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An Operations Optimisation Model for Fresh Food Produce Supply Chain Considering Time-Varying Freshness and Consumer Utility

Abstract. *This paper investigates the optimal decisions of freshness-keeping effort levels, retail pricing, order quantity, and coordination contract parameters in the fresh product supply chain, considering the time-varying produce food freshness and customer utilities. A game equilibrium based on the backward induction method is analyzed, and a coordination contract facilitated to achieve Pareto improvement of firms is investigated. The conclusions demonstrate that closed-form solutions uniquely exist for each firm, but the solutions are inferior to the integrated optimal decisions. A wholesale contract is analyzed based on a linear combination of the supplier's marginal cost and the retailer's marginal revenue that can motivate each firm's actions to align with the optimal decisions. The findings reveal that the two firms can flexibly share the integrated supply chain's optimal profit within the coordination contract and that each firm achieves Pareto improvement. In addition, the monotonicity of the optimal closed-form solutions is discussed for crucial parameters, which may help firms improve their profits. Finally, numerical analysis and managerial insights are given to enhance practicability.*

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JEL Classification: Q11, Q13.

1. Introduction

Fresh food produce, such as vegetables, fruits, meat or dairy products, are a fundamental necessity and an indispensable resource for human survival (Shi et al., 2023). However, as the Consumer Price Index grows globally, it is becoming a more expensive and survival burden for people to buy fresh products. According to the U.S. Department of Labour, the US Consumer Price Index rose 8.3% year-over-year in August 2022, while food prices rose 11.4% year-over-year. The European Union's statistics office showed that food prices rose by 11.1% in June 2022, with most countries posting historical highs. Chinese residents are also under tremendous pressure, with fresh fruit and fresh vegetable prices rising by 16.3% and 6.0%, respectively, in August 2022. Therefore, it is important for firms dealing with fresh food products to balance residents' purchasing ability and freshness preference.

One of the primary metrics reflecting the residents' purchasing ability is the fresh product's retail price (Babaee et al., 2022). High pricing reduces consumer utility, but lowering the retail price hurts firms' revenue (Zhou et al., 2023). In the area of marketing, the consumer utility of the effort to maintain freshness is related to the selling price, the increased level of freshness, and the valuation that the consumer derives from the fresh product (Yang and Tang 2019; Ji et al., 2017). In addition, People nowadays are focussing more and more on the freshness by the comprehensive judgment of colour, odour, appearance, and texture as indicators (Moon et al., 2020) and usually may not be willing to buy the product when the freshness is less than their expectations (Jharkharia and Shukla, 2013). Fresh food produce always has high and varying rates of deterioration when moving from fields to consumers, resulting in a decline in freshness over time and finally affecting market demand (Yang et al., 2020). To meet consumer-acceptable freshness, each fresh food produce supply chain firm needs to make costly freshness-keeping efforts to delay the product's deterioration rate or quality (Liu et al., 2021a). In light of the significance of retail pricing and cost control of freshness-keeping efforts, works contributed by (Cai et al., 2010; Liu et al., 2021b, a, 2022; Zhou et al., 2021) etc. have addressed the joint operations optimisation of pricing and freshness of the fresh food produce in different settings. In particular, we focus on the person who runs the freshness-keeping effort, the market demand form, and the coordination contract.

Following up on the contributions of the previous literature, this article investigates the operational optimisation of the fresh food produce supply chain considering the varying freshness and consumer utility. Unlike the literature, we amend the foundational market demand assumption through two points by considering practical conditions. The first one is that we correlate the freshness-keeping effort levels, product life cycle, and freshness and use an iterative function to express the time-varying freshness, which is in line with the work conducted by (Chen et al., 2018; Zhou et al., 2021). The second point is that the market potential demand is modified as a stochastic variable that follows the zero-one uniform distribution by considering a nonnegative customer utility constraint, which thanks to the contribution of (Yang and Tang, 2019; Ma et al., 2019). Furthermore, this paper extends the implementers of freshness-keeping efforts to multiple firms, which differs from the literature work that emphasized one firm. Such an extension is realistic and necessary.

