the rental capacity of CAS. Therefore, the profit function may be written as below:

$$SPFT_{t_1}^{4}\left(Q_r \left| k, \xi_A, x_B\right.\right) = \begin{cases} SPFT_{t_1}^{2}\left(Q_r \left| k, \xi_A, x_B\right.\right) & if \; Q_r \ge kQ_p - \xi_A \\ SPFT_{t_1}^{3}\left(Q_r \left| k, \xi_A, x_B\right.\right) & if \; Q_r < kQ_p - \xi_A \end{cases}$$

where

$$\begin{aligned} SPFT_{t_1}^{3}\left(Q_r \left| k, \xi_A, x_B\right.\right) = & -c_1 Q_r + r_A \xi_A + v_A\left(kQ_p - Q_r - \xi_A\right) \\ & + \int_{x_B-\alpha}^{Q_r}\left[r_B \xi_B + v_B\left(Q_r - \xi_B\right)\right] f\left(\xi_B\right) d\xi_B \\ & + \int_{Q_r}^{x_B+\alpha}\left[r_B Q_r - p_B\left(\xi_B - Q_r\right)\right] f\left(\xi_B\right) d\xi_B \end{aligned}$$

The optimal solution for case 2-2 is to rent Q_r^* capacity, which is given by

$$Q_r^* = \begin{cases} kQ_p & if \;\; kQ_p - y(p_A + r_A) < x_B \le kQ_p + \alpha \\ x_B + y(p_A + r_A) & if \;\; kQ_p - \xi_A - y(p_A + r_A) \le x_B \le kQ_p - y(p_A + r_A) \\ kQ_p - \xi_A & if \;\; kQ_p - \xi_A - y(v_A) < x_B < kQ_p - \xi_A - y(p_A + r_A) \\ x_B + y(v_A) & if \;\; \mu_B - b \le x_B \le kQ_p - \xi_A - y(v_A) \end{cases}$$

Then, the maximum profit function for the case 2-2 can be written as

$$SPFT_{t_1}^{4*}(Q_r | k, \xi_A, x_B)$$
$$= \begin{cases} SPFT_{t_1}^{2}(kQ_p | k, \xi_A, x_B) & if \;\; kQ_p - y(p_A + r_A) < x_B \le kQ_p + \alpha \\ SPFT_{t_1}^{2}(x_B + y(p_A + r_A) | k, \xi_A, x_B) & if \;\; kQ_p - \xi_A - y(p_A + r_A) \le x_B \le kQ_p - y(p_A + r_A) \\ SPFT_{t_1}^{4}(kQ_p - \xi_A | k, \xi_A, x_B) & if \;\; kQ_p - \xi_A - y(v_A) < x_B < kQ_p - \xi_A - y(p_A + r_A) \\ SPFT_{t_1}^{3}(x_B + y(v_A) | k, \xi_A, x_B) & if \;\; \mu_B - b \le x_B \le kQ_p - \xi_A - y(v_A) \end{cases}$$

Combing the optimal profit functions in the above cases, the corresponding maximum profit functions at t_1 are described as following:

(i) When $\xi_A > kQ_p$,

$$SPFT_{t_1,1}^{*}(Q_r | k, \xi_A, x_B)$$
$$= \begin{cases} SPFT_{t_1}^{1}(kQ_p | k, \xi_A, x_B) & if \; kQ_p + \alpha < x_B \le \mu_B + b \\ SPFT_{t_1}^{2}(kQ_p | k, \xi_A, x_B) & if \;\; kQ_p - y(p_A + r_A) < x_B \le kQ_p + \alpha \\ SPFT_{t_1}^{2}(x_B + y(p_A + r_A) | k, \xi_A, x_B) & if \;\; \mu_B - b \le x_B \le kQ_p - y(p_A + r_A) \end{cases}$$

(ii) When $\xi_A \le kQ_p$,

$$SPFT_{t_1,2}^{*}(Q_r | k, \xi_A, x_B)$$
$$= \begin{cases} SPFT_{t_1}^{1}(kQ_p | k, \xi_A, x_B) & if \; kQ_p + \alpha < x_B \le \mu_B + b \\ SPFT_{t_1}^{2}(kQ_p | k, \xi_A, x_B) & if \;\; kQ_p - y(p_A + r_A) < x_B \le kQ_p + \alpha \\ SPFT_{t_1}^{2}(x_B + y(p_A + r_A) | k, \xi_A, x_B) & if \;\; kQ_p - \xi_A - y(p_A + r_A) \le x_B \le kQ_p - y(p_A + r_A) \\ SPFT_{t_1}^{4}(kQ_p - \xi_A | k, \xi_A, x_B) & if \;\; kQ_p - \xi_A - y(v_A) < x_B < kQ_p - \xi_A - y(p_A + r_A) \\ SPFT_{t_1}^{3}(x_B + y(v_A) | k, \xi_A, x_B) & if \;\; \mu_B - b \le x_B \le kQ_p - \xi_A - y(v_A) \end{cases}$$

4.3.2 Optimal solution at t_0

At time t_0, the grower's problem is to find the optimal planting quantity to maximize the total expected profit.

$$\max SPFT_{t_0}\left(Q_p\right)=\max\left\{-c_0Q_p+E_{D_B}\left[SPFT^*_{t_1,1}\left(Q_r\left|K,D_A,X_B\right.\right)+SPFT^*_{t_1,2}\left(Q_r\left|K,D_A,X_B\right.\right)\right]\right\}$$

subject to $Q_p \geq 0$

where

$$E_{D_B}\left[SPFT^*_{t_1,1}\left(Q_r\left|K,D_A,X_B\right.\right)+SPFT^*_{t_1,2}\left(Q_r\left|K,D_A,X_B\right.\right)\right]$$

$$=\int_n^m\int_{kQ_p}^{\infty}\left[\begin{array}{l}\displaystyle\int_{\mu_B-b}^{kQ_p-y(p_A+r_A)} SPFT^2_{t_1}\left(x_B+y\left(p_A+r_A\right)\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\ \displaystyle+\int_{kQ_p-y(p_A+r_A)}^{kQ_p+\alpha} SPFT^2_{t_1}\left(kQ_p\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\ \displaystyle+\int_{\mu_B+b}^{kQ_p+\alpha} SPFT^1_{t_1}\left(kQ_p\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\end{array}\right]g_{DA}(\xi_A)d\xi_A\tau\left(k\right)dk$$

$$+\int_n^m\int_0^{kQ_p}\left[\begin{array}{l}\displaystyle\int_{\mu_B-b}^{kQ_p-\xi_A-y(v_A)} SPFT^3_{t_1}\left(x_B+y\left(v_A\right)\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\ \displaystyle+\int_{kQ_p-\xi_A-y(v_A)}^{kQ_p-\xi_A-y(p_A+r_A)} SPFT^4_{t_1}\left(kQ_p-\xi_A\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)\,dx_B\\ \displaystyle+\int_{kQ_p-\xi_A-y(p_A+r_A)}^{kQ_p-y(p_A+r_A)} SPFT^2_{t_1}\left(x_B+y\left(p_A+r_A\right)\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\ \displaystyle+\int_{kQ_p-y(p_A+r_A)}^{kQ_p+\alpha} SPFT^2_{t_1}\left(kQ_p\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\\ \displaystyle+\int_{kQ_p+\alpha}^{\mu_B+b} SPFT^1_{t_1}\left(kQ_p\left|k,\xi_A,x_B\right.\right)f_{X_B}(x_B)dx_B\end{array}\right]g_{DA}(\xi_A)d\xi_A\tau\left(k\right)dk$$

Due to the complexity, it is difficult to describe the optimal policy for the planting quantity at t_0. Therefore, we calculate the optimal planting quantity numerically in numerical experiments.

4.4 Numerical experiments

In this section, we analyze the justification of the proposed model and examine how various parameters influence the grower's behavior with the traditional model as the benchmark (See Appendix B.2 for the formula). The basic parameters are set as follows: $c_0 = 30$, $c_1 = 4$, $r_A = 100$, $r_B = 200$, $p_A = 50$, $p_B = 100$, $n = 0.4$, $m = 1$, $\mu_A = 70$, $\sigma_A = 20$, $\mu_B = 70$, $b = 35$, $\alpha = 5$ and $v_i = 0$. When analyzing a parameter, the values of the others are kept at the initial setting as shown above. For each parameter set, the optimal planting quantity and the corresponding expected profit are calculated.

4.4.1 Performance comparison for models

We use the traditional model as a benchmark, where the grower sells fruits only in in-season (See Appendix B.2 for the formula). We compare the planting quantity and the expected profit from the traditional model and the proposed model as shown in Figure 4.2. From Figure 4.2, we observe that compared with the traditional model, both the planting quantity and the expected profit in the proposed model are higher. We can conclude that the flexible operation mode with CAS not only improves the performance of the grower significantly but also increases the grower's planting enthusiasm.

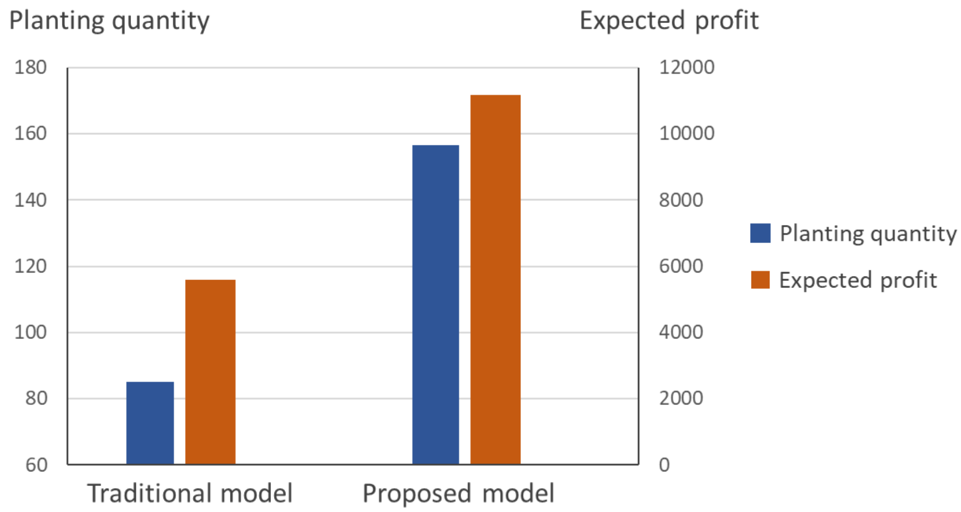

Figure 4.2: Planting quantity and expected profit vs. models

4.4.2 Sensitivity analysis

Effect of the rental cost of CAS c_1

In Figure 4.3, the optimal planting quantity Q_p and the corresponding expected profit under different values of c_1 are plotted. We vary c_1 from 2 to 8. From Figure 4.2, we observe that as c_1 increases, Q_p increases and the expected profit decreases. In this case, the supply cost of products to be sold to the selling season B increases as the rental cost c_1 increases, which reduces the supply quantity in the selling season B. The grower would increase the supply quantity in the selling season A, which results in the increase in the planting quantity. The decrease in the expected profit is as one's expect because the increases in both the rental and the planting cost may decrease the profit.

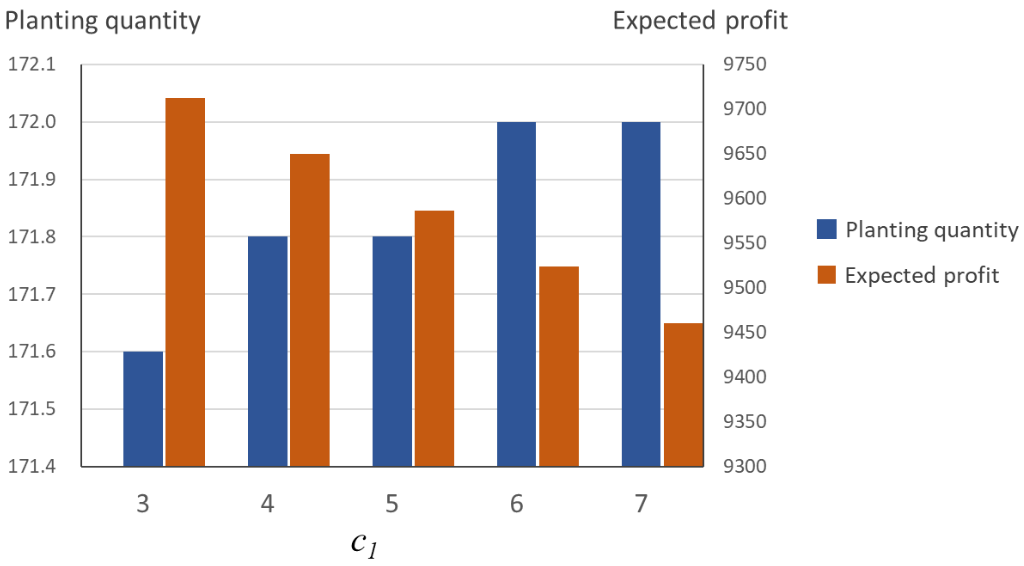

Figure 4.3: Planting quantity and expected profit vs. c_1

Effect of the shortage cost p_i

Figure 4.4 presents the optimal planting quantity Q_p and the corresponding expected profit for the parameter p_B ranging from 100 to 400 with $p_A = 50, 100, 150$. From Figure 4.3, we observe that as p_B increases, Q_p decreases. This is because as p_B increases, the grower would first transfer some products from selling season A to selling season B in order to avoid high shortage cost in the selling season B, which also means higher supply costs in the selling season B. Thus, the grower decreases the planting quantity Q_p to reduce the total supply cost. And in Figure 4.4, as p_A increases, Q_p increases. The reason is that the grower would increase the planting quantity to supply more products for the selling season A in order to decrease the shortage cost in the selling season A. Also, we observe that as p_i increases, the expected profit decreases. This is as expected because the grower incurs a high shortage cost during the selling season.

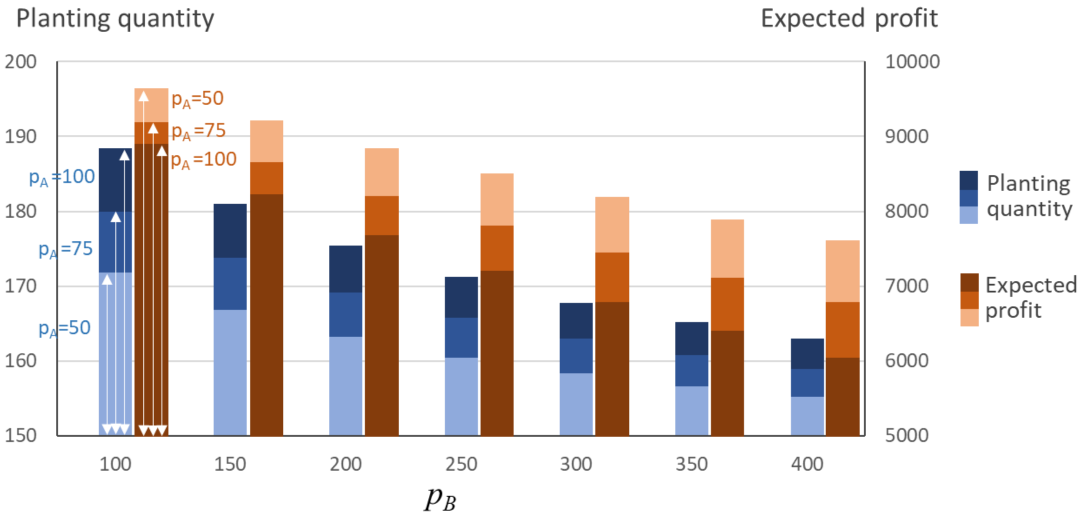

Figure 4.4: Planting quantity and expected profit vs. p_B for various p_A

Effect of the yield uncertainty

Figure 4.5 shows the optimal planting quantity Q_p and the corresponding expected profit under different yield uncertainty, where the output rate K is uniformly distributed with a mean 0.7. The yield uncertainty denoted as (n, m) increases from (0.6, 0.8) to (0.1, 1.3) by a step of 0.05 for both n and m. From Figure 4.5, we can see that both the planting quantity and the expected profit decrease as the yield uncertainty increases. This means that the yield uncertainty prevents growers from increasing planting quantity, which gives the grower an incentive to decrease yield uncertainty by improving the planting technology and management in order to gain higher profit through increasing planting quantity.

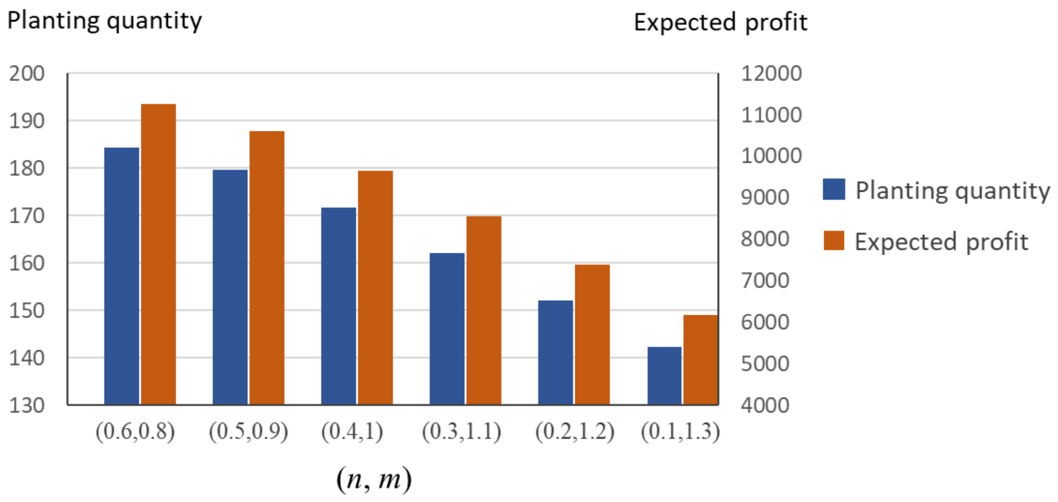

Figure 4.5: Planting quantity and expected profit vs. yield uncertainty

Effect of the value of demand forecast update in the selling season B

Figure 4.6 shows the optimal planting quantity Q_P and the corresponding expected profit for the parameter α with a varying from 5 to 35. The ratio b/α is defined as the forecasting improvement. From Figure 4.6, we observe that as α increases, both Q_P and the expected profit decrease. As α increases, the value of updating the forecast of the demand D_B reduces due to the small reduction in demand variance. The grower would decrease the supply amount in the selling season B. Therefore, the planting quantity decreases. The profit decreases because the uncertainty of the demand in the selling season B increases, which gives the grower an incentive to reduce the demand forecast variance in the off-season.