On the one hand, fresh products are also placed in freshness-keeping efforts such as automatic water sprinkling or water misting systems during the sales season in the new retail environment, not only in the transportation or logistics stages, which are analysed by (Cai et al., 2010; Yu and Xiao, 2017; Liu et al., 2023). On the other hand, costly freshness-keeping efforts throughout the supply chain must be coordinated by a reasonable payment transfer, which has rarely been considered in the previous literature. Based on the practicality and the above assumptions, this paper addresses the following questions: (1) what are the closed-form solutions for optimal fresh-keeping effort levels, retail pricing, and order quantity, and (2) how do management insights can be gained by considering the time-varying freshness and consumer utility.

A game equilibrium based on the backward induction method is analysed, and a coordination contract that facilitates Pareto improvement for firms is explored to answer the above questions. Furthermore, the monotonicity of the optimal closed-form solutions and the optimal lot size strategy with multiple cycles are investigated to discuss management insights. The contributions of this paper are threefold. First, this paper investigates firms' optimal closed-form solutions, including freshness-keeping level, retail pricing, and order quantity under time-varying freshness and consumer utility. Second, a wholesale price contract based on a linear combination of the supplier's marginal cost and the retailer's marginal revenue is discussed to motivate each firm's actions to align with the optimal decisions. The two firms can flexibly share the integrated supply chain’s optimal profit and achieve Pareto improvement. Third, the monotonicity of the optimal closed-form solutions is discussed for price sensitivity, freshness sensitivity, natural attenuation, and lead time.

The remainder of the paper is organised as follows: Section 2 reviews the literature on optimising and coordinating the fresh food supply chain. In Section 3, the problem definition and assumptions are presented. In Section 4, equilibrium analysis and a Pareto improvement are discussed. Finally, some conclusions and future research are given in Section 5.

2. Literature review

Previous relevant studies on the fresh food produce supply chain have been reviewed. Fresh products are characterised as perishable goods, but they are essential to residents' lives, with a short life cycle and a high fluctuation for freshness (Yan et al. 2020). Thus, a prominent work is to investigate the operational optimisation of retail pricing and freshness of fresh products to maximise the firm's (or supply chain's) profitability while satisfying customers' consumption utility and freshness preferences (Cai et al., 2010; Jharkharia and Shukla, 2013). Many scholars have explored this work in different settings. A representation contribution by (Cai et al., 2010) considers the optimisation and coordination of the fresh food produce supply chain with freshness-keeping efforts. They assume that the distributor must make an appropriate effort to preserve the freshness of the product during the transportation process, and they believe that market demand follows a multiplicative functional form that depends on the freshness level and the selling price. Many scholars continuously adopted such an assumption (e.g., Ma et al., 2019; Dan et al., 2023, etc.). The assumptions represented by Liu et al. (2015), Yu and Xiao (2017), Yang and Tang (2019), etc., assume that the market demand is an additive functional form, i.e., market demand is presented as a linear function of retail price and freshness-keeping effort level. The market demand is a time integral in the form of an additive function of price and freshness, and the market demand potential is not a constant but a random variable that obeys a uniform distribution.

A close work to this paper contributed by (Zhou et al., 2021) investigates a maximise marginal revenue problem where a firm assigns special funds for the freshness-keeping effort with each post-production process. In particular, they use a freshness iteration function to measure the freshness of the product at a time and assume that the consumers' utility is affected by the produce's freshness and changes over time. Meanwhile, a consumer utility is introduced to characterise the customer's purchase decision, i.e., the consumer will choose to buy the product if his utility is no less than a certain threshold (Ma et al., 2019). Although Zhou et al. (2021) consider that all firms in the fresh supply chain implement freshness-keeping efforts, the paper focuses on the optimal freshness-keeping investment decision under particular financial constraints. It does not examine the optimal retail price or the issue of channel coordination. In this paper, we extend the consumer utility with the freshness-keeping effort related to the sale price and increased freshness level (Ji et al., 2017). Furthermore, we assume that the valuation that a consumer derives from the freshness and price is uniformly distributed from zero to one (Yan and Pei, 2009) and assume that the consumer makes the purchase decision when his utility is not less than zero (Yang and Tang, 2019). The demand function can be deduced by the valuation of the consumers' utilities. Finally, operational optimizations and coordination of the fresh food supply chain are explored based on these assumptions.

Implementing freshness-keeping efforts comes at a cost, necessitating analysing the coordination contract (Liu et al., 2023). Under the contract, the objectives of an independent firm will align with the optimal objective derived from a centralised decision (Cachon, 2003). Considering that the distributor has to make an appropriate effort to keep the product fresh, Cai et al. (2010) developed a price-discount sharing contract with a compensation contract to facilitate coordination between the producer and the distributor. Multiple coordination contracts have recently been introduced in different fresh food produce supply chains. It can be found that although the types of coordination contracts are diverse, they are similar in some sense, i.e., benefit sharing and cost pooling. This paper analyses the coordination of wholesale price contracts, the most straightforward cooperative mechanism implemented by firms (Haitao Cui et al., 2007). Therefore, the analysed wholesale price contract based on a linear combination of the supplier's marginal cost and the retailer's marginal revenue can motivate each firm's actions to align with the optimal decisions, in which both firms can flexibly share the optimal profits of the centralised supply chain.

In short, the highlights or contributions of this paper are fourfold. First, with multiple firms implementing freshness efforts, the market demand is modified to be a time integration in which the product function is an additive function, including price and freshness. Second, the firms' operational optimisation decisions are analysed under sequential games, and Pareto improvements are considered, considering time-varying freshness and consumer utility. Third, a wholesale price contract that is a linear combination of marginal cost and revenue is analysed to motivate each firm's actions to align with the optimal decisions. Finally, the monotonicity of the optimal closed-form solutions is analysed concerning price sensitivity, freshness sensitivity, natural attenuation, and lead time.

3. The Model

We consider a two-echelon fresh food produce supply chain comprising a single supplier and a single retailer. The product has a finite life cycle, T and the game between both is shown in Figure 1. First, at time zero, the retailer orders Q units of fresh food produce from the supplier before the selling season and then sells them to consumers during the selling season. Second, the supplier deliveries the ordered product to the retailer at a time t_S with a freshness-keeping effort level e_S, at which time the freshness of the product is θ_S. Third, the retailer inspects and receives the product. If θ_S is lower than $\widetilde{\theta_S}$, the retailer rejects the product, and the transaction closes; otherwise, the retailer agrees to accept the product and pays the wholesale price according to θ_S, namely, the wholesale price w is a reaction function of θ_S. Finally, the retailer sells these received products in the market, accompanied by optimal pricing p and freshness-keeping effort level e_R.

In works contributed by Yu & Xiao (2017), Moon et al. (2020), etc., the market demand is assumed to be an additive function form like that $\phi - \beta p + \lambda e$, in which the parameter ϕ is considered to be the constant market potential demand and e is the freshness-keeping effort level by a single firm. This paper extends this basic assumption about market demand through two points by considering practical conditions. The first point is that we correlate the freshness-keeping effort level, product life cycle, and freshness. Customers cannot know the firm's freshness-keeping effort level when they go shopping, and what is presented to their eyes is the product's freshness. In addition, freshness decreases gradually over time throughout the whole life cycle. Therefore, in line with the work conducted by (Zhou et al. 2021), the iterative function of freshness is defined as $\theta_j = \theta_{j-1} - \left(1 - k_j e_j\right)\eta\left(t_j/T\right)^2, j = [1,2,\dots,n]$, and then the freshness the retailer receives is shown as $\theta_S = 1 - \eta(1 - k_S e_S)(t_S/T)^2$ as well as the consumer purchases at time

t is represented as $\theta_{R_t} = 1 - \eta \frac{(1-k_S e_S)t_S^2 + (1-k_R e_R)(t-t_S)^2}{T^2}, t \in (t_S, T]$. Parameter k_i denotes the sensitivity coefficient of preservation to freshness-keeping effort with $k_i > 0, i \in \{S, R\}$, and parameter η indicates the extreme value of the natural attenuation of fresh food produce when the firms do not make freshness-keeping efforts.