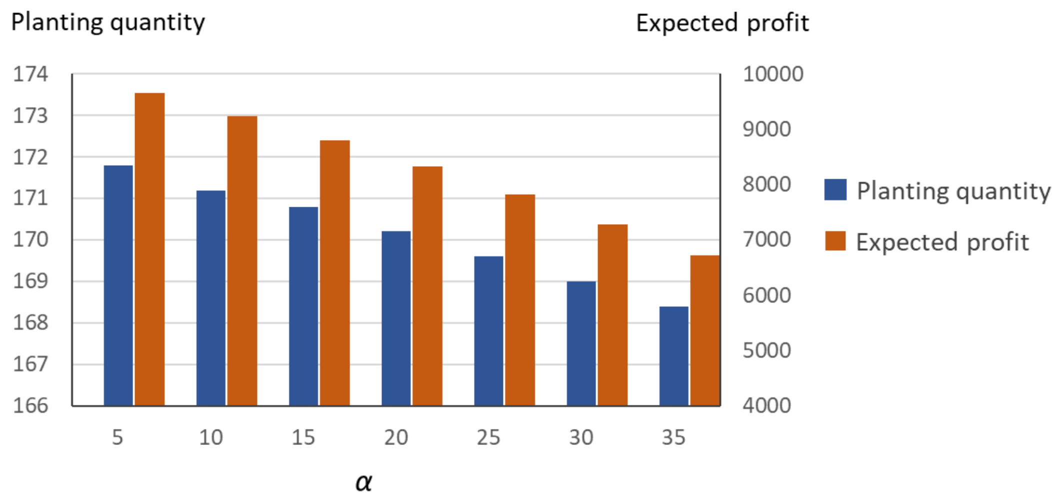

Figure 4.6: Planting quantity and expected profit vs. α

Profit sensitivity analysis

This part is to examine in an example how parameters affect the profit, which parameter may affect the profit the most largely and which is valuable for the grower to invest. We set the basic parameters as follows: $c_0 = 30$, $c_1 = 7$, $r_A = 100$, $r_B = 200$, $p_A = 100$, $p_B = 300$, $n = 0.3$, $m = 1.1$, $\mu_A = 70$, $\sigma_A = 20$, $\mu_B = 70$, $b = 35$, $\alpha = 35$ and $v_i = 0$.

We compare how the planting cost c_1, the shortage cost p_i, the variation of the output rate and the variation of the demand D_B affect the expected profit, respectively. And we do the comparison by decreasing c_1, p_i, m-n, α by 6 steps from 10%~60% with a step of 10%, respectively. The corresponding profits are shown in Figure 4.7. From Figure 4.7, we observe that besides the shortage cost p_B, uncertainties of the yield and the demand, denoted by (n, m) and α, respectively, are the most influential parameters on profit. And for other parameters, the effect order is $p_A > c_1$. We can conclude that the grower should invest to improve the planting technology and management to keep the output rate in a small range, and to enhance the ability of demand forecast for the off-season.

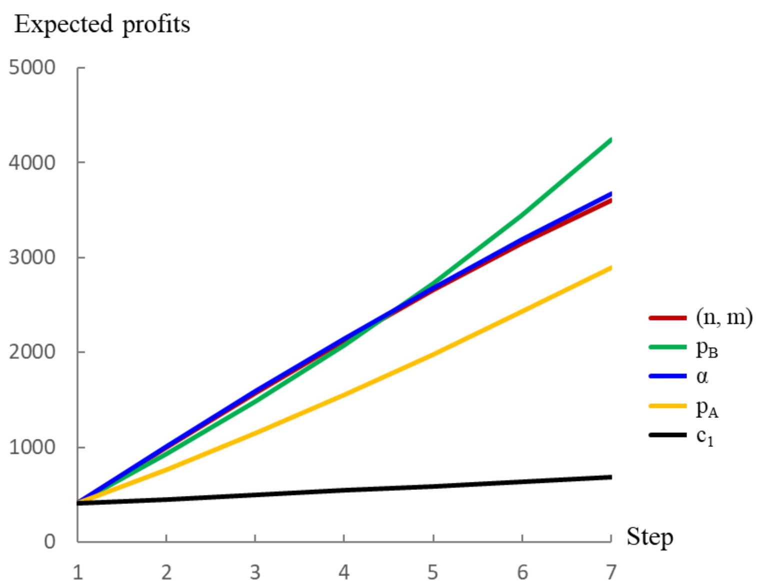

Figure 4.7: Profit vs. parameters

4.5 Chapter summary

In this chapter, we studied a single-period, three-stage model in a fresh fruit supply chain with controlled atmosphere storages (CAS). With rural CAS, the grower produces fresh fruits and then sells them to a two-stage market, i.e., in-season and off-season, in sequence. At the beginning of the planting season, the grower determines the planting quantity. Before the selling season, the grower updates the two-stage demand forecast. At the beginning of the selling season, the grower determines the rental capacity for CAS and stores products. Then, the remained products are assigned to the selling season A (in-season). At the beginning of the selling season B (off-season), the grower sells fruits stored in CAS.

We formulated the grower's profit function, provided the solution for the grower to make the optimal planting quantity and derived the optimal rental capacity of CAS. In particular, we analyzed this model in a special case. We showed numerical experiments and analyzed how the parameters c_1, p_i, the yield uncertainty and the value of demand forecast update influence the grower's behavior in such a supply chain.

In numerical experiments, we found that decreasing the rental cost of CAS, the shortage cost, the yield uncertainty and the forecast error in the selling season B, can improve the grower's profit. For the traditional model, we observe that both the planting quantity and the expected profit in the traditional model are lower than that in the proposed one. We can conclude that the flexible operation mode with CAS not only improves the performance of the grower significantly but also increases the grower's planting enthusiasm. From the sensitivity analysis, we find besides the shortage cost, uncertainties of the yield and the demand are the most influential parameters on profit. Therefore, we can get managerial insights that the grower should invest to improve the planting technology and management to keep the output rate in a small range, and to enhance the ability of demand forecast for the off-season.

Chapter 5

Conclusion and future study

This dissertation attempts to develop flexible operation modes in fresh fruit supply chains (FSCs) with these two types of cold storages, i.e., regular atmosphere storage (RAS) and controlled atmosphere storage (CAS), respectively, in order to help growers get affluent and increase the enthusiasm of planting.

We propose the flexible supply contract with put options (SCPO) for a rural fresh FSC with RAS, where the grower stores fresh fruits in RAS to extend the shelf life, which incurs extra storage costs that can be recovered by salvaging at a higher price later. Put options give the buyer the right, but not the obligation, to decrease the initial order, one for each option. At the beginning of the planning horizon, the buyer places an initial order and purchases put options with a preliminary demand forecast. Considering the buyer's order and the random yield, the grower determines the planting quantity. During the planting season, the buyer updates the demand forecast. At the beginning of the selling season, the buyer exercises put options if necessary. Then, the grower delivers the final order and stores surplus products in RAS to extend their shelf life, which incurs extra storage costs that can be recovered by salvaging at a higher price later. The proposed model is analyzed from both the grower's and the buyer's perspectives. And the buyer's and the grower's profit functions are formulated, and we derive the buyer's optimal policies for the initial order and put options as well as the grower's optimal policy for the planting quantity. The grower's optimal supply tariff can be obtained only numerically. In particular, we obtain closed-form formulae to determine the buyer's optimal order policy and the grower's optimal planting quantity in a special case. We show numerical experiments and analyze how the parameters affect the performances of both the grower and the buyer.

For CAS, we consider a single-period, three-stage model in a rural fresh FSC with CAS. With CAS, the grower produces fresh fruits and then sells them to a two-stage market, i.e., in-season and off-season, in sequence. At the beginning of the planting season, the grower determines the planting quantity. Before the selling season, the grower updates the two-stage demand forecast. At the beginning of the selling season, the grower determines the rental capacity for CAS and stores products. Then, the remained products are assigned to the selling season A (in-season). At the beginning of the selling season B (off-season), the grower sells fruits stored in CAS. We formulate the grower's profit function, propose the solution for the grower to make the optimal planting quantity and derive the optimal rental capacity of CAS. In particular, we study this model in a special case, and analyze numerically how the parameters influence the grower's behavior in such a supply chain.

5.1 Summary of results

In Chapter 3, we modeled a single-period, two-stage contract with put options (SCPO) in a fresh fruit supply chain (FSC) with regular atmosphere storages (RAS). The proposed model was analyzed from both the grower's and the buyer's perspectives. And the buyer's and the grower's profit functions were formulated, which were then used to derive the buyer's optimal policies for the initial order and put options as well as the grower's optimal policy for the planting quantity. The grower's optimal supply tariff can be obtained only numerically. In particular, we obtained closed-form formulae to determine the buyer's optimal order policy and the grower's optimal planting quantity in a special case. We showed numerical experiments in which we examined the effectiveness of the proposed model and analyzed how the parameters v_g, g, p and the yield uncertainty influence the optimal policies and expected profits in such a supply chain.