The second point is that the market potential demand is modified by considering the customer utility. Whether a consumer buys a product at a time $t \in (t_S, T]$ depends on the utility value U_t, which is made up of price p and freshness θ_{R_t}, and he does not buy a product if $U(\theta_{R_t}, p) < 0$ comes. In this paper, thanks to the contribution of (Yang and Tang 2019; Ma et al. 2019), we assume a consumer's utility function obeys $U(\theta_{R_t}, p) = U_0 - \alpha p + \beta \theta_{R_t}$ form(Ji et al. 2017). Where U_0 denotes an initial utility for products and follows the uniform distribution [0,1], reflecting the heterogeneity of consumers' combined freshness and consumption ability(Yan and Pei 2009). Parameters α and β represent the coefficient of consumer sensitivity to retail price and freshness, respectively. In summary, the market demand used in this paper is deduced as Eq. (1),

$$D = \int_{t_S}^{T} \phi P\left(U(\theta_{R_t}, p) > 0\right) dt = \phi(T - t_S)\left(1 - \alpha p + \frac{1}{3}\beta\left(2\theta_S + \theta_{R_T}\right)\right) \quad (1)$$

In addition, the following assumptions are presented to make the model manageable and realistic.

- Let c be the supplier's transaction cost per product unit with $0 < c < p$. This transaction cost c includes all charges (such as production cost, transportation cost, storage cost, and etc.) except for the freshness-keeping effort costs.
- Let $C(e_i)$ be the firm i' fresh-keeping effort cost and equals to $h_i e_i^2/2$ referred to the work of (Yang and Tang 2019; Ma et al. 2019; Liu et al. 2021b), where h_i is the influence coefficient of the firm $i's$ freshness-keeping effort with $h_i > 0, i \in \{S, R\}$.
- Both the supplier and the retailer are risk neural and maximise their profits.
- All information is common knowledge, i.e., each firm knows all costs, parameters, and rules.
- There is no quantity loss, and the salvage or stock-out of fresh products is neglected. Furthermore, since the freshness is a signal of fresh food quality(Liu et al., 2019), we assume that as long as a consumer agrees to buy a product, he accepts the freshness (or quality) of that product, i.e., product quality has no effect on retail pricing(Yang et al., 2020).

The retailer would adjust his price throughout the selling season in a realistic market. Such a dynamic pricing strategy would allow the retailer to adapt his retail price to reflect food freshness and demand conditions (Liu et al., 2021a). For example, if food freshness or demand were less than expected, the retailer could accelerate price discounts. This dynamic pricing problem is complicated, even when freshness maintenance or supply chain coordination is not considered. Therefore, to obtain initial insights, this paper assumes that the retailer sets his retail price simultaneously with his ordering decision, and the price is fixed throughout the selling season.

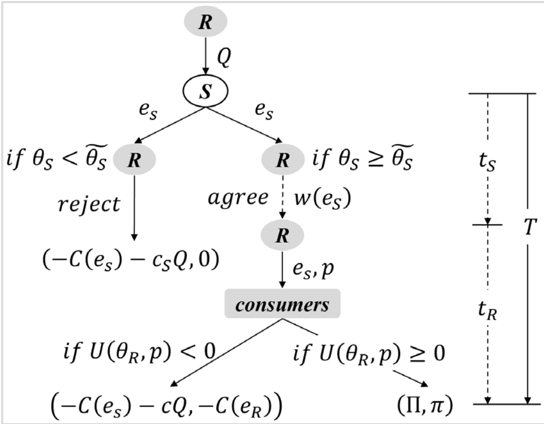

Figure 1. The game timeline of the two-echelon fresh food produce supply chain
Source: Authors' own creation.

4. Model Analysis

In this section, a sequential game is first analysed, and then the firm's Pareto improvement strategy is explored based on a wholesale price contract.

4.1 Equilibrium analysis

Given w and e_S, the retailer's profit function is shown as Eq. (2), in which p and e_R are the retailer's decision variables. Without loss of generality, the default assumption is that the retailer receives the whole products delivered by the supplier, i.e., the value of $\widetilde{\theta_S}$ is lower and it does not affect the game until this stage. The numerical analysis later shows that this value is located in the higher zone.

$$\pi_R(p, e_R) = (p - w)\phi(T - t_S)\left(1 - \alpha p + \frac{1}{3}\beta\left(2\theta_S + \theta_{R_T}\right)\right) - \frac{h_R e_R^2}{2} \tag{2}$$

At this stage, the retailer makes decisions about pricing and the freshness management effort simultaneously. Therefore, the retailer's reaction function can be obtained by jointly establishing the first-order optimality conditions for $\pi_R(p, e_R)$ with respect to p and e_R, as shown in Eq. (3).