In the numerical analysis, some managerial insights in SCPO have been observed:

1. The grower's performance of the proposed SCPO model is better than that of SCPO model with other conditions. Compared to the traditional operational mode, the proposed SCPO model can improve the grower's and buyer's performances, simultaneously. And the proposed SCPO model is more beneficial to the grower, which protects the grower's profit.

2. With rural cold storages, the grower can get affluent. A higher preservation level of RAS and a low yield uncertainty enhances a grower's enthusiasm for planting.

3. Supply chain participants benefit from each other's risk aversion.

4. The higher the demand uncertainty, the more beneficial the SCPO model is for supply chain participants. With high uncertainties of the yield and the demand, the grower's and buyer's profits can be enhanced up to 53% and 29%, respectively.

5. With SCPO model, comparing parameters' effect on expected profit, the spot market price may affect the grower's profit most largely.

In Chapter 4, we studied a single-period, three-stage model in a fresh fruit supply chain with controlled atmosphere storages (CAS). With CAS, the grower produces fresh fruits and then sells them to a two-stage market, i.e., in-season and off-season, in sequence. We formulated the grower's profit function, provided the solution for the grower to make the optimal planting quantity and derived the optimal rental capacity of CAS. In particular, we analyzed this model in a special case. We showed numerical experiments and analyzed how the parameters c_1, p_i, the yield uncertainty and the value of demand forecast update influence the grower's behavior in such a supply chain. In numerical experiments, we found that decreasing the rental cost of CAS, the shortage cost, the yield uncertainty and the forecast error in the selling season B, can improve the grower's profit. For the traditional model, we observe that both the planting quantity and the expected profit in the traditional model are lower than that in the proposed one. We can conclude that the flexible operation mode with CAS not only improves the performance of the grower significantly but also increases the grower's planting enthusiasm. From the sensitivity analysis, we find besides the shortage cost, uncertainties of the yield and the demand are the most influential parameters on profit. Therefore, we can get managerial insights that the grower should invest to improve the planting technology and management to keep the output rate in a small range, and to enhance the ability of demand forecast for the off-season.

5.2 Future study

The results presented in this research can be seen as a framework that can be further developed to study flexible operation modes with cold storages in more realistic situations. Future study as a natural extension would analyze the case of a limited scale of cold storages. It would also be interesting to study the operation mode in a fresh FSC with multiple types of cold storages.

Bibliography

Omar Ahumada, J. Rene Villalobos and A. Nicholas Mason. Tactical planning of the production and distribution of fresh agricultural products under uncertainty. *Agricultural systems*, 112:17-26, 2012. doi:https://doi.org/10.1016/j.agsy.2012.06.002.

Omar Ahumada and J. Rene Villalobos. Application of planning models in the agri-food supply chain: A review. *European Journal of Operational Research*, 196(1):1-20, 2009. doi:https://doi.org/10.1016/j.ejor.2008.02.014.

———. A tactical model for planning the production and distribution of fresh produce. *Annals of Operations Research*, 190(1):339-358, 2011. doi:10.1007/s10479-009-0614-4.

M. M. E. Alemany, Ana Esteso, Ángel Ortiz and Mariana Del Pino. Centralized and distributed optimization models for the multi-farmer crop planning problem under uncertainty: Application to a fresh tomato argentinean supply chain case study. *Computers & Industrial Engineering*, 153:107048, 2021. doi:https://doi.org/10.1016/j.cie.2020.107048.

Isabella M. Brasil and Mohammed Wasim Siddiqui. Chapter 1 - postharvest quality of fruits and vegetables: An overview. *Preharvest modulation of postharvest fruit and vegetable quality*, 2018. doi:https://doi.org/10.1016/B978-0-12-809807-3.00001-9.

Gérard P. Cachon. Supply chain coordination with contracts. *Handbooks in operations research and management science*, 11 2003. doi:https://doi.org/10.1016/S0927-0507(03)11006-7.

Xiaoqiang Cai, Jian Chen, Yongbo Xiao, Xiaolin Xu and Gang Yu. Fresh-product supply chain management with logistics outsourcing. *Omega*, 41(4):752-765,

2013. doi:https://doi.org/10.1016/j.omega.2012.09.004.

Luis P Catalá, Guillermo A Durand, Aníbal M Blanco and J Alberto Bandoni. Mathematical model for strategic planning optimization in the pome fruit industry. *Agricultural systems*, 115:63-71, 2013.

Luis P Catalá, M Susana Moreno, Aníbal M Blanco and J Alberto Bandoni. A bi-objective optimization model for tactical planning in the pome fruit industry supply chain. *Computers and Electronics in Agriculture*, 130:128-141, 2016.

Frank Chen and Mahmut Parlar. Value of a put option to the risk-averse newsvendor. *Iie Transactions*, 39(5):481-500, 2007.

Wenchong Chen, Jing Li and Xiaojie Jin. The replenishment policy of agri-products with stochastic demand in integrated agricultural supply chains. *Expert Systems with Applications*, 48:55-66, 2016. doi:https://doi.org/10.1016/j.eswa.2015.11.017.

E.D. Cittadini, M.T.M.H. Lubbers, N. De Ridder, H. Van Keulen and G.D.H. Claassen. Exploring options for farm-level strategic and tactical decision-making in fruit production systems of south patagonia, argentina. *Agricultural systems*, 98(3):189-198, 2008.

Alysson M. Costa, Lana Mara R. Dos Santos, Douglas J. Alem and Ricardo H. S. Santos. Sustainable vegetable crop supply problem with perishable stocks. *Annals of Operations Research*, 219(1):265-283, 2014. doi:10.1007/s10479-010-0830-y.

K. Darby-Dowman, S. Barker, E. Audsley and D. Parsons. A two-stage stochastic programming with recourse model for determining robust planting plans in horticulture. *Journal of the Operational Research Society*, 51(1):83-89, 2000. doi:10.1057/palgrave.jors.2600858.

Khandra Fahmy and Kohei Nakano. Effective transport and storage condition for preserving the quality of ‘jiro’persimmon in export market. *Agriculture and Agricultural Science Procedia*, 9:279-290, 2016.

Yangang Feng, Yi Hu and Lin He. Research on coordination of fresh agricultural product supply chain considering fresh-keeping effort level under retailer risk avoidance. *Discrete Dynamics in Nature and Society*, 2021:1-15, 2021. doi:10.1155/2021/5527215.

Ibrahim Fikry, Mohamed Gheith and Amr Eltawil. An integrated production-logistics-crop rotation planning model for sugar beet supply chains. *Computers & Industrial Engineering*, 157:107300, 2021.

Amirmohsen Golmohammadi and Elkafi Hassini. Capacity, pricing and production under supply and demand uncertainties with an application in agriculture. *European Journal of Operational Research*, 275(3):1037-1049, 2019. doi:https://doi.org/10.1016/j.ejor.2018.12.027.

P. J. C. Hamer. A decision support system for the provision of planting plans for brussels sprouts. *Computers and Electronics in Agriculture*, 11(2):97-115, 1994. doi:https://doi.org/10.1016/0168-1699(94)90001-9.

Susan M Hester and Oscar Cacho. Modelling apple orchard systems. *Agricultural systems*, 77(2):137-154, 2003.

Xiangyu Hou, Rene Haijema and Dacheng Liu. Display, disposal, and order policies for fresh produce with a back storage at a wholesale market. *Computers & Industrial Engineering*, 111:18-28, 2017. doi:https://doi.org/10.1016/j.cie.2017.06.038.

Burak Kazaz. Production planning under yield and demand uncertainty with yield-dependent cost and price. *Manufacturing & Service Operations Management*, 6(3):209-224, 2004. doi:10.1287/msom.1030.0024.

Changhua Liao and Qihui Lu. Coordinating a three-level fresh agricultural product supply chain considering option contract under spot price uncertainty. *Discrete Dynamics in Nature and Society*, 2022:1-19, 2022. doi:10.1155/2022/2991241.

Ziru Liao and Meifang Li. Analysis of fruit production situation and the concentration degree of its industrial in china. *China Fruits*,(3):129-134, 2023. doi:10.16626/j.cnki.issn1000-8047.2023.03.027.

Cong Liu, Zhibin Jiang, Liming Liu and Na Geng. Solutions for flexible container leasing contracts with options under capacity and order constraints. *International Journal of Production Economics*, 141(1):403-413, 2013. doi:https://doi.org/10.1016/j.ijpe.2012.09.005.

Hengyu Liu, Juliang Zhang, Chen Zhou and Yihong Ru. Optimal purchase and inventory retrieval policies for perishable seasonal agricultural products. *Omega*, 79:133-145, 2018.

Xueli Ma, Shuyun Wang, Sardar M. N. Islam and Xiaobing Liu. Coordinating a three-echelon fresh agricultural products supply chain considering freshness-keeping effort with asymmetric information. *Applied Mathematical Modelling*, 67:337-356, 2019. doi:https://doi.org/10.1016/j.apm.2018.10.028.

Guillermo L. Masini, Aníbal M. Blanco, Noemí Petracci and J. Alberto Bandoni. Chapter 5: Supply chain tactical optimization in the fruit industry. *Process systems engineering*, 2011.