$$\begin{cases} p = \frac{-w\beta^2\eta^2\phi k_R^2(T-t_S)^5 + 3T^2 h_R(T^2(3+3w\alpha+3\beta-\beta\eta)+2T\beta\eta t_S+\beta\eta(-4+3e_S k_S)t_S^2)}{18T^4\alpha h_R - \beta^2\eta^2\phi k_R^2(T-t_S)^5} \\ e_R = \frac{\beta\eta\phi k_R(T-t_S)^3(T^2(-3+3w\alpha+\beta(-3+\eta))-2T\beta\eta t_S+\beta\eta(4-3e_S k_S)t_S^2)}{-18T^4\alpha h_R + \beta^2\eta^2\phi k_R^2(T-t_S)^5} \end{cases} \tag{3}$$

Predicting that the retailer will make decisions based on Eq. (3), the profit function of the supplier can be expressed as follows.

$$\pi_S(e_S, w) = -\frac{1}{2}e_S^2 h_S - \frac{3T^2(c-w)\alpha\phi h_R(T-t_S)(T^2(-3+3w\alpha+\beta(-3+\eta))-2T\beta\eta t_S+\beta\eta(4-3e_S k_S)t_S^2)}{-18T^4\alpha h_R+\beta^2\eta^2\phi k_R^2(T-t_S)^5} \quad (4)$$

Second, the supplier's wholesale price is examined in the penultimate stage. Wholesale price is the supplier's decision variable that reflects not only the revenue per unit of the product claimed by the supplier from the retailer but also the transfer payments set by the retailer based on the supplier's freshness-keeping effort level. Solving the first-order condition for $\pi_S(e_S, w)$ with respect to w yields the supplier's wholesale price, as shown in Eq. (5).

$$w(e_S) = \frac{T^2(3+3c\alpha+3\beta-\beta\eta)+2T\beta\eta t_S+\beta\eta(-4+3e_S k_S)t_S^2}{6T^2\alpha} \quad (5)$$

It is easy to confirm that the wholesale price is an increasing function of e_s, which means that the fresher the product delivered to the retailer, the more revenue the supplier will obtain. Finally, with the wholesale price mentioned above, the optimal freshness-keeping effort level of the supplier can be calculated as shown in Eq. 6.

$$e_S = \frac{3\beta\eta\phi h_R k_S(T-t_S)t_S^2(T^2(-3+3c\alpha+\beta(-3+\eta))-2T\beta\eta t_S+4\beta\eta t_S^2)}{2\beta^2\eta^2\phi h_S k_R^2(T-t_S)^5-9h_R(4T^4\alpha h_S+\beta^2\eta^2\phi k_S^2 t_S^4(-T+t_S))} \quad (6)$$

The game equilibrium between the supplier and the retailer can be inferred by the forward one-by-one substitution, as shown in Proposition 1.

Proposition 1. *The game equilibrium of the supplier and retailer exists uniquely, in which the closed-form solutions are shown in Eq. (7).*

$$\begin{cases} e_S = 3\beta\eta\phi h_R k_S(T-t_S)t_S^2\frac{\Delta}{\Lambda} \\ w = c + \frac{h_S(18h_R\alpha T^4-\beta^2\eta^2\phi k_R^2(T-t_S)^5)\Delta}{3T^2\alpha\Lambda} \\ e_R = \beta\eta\phi h_S k_R(T-t_S)^3\frac{\Delta}{\Lambda} \\ p = \left(1+\frac{3T^2 h_R h_S\Delta}{(w^*-c)\Lambda}\right)w^* \\ Q = 3T^2\alpha\phi h_R h_S(T-t_S)\frac{\Delta}{\Lambda} \end{cases} \quad (7)$$

where $\Delta = T^2\big(-3+3c\alpha+\beta(-3+\eta)\big) - 2\beta\eta t_S(T-2t_S)$,
$\Lambda = 2\phi h_S\beta^2\eta^2 k_R^2(T-t_S)^5 - 9h_R(4\alpha h_S T^4 + \phi\beta^2\eta^2 k_S^2 t_S^4(-T+t_S))$.