Jordi Mateo-Fornés, Wladimir Soto-Silva, Marcela C. González-Araya, Lluís M. Plà-Aragonès and Francesc Solsona-Tehas. Managing quality, supplier selection, and cold-storage contracts in agrifood supply chain through stochastic optimization. *International Transactions in Operational Research*, 30(4):1901-1930, 2021. doi:https://doi.org/10.1111/itor.13069.

Ilkyeong Moon, Yoon Jea Jeong and Subrata Saha. Investment and coordination decisions in a supply chain of fresh agricultural products. *Operational Research*, 20(4):2307-2331, 2020. doi:10.1007/s12351-018-0411-4.

Tri-Dung Nguyen, Tri Nguyen-Quang, Uday Venkatadri, Claver Diallo and Michelle Adams. Mathematical programming models for fresh fruit supply chain optimization: A review of the literature and emerging trends. *AgriEngineering*, 3:519-541, 2021.

Yumi Oum, Shmuel Oren and Shijie Deng. Hedging quantity risk with standard power options in a competitive wholesale electricity market. *Naval Research Logistics*, 53(7):697-712, 2006.

P. Paam, R. Berretta, M. Heydar and R. García-Flores. The impact of inventory management on economic and environmental sustainability in the apple industry. *Computers and Electronics in Agriculture*, 163:104848, 2019. doi:https://doi.org/10.1016/j.compag.2019.06.003.

Parichehr Paam, Regina Berretta, Rodolfo García-Flores and Sanjoy Kumar Paul. Multi-warehouse, multi-product inventory control model for agri-fresh products – a case study. *Computers and Electronics in Agriculture*, 194:106783, 2022.

Fahimeh Pourmohammadi, Ebrahim Teimoury and Mohammad Reza Gholamian. A scenario-based stochastic programming approach for designing and planning wheat supply chain (a case study). *Decision Science Letters*, 9(4):537-546, 2020.

Yan Shi and Fulin Wang. Agricultural supply chain coordination under weather-related uncertain yield. *Sustainability*, 14(9):5271, 2022. doi:10.3390/su14095271.

Mohammed Wasim Siddiqui. *Preharvest modulation of postharvest fruit and vegetable quality*, 2017. 0128098082**.**

Sarbjit Singh. An inventory model for perishable items having constant demand with time dependent holding cost. *Mathematics and Statistics*, 4(2):58-61, 2016.

Wladimir E. Soto-Silva, Marcela C. González-Araya, Marcos A. Oliva-Fernández and Lluís M. Plà-Aragonés. Optimizing fresh food logistics for processing: Application for a large chilean apple supply chain. *Computers and Electronics in Agriculture*, 136:42-57, 2017. doi:https://doi.org/10.1016/j.compag.2017.02.020.

Lanying Sun and Xiaoyan Li. Comparison analysis on the bilateral efforts of farmers and the third-party organization under multiple contract modes. *Kybernetes*, 48(5):818-834, 2018. doi:10.1108/K-03-2018-0102.

Tue Takner and Bilge Bilgen. Optimization models for harvest and production planning in agri-food supply chain: A systematic review. *Logistic*, 5(3):52, 2021.

Barış Tan and Nihan Çömden. Agricultural planning of annual plants under demand, maturation, harvest, and yield risk. *European Journal of Operational Research*, 220(2):539-549, 2012. doi:https://doi.org/10.1016/j.ejor.2012.02.005.

Nana Wan, Li Li, Xiaozhi Wu and Jianchang Fan. Coordination of a fresh agricultural product supply chain with option contract under cost and loss disruptions. *PLOS ONE*, 16(6):0252960, 2021. doi:10.1371/journal.pone.0252960.

Chong Wang and Xu Chen. Joint order and pricing decisions for fresh produce with put option contracts. *Journal of the Operational Research Society*, 69(3):474-484, 2018. doi:10.1057/s41274-017-0228-1.

Qunzhi Wang and De-Bi Tsao. Supply contract with bidirectional options: The buyer's perspective. *International Journal of Production Economics*, 101(1):30-52, 2006.

Cleve Willis and William Hanlon. Temporal model for long-run orchard decisions. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 24(3):17-28, 1976.

Guangyin Xu, Jihao Feng, Fenglei Chen, Heng Wang and Zhenfeng Wang. Simulation-based optimization of control policy on multi-echelon inventory system for fresh agricultural products. *International Journal of Agricultural and Biological Engineering*, 12(2):184-194, 2019.

Bo Yan, Xiaoxu Chen, Qin Yuan and Xiaotai Zhou. Sustainability in fresh agricultural product supply chain based on radio frequency identification under an emergency. *Central European Journal of Operations Research*, 28:1-19, 2020a. doi:10.1007/s10100-019-00657-6.

Bo Yan, Gaodi Liu, Xiaohua Wu and Jiwen Wu. Decision-making on the supply chain of fresh agricultural products with two-period price and option contract. *Asia-Pacific Journal of Operational Research*, 38(1):2050038, 2020b. doi:10.1142/S0217595920500384.

Lei Yang, Ruihong Tang and Kebing Chen. Call, put and bidirectional option contracts in agricultural supply chains with sales effort. *Applied Mathematical Modelling*, 47:1-16, 2017. doi:https://doi.org/10.1016/j.apm.2017.03.002.

Fei Ye, Qiang Lin and Yina Li. Coordination for contract farming supply chain with stochastic yield and demand under cvar criterion. *Operational Research*, 20(1):369-397, 2017. doi:10.1007/s12351-017-0328-3.

Jianxiong Zhang, Guowei Liu, Qiao Zhang and Zhenyu Bai. Coordinating a supply chain for deteriorating items with a revenue sharing and cooperative investment contract. *Omega*, 56:37-49, 2015. doi:https://doi.org/10.1016/j.omega.2015.03.004.

Xia Zhao and Fangwei Wu. Coordination of agri-food chain with revenue-sharing contract under stochastic output and stochastic demand. *Asia-Pacific Journal of Operational Research*, 28(4):487-510, 2011.

Yingxue Zhao, Xiaoge Meng, Shouyang Wang and T. C. Edwin Cheng. *Contract analysis and design for supply chains with stochastic demand*, 234 2016. ISBN 978-1-4899-7632-1**.** doi:10.1007/978-1-4899-7633-8.

Qi Zheng, Li Zhou, Tijun Fan and Petros Ieromonachou. Joint procurement and pricing of fresh produce for multiple retailers with a quantity discount contract. *Transportation Research Part E: Logistics and Transportation Review*, 130:16-36, 2019. doi:https://doi.org/10.1016/j.tre.2019.08.013.

Appendix A

A.1 Proof of Proposition 1

In the NV model, the grower's problem at t_0 is:

$$\max PFT_{nvg}\left(Q_{nvp}\right)=\max\left[\begin{array}{l}-cQ_{nvp}+wQ_{nvo}-\int\limits_{0}^{Q_{nvo}/Q_{nvp}} g\left(Q_{nvo}-kQ_{nvp}\right)\tau\left(k\right)dk \\ +\int\limits_{Q_{nvo}/Q_{nvp}}^{\infty} v_g\left(kQ_{nvp}-Q_{nvo}\right)\tau\left(k\right)dk\end{array}\right]$$

Taking the second derivative of $PFT_{nvg}\left(Q_{nvp}\right)$ with respective to Q_{nvp}, we have

$$\frac{d^2PFT_{nvg}\left(Q_{nvp}\right)}{d^2Q_{nvp}}=\left(v_g-g\right)\frac{Q_{nvo}^2}{Q_{nvp}^3}\tau\left(\frac{Q_{nvo}}{Q_{nvp}}\right)$$

Considering the assumption $g>v_g$ in Section 3.2.1, $\frac{d^2PFT_{nvg}\left(Q_{nvp}\right)}{d^2Q_{nvp}}\le 0$ holds.

Therefore, the objective function $PFT_{nvg}\left(Q_{nvp}\right)$ is concave in Q_{nvp}.

Equating $\frac{dPFT_{nvg}\left(Q_{nvp}\right)}{dQ_{nvp}}$ to zero, we get

$$\frac{dPFT_{nvg}\left(Q_{nvp}\right)}{dQ_{nvp}}=g\int_0^{Q_{nvo}/Q_{nvp}} k\tau\left(k\right)dk+v_g\int_{Q_{nvo}/Q_{nvp}}^{\infty} k\tau\left(k\right)dk-c=0 \qquad \text{(A.1)}$$

Obviously, $\frac{dPFT_{nvg}\left(Q_{nvp}\right)}{dQ_{nvp}}$ is continuous with respect to Q_{nvp}.

Considering the assumption $g > c/\bar{k} > v_g$ in Section 3.2.1, we have

$$\lim_{Q_{nvp}\to 0} \frac{dPFT_{nvg}\left(Q_{nvp}\right)}{dQ_{nvp}} = -c + g\int_0^\infty k\tau\left(k\right)dk > 0$$

$$\lim_{Q_{nvp}\to \infty} \frac{dPFT_{nvg}\left(Q_{nvp}\right)}{dQ_{nvp}} = -c + v_g\int_0^\infty k\tau\left(k\right)dk < 0$$

Therefore, there exists a non-negative value of $Q_{nvp}^{'}$ satisfies the equation (A.1), and the optimal planting quantity is $Q_{nvp}^{*} = Q_{nvp}^{'}$.

A.2 Proof of Proposition 2

In the SCPO model, the buyer's problem at t_0 is:

$$\max PFT_{ob}\left(Q_0, q_0\right)$$
$$= \max \left\{ \begin{array}{l} -wQ_0 - w_o q_0 + \int\limits_0^{Q_0 - q_0} \left[w_{ep} q_0 + r\xi + v_b (Q_0 - q_0 - \xi)\right] f\left(\xi\right) d\xi \\ + \int\limits_{Q_0 - q_0}^{Q_0} \left[w_{ep}\left(Q_0 - \xi\right) + r\xi\right] f\left(\xi\right) d\xi + \int\limits_{Q_0}^{\infty} \left[rQ_0 - p(\xi - Q_0)\right] f\left(\xi\right) d\xi \end{array} \right\}$$

Taking the second partial derivative of $PFT_{ob,t_0}\left(Q_0, q_0\right)$ with respect to Q_0, we have

$$\frac{\partial^2}{\partial Q_0^2} PFT_{ob,t_0}\left(Q_0, q_0\right) = \left(w_{ep} - r - p\right) f\left(Q_0\right) + \left(v_b - w_{ep}\right) f\left(Q_0 - q_0\right)$$

And we can calculate the hessian matrix:

$$\begin{vmatrix} \frac{\partial^2}{\partial Q_0^2} PFT_{ob,t_0} & \frac{\partial^2}{\partial q_0 \partial Q_0} PFT_{ob,t_0} \\ \frac{\partial^2}{\partial Q_0 \partial q_0} PFT_{ob,t_0} & \frac{\partial^2}{\partial q_0^2} PFT_{ob,t_0} \end{vmatrix} = \left(w_{ep} - r - p\right)\left(v_b - w_{ep}\right) f\left(Q_0\right) f\left(Q_0 - q_0\right)$$

Considering the assumptions $w_{ep} \leq w$, $r + p > w + w_o$ and $v_b \leq w_{ep} - w_o$ in Section 3.2.3, the objective function $PFT_{ob,t_0}\left(Q_0, q_0\right)$ is concave.

Differentiating $PFT_{ob}\left(Q_0, q_0\right)$ with respect to Q_0 and q_0, respectively, and equating them to zero, we have

$$F\left(Q_0\right) = \frac{r + p - w - w_o}{r + p - w_{ep}} \tag{A.2}$$

$$F\left(Q_0 - q_0\right) = \frac{w_{ep} - v_b}{w_o} \tag{A.3}$$

If there exist non-negative values of $Q_0^{'}$ and $q_0^{'}$ which satisfies the equation (A.2) and (A.3), then the optimal solution is $Q_0^* = Q_0^{'}$ and $q_0^* = q_0^{'}$.

A.3 Proof of Proposition 3

In the SCPO model, at $t_{0,3}$, the grower's problem is:

$$
\begin{aligned}
&\max PFT_{og}\left(Q_{op}\right)\\
&=\max\left\{\begin{array}{l}
-cQ_{op}\\
+\int_{0}^{Q_0-q_0}\left\{\begin{array}{l}-w_{ep}q_0+\int_{0}^{(Q_0-q_0)/Q_{op}}\left[-g\left(Q_0-q_0-kQ_{op}\right)\right]\tau(k)\,dk\\
+\int_{(Q_0-q_0)/Q_{op}}^{\infty}v_g\left[kQ_{op}-\left(Q_0-q_0\right)\right]\tau(k)\,dk\end{array}\right\}f(\xi)\,d\xi\\
+\int_{Q_0-q_0}^{Q_0}\left\{\begin{array}{l}-w_{ep}(Q_0-\xi)+\int_{0}^{\xi/Q_{op}}\left[-g\left(\xi-kQ_{op}\right)\right]\tau(k)\,dk\\
+\int_{\xi/Q_{op}}^{\infty}v_g\left(kQ_{op}-\xi\right)\tau(k)\,dk\end{array}\right\}f(\xi)\,d\xi\\
+\int_{Q_0}^{\infty}\left\{\int_{0}^{Q_0/Q_{op}}\left[-g\left(Q_0-kQ_{op}\right)\right]\tau(k)\,dk+\int_{Q_0/Q_{op}}^{\infty}v_g\left(kQ_{op}-Q_0\right)\tau(k)\,dk\right\}f(\xi)\,d\xi
\end{array}\right\}
\end{aligned}
$$

Taking the derivative and second derivative of $PFT_{og}\left(Q_{op}\right)$ with respective to Q_{op}, respectively, we have

$$
\begin{aligned}
\frac{dPFT_{og}\left(Q_{op}\right)}{dQ_{op}}&=-c+g\int_{0}^{Q_0/Q_{op}}k\tau(k)dk+v_g\int_{Q_0/Q_{op}}^{\infty}k\tau(k)dk\\
&\quad+\left(g-v_g\right)\left[F\left(Q_0-q_0\right)\int_{\xi/Q_{op}}^{(Q_0-q_0)/Q_{op}}k\tau(k)dk+F\left(Q_0\right)\int_{Q_0/Q_{op}}^{\xi/Q_{op}}k\tau(k)dk\right]
\end{aligned}
$$

$$
\begin{aligned}
\frac{d^2PFT_{og}\left(Q_{op}\right)}{d^2Q_{op}}&=-\left(g-v_g\right)\left[F\left(Q_0\right)-F\left(Q_0-q_0\right)\right]\frac{\xi^2}{Q_{op}^3}\tau\left(\frac{\xi}{Q_{op}}\right)\\
&\quad-\left(g-v_g\right)\left\{F\left(Q_0-q_0\right)\frac{\left(Q_0-q_0\right)^2}{Q_{op}^3}\tau\left(\frac{Q_0-q_0}{Q_{op}}\right)+\left[1-F\left(Q_0\right)\right]\frac{Q_0^2}{Q_{op}^3}\tau\left(\frac{Q_0}{Q_{op}}\right)\right\}
\end{aligned}
$$

Similar with A.1 Proof of Proposition 1, we can prove that there exists a non-negative value of Q_{op} which satisfies the following equation

$$\frac{dPFT_{og}\left(Q_{op}\right)}{dQ_{op}} = -c + g\int_{0}^{Q_0/Q_{op}} k\tau\left(k\right)dk + v_g\int_{Q_0/Q_{op}}^{\infty} k\tau\left(k\right)dk$$
$$+\left(g - v_g\right)\left[F\left(Q_0 - q_0\right)\int_{\xi/Q_{op}}^{(Q_0-q_0)/Q_{op}} k\tau\left(k\right)dk + F\left(Q_0\right)\int_{Q_0/Q_{op}}^{\xi/Q_{op}} k\tau\left(k\right)dk\right] = 0$$

Considering the assumption $g > v_g$ in Section 3.2.1, we easily have $\frac{d^2PFT_{og}\left(Q_{op}\right)}{d^2Q_{op}} \le 0$. Therefore, the objective function $PFT_{og}\left(Q_{op}\right)$ is concave in Q_{op}.

Therefore, there exists a non-negative value of $Q_{op}^{'}$ which satisfies the following equation

$$v_g\int_{Q_0/Q_{op}}^{\infty} k\tau\left(k\right)dk + \left(g - v_g\right)\begin{bmatrix} F\left(Q_0 - q_0\right)\int_{\xi/Q_{op}}^{(Q_0-q_0)/Q_{op}} k\tau\left(k\right)dk \\ +F\left(Q_0\right)\int_{Q_0/Q_{op}}^{\xi/Q_{op}} k\tau\left(k\right)dk \end{bmatrix} = c - g\int_{0}^{Q_0/Q_{op}} k\tau\left(k\right)dk \quad \text{(A.4)}$$

and the optimal planting quantity is $Q_{op}^{*} = Q_{op}^{'}$.

A.4 Proof of Proposition 4

Considering the output rate in this case is uniformly distributed, we get the equation (A.5) according to the equation (A.1).

$$Q_{nvp}^2 = \left(\frac{g - v_g}{gn^2 - v_g m^2 + 2(m-n)c}\right)Q_{nvo}^2 \quad \text{(A.5)}$$

It can be readily proved that $\frac{g - v_g}{gn^2 - v_g m^2 + 2(m-n)c} > 0$ holds. Let $Q_{nvp} = Q_{nvp1} > 0$ satisfy the equation (A.5), we can get

$$Q_{nvp1} = Q_{nvo}\sqrt{\frac{g - v_g}{gn^2 - v_g m^2 + 2(m-n)c}}$$

Considering the assumption $\frac{Q_{nvo}}{m} \le Q_{nvp} \le \frac{Q_{nvo}}{n}$, the optimal planting quantity can be derived as three cases.

- If $\frac{Q_{nvo}}{m} \le Q_{nvp1} \le \frac{Q_{nvo}}{n}$, the optimal planting quantity $Q_{nvp}^* = Q_{nvp1}$.
- If $Q_{nvp1} > \frac{Q_{nvo}}{n}$, the optimal planting quantity $Q_{nvp}^* = \frac{Q_{nvo}}{n}$.
- If $Q_{nvp1} < \frac{Q_{nvo}}{m}$, the optimal planting quantity is $Q_{nvp}^* = \frac{Q_{nvo}}{m}$.