Substituting the closed-form solutions into $\pi_R(p, e_R)$, $\pi_S(e_S, w)$, respectively, the retailer's and the supplier's profits can be calculated which are shown as follows.

$$\pi_R = \frac{3\phi h_R h_S\alpha(w-c)(T-t_S)T^2\Delta}{2\Lambda}, \pi_S = -\frac{\phi h_R h_S(T-t_S)\Delta^2}{2\Lambda} \quad (8)$$

Figure 2 shows the sensitivity analysis of key parameters (including α, β, η and t_S) to the supplier's and the retailer's profit. It can be seen that both firms' profits increase with increasing parameter β as well as decrease with increasing parameters α, η or t_S.

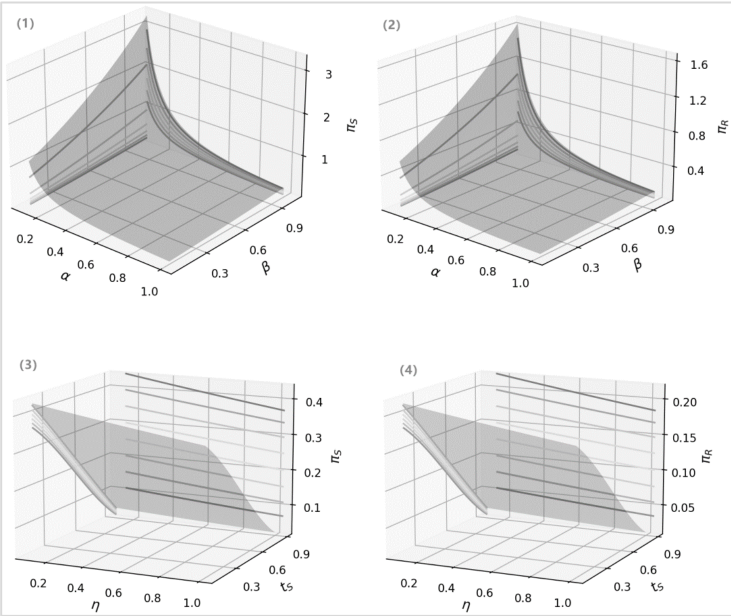

Figure 2. Sensitivity analysis of key parameters to profits

$(c = 0.2, \phi = 1.0, h_S = h_R = k_S = k_R = 0.5, T = 1.0, \ \eta = 0.5, t_S = 0.2\ (or\ \alpha = \beta = 0.5)\ for\ subfigure\ 1, 2\ (or\ 3,4))$

Source: Authors' own creation.

4.2 Pareto improvement

Supplier and retailer should work together to optimise the integrated supply chain and achieve a win-win outcome. In this decision-making mindset, the supplier and the retailer are considered as a unit. Therefore, the profit function of the centralized freshness produces supply chain is given as follows.

$$\Pi(e_S, e_R, p) = \phi(p - c)(T - t_S)\left(1 - \alpha p + \frac{1}{3}\beta\left(2\theta_S + \theta_{R_T}\right)\right) - \sum_{i=[S,R]} \frac{h_i e_i^2}{2} \quad (9)$$

In Eq. (9), the first item is the sales revenue of fresh products, and the last item presents the sum of the supplier's and retailer's fresh-keeping costs. Based on Eq. (9), the optimal solutions are deduced using backward induction in the following two steps. In the first step, we solve the reaction function of p and e_R for e_S as well as modify the function $\Pi(e_S, e_R, p)$ to $\Pi(e_R)$ by substituting p and e_S into formula (9). In the second step, optimal freshness-keeping levels e_S^* is calculated through the first-order optimal conditions of $\Pi(e_R)$, and then that $p^* = p(e_S^*)$ and $e_R^* = e_R(e_S^*)$ are obtained. *Proposition* 2 illustrates the optimal solutions for each firm's freshness-keeping level and retail pricing.

Proposition 2. *The global optimisation freshness-keeping levels and pricing decisions uniquely exist, which closed-form solutions are shown as follows:*

$$\begin{cases} e_S^* = \dfrac{6\beta\eta\phi h_R k_S (T-t_S) t_S^2 \Delta}{\Lambda + 9 h_R \beta^2 \eta^2 \phi k_S^2 t_S^4 (T-t_S)} \\ e_R^* = \dfrac{2\beta\eta\phi h_S k_R (T-t_S)^3 \Delta}{\Lambda + 9 h_R \beta^2 \eta^2 \phi k_S^2 t_S^4 (T-t_S)} \\ p^* = c + \dfrac{6 h_R T^2 h_S \Delta}{\Lambda + 9 h_R \beta^2 \eta^2 \phi k_S^2 t_S^4 (T-t_S)} \end{cases} \tag{10}$$