Combining the above cases, we conclude our proof.

A.5 Proof of Proposition 5

Taking the partial derivative of Q_0 with respective to w_o, w_{ep} and p, respectively, we have

$$\frac{\partial Q_0}{\partial w_o} = -\frac{2\beta}{p + r - w_{ep}} < 0$$

$$\frac{\partial Q_0}{\partial w_{ep}} = \frac{2\beta(p + r - w - w_o)}{(p + r - w_{ep})^2} > 0$$

$$\frac{\partial Q_0}{\partial p} = \frac{2\beta(w + w_o - w_{ep})}{\left(p + r - w_{ep}\right)^2} > 0$$

Thus, Q_0 increases with w_{ep} and p, and decreases with w_o.

Taking the partial derivative of q_0 with respective to w_o, w_{ep}, β, p and v_b, respectively, we have

$$\frac{\partial q_0}{\partial w_o} = \frac{2\beta(p+r-v_b)}{(v_b-w_{ep})(p+r-w_{ep})} < 0$$

$$\frac{\partial q_0}{\partial w_{ep}} = \frac{2\beta w_o}{(v_b-w_{ep})^2} + \frac{2\beta(p+r-w-w_o)}{(p+r-w_{ep})^2} > 0$$

$$\frac{\partial q_0}{\partial \beta} = \frac{2w_o}{v_b-w_{ep}} + \frac{2(p+r-w-w_o)}{p+r-w_{ep}} > 0$$

$$\frac{\partial q_0}{\partial p} = \frac{2\beta(w+w_o-w_{ep})}{(p+r-w_{ep})^2} > 0$$

$$\frac{\partial q_0}{\partial v_b} = -\frac{2\beta w_o}{(v_b-w_{ep})^2} < 0$$

Therefore, q_0 increases with w_{ep}, β and p, and decreases with w_o and v_b.

A.6 Proof of Proposition 6

(i) In plan 1, taking the second derivative of $SPFT_{og}^{1}\left(Q_{op}\right)$ with respect to Q_{op}, we have

$$\frac{d^2 SPFT_{og}^{1}\left(Q_{op}\right)}{d^2 Q_{op}} = -\frac{\left(g-v_g\right)\left(m^2+mn+n^2\right)}{6\beta} < 0$$

Therefore, the objective function $SPFT_{og}^{1}\left(Q_{op}\right)$ is concave.

Taking the derivative of $SPFT_{og}^{1}\left(Q_{op}\right)$ with respect to Q_{op}, and equating it to zero, we have the following equation:

$$\frac{dSPFT_{og}^{1}\left(Q_{op}\right)}{dQ_{op}} = -2\left(n^2+m^2+nm\right)(g-v_g)Q_{op} + 3(n+m)\left[\gamma(g-v_g)+\beta(g+v_g)\right]-12c\beta = 0 \quad \text{(A.6)}$$

Let $Q_{op} = Q_{op,1}$ satisfy the equation (A.6), we can get

$$Q_{op,1} = \frac{3(n+m)\left[\gamma(g-v_g)+\beta(g+v_g)\right]-12c\beta}{2\left(n^2+m^2+nm\right)(g-v_g)}$$

Considering the assumption $\frac{Q_0-q_0}{n} \le Q_{op} \le \frac{Q_0}{m}$ in plan 1, the optimal planting quantity can be derived as three cases.

- If $\frac{Q_0-q_0}{n} \le Q_{op,1} \le \frac{Q_0}{m}$, the optimal planting quantity $Q_{op}^{*} = Q_{op,1}$.
- If $Q_{op,1} > \frac{Q_0}{m}$, the optimal planting quantity $Q_{op}^{*} = \frac{Q_0}{m}$.
- If $Q_{op,1} < \frac{Q_0-q_0}{n}$, the optimal planting quantity is $Q_{op}^{*} = \frac{Q_0-q_0}{n}$.

Combining these 3 cases, we conclude our proof in plan 1.

(ii) In plan 2, considering the output rate in this case is uniformly distributed, we get the following equation according to the equation (A.4).

$$Q_{op}^2 = \frac{\left(v_g-g\right)\left[2q_0^3+6\left(q_0-\beta\right)Q_0^2-6\left(\gamma-\beta+q_0\right)Q_0q_0+3\left(\gamma-\beta\right)q_0^2\right]}{6\beta\left[gn^2-v_gm^2+2c\left(m-n\right)\right]} \quad \text{(A.7)}$$

It can be readily proved that the right side of the equation (A.7) is positive. Let $Q_{op} = Q_{op,2} > 0$ satisfy the equation (A.7), we can get

$$Q_{op,2} = \sqrt{\frac{\left(v_g-g\right)\left[2q_0^3+6\left(q_0-\beta\right)Q_0^2-6\left(\gamma-\beta+q_0\right)Q_0q_0+3\left(\gamma-\beta\right)q_0^2\right]}{6\beta\left[gn^2-v_gm^2+2c\left(m-n\right)\right]}}$$

Considering the assumption $\frac{Q_0}{m} \le Q_{op} \le \frac{Q_0 - q_0}{n}$ in plan 2, the optimal planting quantity can be derived as the following cases.

- If $\frac{Q_0}{m} \le Q_{op,2} \le \frac{Q_0 - q_0}{n}$, the optimal planting quantity $Q_{op}^* = Q_{op,2}$.
- If $Q_{op,2} > \frac{Q_0 - q_0}{n}$, the optimal planting quantity $Q_{op}^* = \frac{Q_0 - q_0}{n}$.
- If $Q_{op,2} < \frac{Q_0}{m}$, the optimal planting quantity is $Q_{op}^* = \frac{Q_0}{m}$.

Combining these 3 cases, we conclude our proof in plan 2.

(iii) In plan 3, taking the derivative of $SPFT_{og}^3\left(Q_{op}\right)$ with respect to Q_{op} and equating it to zero, we get the following equation:

$$\frac{dSPFT_{og}^3\left(Q_{op}\right)}{dQ_{op}} = -\frac{A_3 Q_{op}^3 - B_3 Q_{op}^2 + C_3}{12\beta\left(m-n\right)Q_{op}^2} = 0 \tag{A.8}$$

Let $Q_{op} = Q_{op,3}$ satisfy the equation (A.8), we can get

$$Q_{op,3} = E_3^{\frac{1}{3}} + \frac{B_3}{3A_3} + \frac{B_3^{\,2}}{9A_3^{\,2}E_3^{\frac{1}{3}}}$$

Taking the second derivative of $SPFT_{og}^3\left(Q_{op}\right)$ with respect to Q_{op}, we have

$$\frac{d^2SPFT_{og}^3\left(Q_{op}\right)}{d^2Q_{op}} = -\frac{\left(g-v_g\right)\left[m^3Q_{op}^3 - \left(Q_0-q_0\right)^2\left(3\gamma-3\beta-2Q_0+2q_0\right)\right]}{6\beta\left(m-n\right)Q_{op}^3} \tag{A.9}$$

Then equating it to zero, we can get the zero point of $\frac{d^2SPFT_{og}^3\left(Q_{op}\right)}{d^2Q_{op}}$, which is denoted by $Q_{op,0}$, $Q_{op,0} = Q_{op}$, as following

$$Q_{op,0} = \frac{\sqrt[3]{(Q_0 - q_0)^2 \left[3(\gamma - \beta) - 2(Q_0 - q_0)\right]}}{m}$$

Note the assumption $\frac{Q_0 - q_0}{m} \le Q_{op} \le \left\{\frac{Q_0 - q_0}{n}, \frac{Q_0}{m}\right\}$ in plan 3. We can get the ratio of $Q_{op,0}$ and the minimal value of the planting quantity $\frac{Q_0 - q_0}{m}$ is

$$\frac{Q_{op,0}}{\frac{Q_0 - q_0}{m}} = \frac{3(\gamma - \beta)}{Q_0 - q_0} - 2$$

Since the buyer's firm order $Q_0 - q_0$ is larger than or equal the minimal demand $\gamma - \beta$, we can get $Q_{op,0} \le \frac{Q_0 - q_0}{m}$. In addition, since the expression $m^3 Q_{op}^3 - (Q_0 - q_0)^2 (3\gamma - 3\beta - 2Q_0 + 2q_0)$ in equation (A.9) increases with Q_{op}, we have $m^3 Q_{op}^3 - (Q_0 - q_0)^2 (3\gamma - 3\beta - 2Q_0 + 2q_0) \ge 0$. Therefore, $\frac{d^2 SPFT_{og}^3(Q_{op})}{d^2 Q_{op}} \le 0$ and the objective function $SPFT_{og}^3(Q_{op})$ is concave.

Considering the assumption $\frac{Q_0 - q_0}{m} \le Q_{op} \le \left\{\frac{Q_0 - q_0}{n}, \frac{Q_0}{m}\right\}$ in plan 3, the optimal planting quantity can be derived as three cases.

- If $\frac{Q_0 - q_0}{m} \le Q_{op,3} \le \left\{\frac{Q_0 - q_0}{n}, \frac{Q_0}{m}\right\}$, the optimal planting quantity $Q_{op}^* = Q_{op,3}$.

- If $Q_{op,3} > \left\{\frac{Q_0 - q_0}{n}, \frac{Q_0}{m}\right\}$, the optimal planting quantity

$$Q_{op}^{*} = \min\left\{\frac{Q_0 - q_0}{n}, \frac{Q_0}{m}\right\}.$$

- If $Q_{op,3} < \frac{Q_0 - q_0}{m}$, the optimal planting quantity is $Q_{op}^{*} = \frac{Q_0 - q_0}{m}$.

Combining the above cases, we conclude our proof in plan 3.

Similarly, the optimal planting quantity in plan 4 can be proven.

A.7 SCPO model without considering random yield

This is a supply contract with put options for a fresh FSC with RAS, under deterministic yield and stochastic demand. At the beginning of the planting season t_0, the grower provides a supply tariff (w_o, w_{ep}). With the supply tariff, the buyer determines the order policy (Q_0, q_0) based on the market demand forecast. With the buyer's order, the grower determines the planting quantity Q_{op}. At the beginning of the selling season t_1, according to the updated information, the buyer can exercise options q_{ep} at the unit exercise price w_{ep} to adjust the initial order quantity downward if necessary. Then, the grower delivers the final order Q_0-q_{ep} to the buyer and any unsatisfied order can be satisfied via the spot market. The grower's surplus products can be stored in RAS, which can be salvaged at v_g for each unit later. At the end of the selling season, the buyer obtains an additional cash inflow from salvaging unsold products or incurs a shortage cost.

Based on the above description, the buyer's optimal order policy is the same as that in the proposed SCPO model. With the buyer's order, the grower determines the planting quantity Q_{op} to maximize the profit function as below

$$\max PFT'_{og}\left(Q_{op}\right) = \max\left\{\begin{aligned} &-cQ_{op} + \int_{\gamma-\beta}^{Q_0-q_0} \left\{-w_{ep}q_0 + v_g\left[Q_{op} - \left(Q_0 - q_0\right)\right]\right\} f\left(\xi\right) d\xi \\ &+ \int_{Q_0-q_0}^{Q_0} \left[-w_{ep}(Q_0 - \xi)\right] f\left(\xi\right) d\xi + \int_{Q_0-q_0}^{Q_{op}} v_g\left(Q_{op} - \xi\right) f\left(\xi\right) d\xi \\ &+ \int_{Q_{op}}^{Q_0} \left[-g\left(\xi - Q_{op}\right)\right] f\left(\xi\right) d\xi + \int_{Q_0}^{\gamma+\beta} \left[-g\left(Q_0 - Q_{op}\right)\right] f\left(\xi\right) d\xi \end{aligned}\right\}$$

subject to $Q_0 - q_0 \le Q_{op} \le Q_0$

Taking the second derivative of $PFT'_{og}\left(Q_{op}\right)$ with respect to Q_{op}, we get

$$\frac{d^2 PFT'_{og}\left(Q_{op}\right)}{d^2 Q_{op}} = \frac{\left(v_g - g\right)}{2\beta} < 0$$

Therefore, the objective function $PFT'_{og}\left(Q_{op}\right)$ is concave.

Taking the derivative with respect to Q_{op} and equating it to zero, we get

$$\frac{dPFT'_{og}\left(Q_{op}\right)}{dQ_{op}} = \left(v_g - g\right)Q_{op} + \left(\gamma + \beta\right)(g - v_g) - 2\beta(c - v_g) = 0 \qquad \text{(A.10)}$$

Let $Q_{op} = Q_{op'}$ satisfy the equation (A.10), we can get

$$Q_{op'} = \gamma + \beta - \frac{2\beta(c - v_g)}{(g - v_g)}$$

Considering the assumption $Q_0 - q_0 \le Q_{op} \le Q_0$, we can get the optimal planting quantity

$$Q_{op}^{*} = \begin{cases} Q_0 - q_0 & if \;\; Q_{op'} < Q_0 - q_0 \\ Q_{op'} & if \;\; Q_0 - q_0 \le Q_{op'} \le Q_0 \\ Q_0 & if \;\; Q_0 < Q_{op'} \end{cases}$$

At t_0, the grower's problem is to find the optimal supply tariff to maximize the following formula,

$$\max PFT_{og,t_0}^{'}\left(w_o, w_{ep}\right) = \max\left[wQ_0 + w_o q_0 + PFT_{og}^{'}\left(Q_{op}\right)\right] \qquad (A.11)$$

subject to $w_o > 0, \quad w_{ep} > 0$

Similarly, the optimal supply tariff would be solved numerically.

Appendix B

B.1 Proof of Proposition 1

When $\xi_A > kQ_p$, the grower's problem is

$$\max PFT_{t_1}^1\left(Q_r \left|k, \xi_A, x_B\right.\right) = \max\left\{r_A\left(kQ_p - Q_r\right) - p_A\left[\xi_A - \left(kQ_p - Q_r\right)\right] + \mathrm{E}\left[PFT_{t_2 B}\left(Q_r \left|x_B\right.\right)\right]\right\}$$

Taking the second derivative of $PFT_{t_1}^1\left(Q_r \left|k, x_A, x_B\right.\right)$ with respect to Q_r, we have

$$\frac{d^2 PFT_{t_1}^1\left(Q_r \left|k, x_A, x_B\right.\right)}{dQ_r^2} = -\left(r_B + p_B - v_B\right) f_{X_B}(Q_r)$$

Considering $r_B > v_B$, the objective function $PFT_{t_1}^1\left(Q_r \left|k, x_A, x_B\right.\right)$ is concave in Q_r.

Taking the derivative of $PFT_{t_1}^1\left(Q_r \left|k, x_A, x_B\right.\right)$ with respect to Q_r and equating it to zero, we get the following equation:

$$\frac{dPFT_{t_1}^1\left(Q_r \left|k, x_A, x_B\right.\right)}{dQ_r} = F_{D_B|x_B}\left(Q_r\right) - \frac{r_B + p_B - c_1 - (r_A + p_A)}{r_B + p_B - v_B} = 0 \qquad \text{(B.1)}$$

If there exists a non-negative value of $Q_r = s_1\left(x_B\right)$ which satisfies equation (B.1), considering the assumption $0 \le Q_r \le kQ_p$, the optimal rental capacity of CAS can be derived as the following 3 cases.

- If $0 \le s_1\left(x_B\right) \le kQ_p$, the optimal rental capacity of CAS $Q_r^* = s_1\left(x_B\right)$.
- If $s_1\left(x_B\right) > kQ_p$, the optimal rental capacity of CAS $Q_r^* = kQ_p$.
- If $s_1\left(x_B\right) < 0$, the optimal rental capacity of CAS $Q_r^* = 0$.

Combining the above cases, we conclude our proof for $\xi_A > kQ_p$.

Similarly, the optimal rental capacity of CAS for $\xi_A \le kQ_p$ can be proven.

B.2 The traditional model in a fresh FSC with CAS

This is a traditional single-period two-stage model in a fresh FSC with CAS under random yield and stochastic demand. The grower produces fresh fruits and then sells them to the in-seasonal market. At the planting point t_0, the grower determines the planting quantity Q_{np} to plant at unit planting cost c_0. At the beginning of the selling season t_1, the grower sells the produce. At the end of the selling season, the grower may salvage the unsold products or incur shortage cost.

Based on the above description, the grower's expected profit at t_0 is

$$SPFT_{A,t_0}\left(Q_{np}\right) = -c_0 Q_{np} + \int_n^m \left\{ \int_0^{kQ_{np}} \left[r_A \xi_A + v_A\left(kQ_{np} - \xi_A\right)\right] g_{DA}(\xi_A) d\xi_A \right\} \tau\left(k\right) dk$$
$$+ \int_n^m \left\{ \int_{kQ_{np}}^{\infty} \left[r_A kQ_{np} - p_A\left(\xi_A - kQ_{np}\right)\right] g_{DA}(\xi_A) d\xi_A \right\} \tau\left(k\right) dk$$

The first term is the planting cost. The second term is the revenue from sold and salvaged products when the demand in selling season A is smaller than the output quantity. And the third term is the revenues from sold products and the shortage cost when the demand in selling season A is larger than the output quantity.

At t_0, the grower's problem is to determine the optimal planting quantity Q_{np} to maximize the total expected profit over the planning period.

$$\max SPFT_{A,t_0}\left(Q_{np}\right)$$

$$\text{subject to } Q_{np} \geq 0$$

The optimal planting quantity Q_{np} for in-season is calculated numerically.

Acknowledgement

I would like to express my gratitude to all those who helped me during my PhD years. My deepest gratitude goes first and foremost to my supervisor Professor Hiroaki Matsukawa, for the constant support, guidance and supervision, who gives me inspiration both in study and life, especially in the epidemic period. He provided me with excellent chances and advice in field investigation and writing research papers, and with constructive feedback to help me better my work.

I acknowledge Keio University, Atsushi Tamura Memorial Fund and The Goldman Sachs Scholars Fund for the helpful scholarship, which gave me support in life, field investigation and so on.

I am worth mentioning my friends, who gave me enthusiastic support during my confusion and depression periods. I appreciate all the support I received from them. I would like to express my sincere thanks to my beloved parents, who always support and encourage me without any conditions, and under whose protection I have been able to enjoy life. Finally, I thank my lovely cat Orange Pi for his company.