Proposition 2 illustrates that both the supplier and the retailer implement optimal freshness-keeping levels and maximize the integrated supply chain's profit by companying the optimal pricing set by the retailer. Substituting the closed-form solutions mentioned above into Eq. (1) and (9), then the integrated fresh food produce supply chain's optimal profit and production quantity can be calculated as follows,

$$\Pi^* = -\frac{\phi h_R h_S (T-t_S)\Delta^2}{(\Lambda + 9\phi h_R \beta^2 \eta^2 k_S^2 t_S^4 (T-t_S))}, \; Q^* = \frac{6\alpha\phi h_R h_S (T-t_S) T^2 \Delta}{(\Lambda + 9 h_R \beta^2 \eta^2 \phi k_S^2 t_S^4 (T-t_S))}. \tag{11}$$

Comparing Eq. (8) and Eq. (11), the Pareto improvement space achieved by the cooperation of the two firms can be calculated, as shown in Eq. (12). Figure 3 shows the sensitivity analysis of the key parameters to Π^* and Pareto improvement space. It can be seen that both firms can achieve a win-win outcome if they agree to cooperate. Meanwhile, the Pareto improvement space increases with increasing parameter β as well as decreases with increasing parameters α, η or t_S.

$$\Pi^* - (\pi_R + \pi_S) = \frac{1}{2}\phi h_R h_S (T - t_S)\Delta^2 \left(\frac{3\left(\Lambda - 3\phi h_R \beta^2 \eta^2 k_S^2 t_S^4 (T-t_S)\right)}{2\Lambda^2} - \frac{2}{\Lambda + 9 h_R \beta^2 \eta^2 \phi k_S^2 t_S^4 (T-t_S)} \right) \tag{12}$$

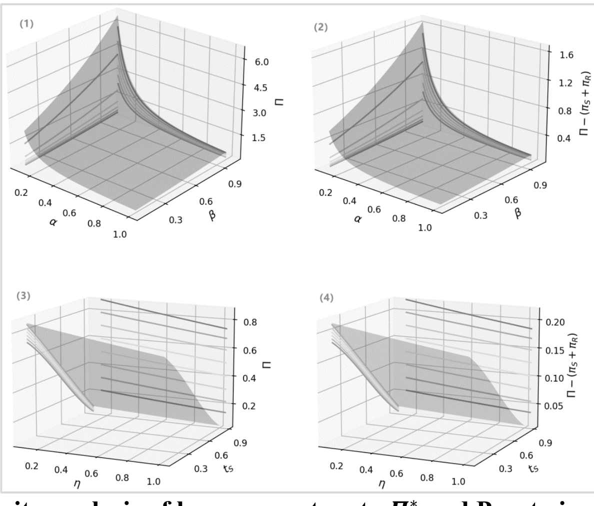

Figure 3. Sensitivity analysis of key parameters to Π^* and Pareto improvement space

Source: Authors' own creation.

Corollary 1 explores the monotonicity of the closed-form solution for optimal decisions and the integrated supply chain's profit with respect to the critical parameters α, β, and η.

Corollary 1. *The following conclusions hold.*

$(1). e_S^*, e_R^*, p^*, Q^*$ and Π^* $decrease$ $with$ $parameter$ α, and $increase$ $with$ $parameter$ β;

$(2). e_S^*$ and e_R^* $increase$ $with$ $parameter$ η, and p^*, Q^* and Π^* $decrease$ $with$ $parameter$ η;

$(3). e_S < e_S^*, e_R < e_R^*$;

$(4). Q < Q^*$;

$(5). \pi_S + \pi_R < \Pi^*$;

$(6). p > p^*$.

The first conclusion of Corollary 1 implies that the price sensitivity coefficient has a negative relationship with optimal decision-making, and the freshness sensitivity coefficient has a positive impact on them. This conclusion can help firms price or invest in freshness-keeping for high-price-sensitive products or consumers with high freshness sensitivity. The second conclusion shows that firms need to reinforce their freshness-keeping efforts when the product has high natural attenuation. However, this reinforcement investment reduces the profit of the firm. Shortening the lead time is an obvious option for the product with high natural attenuation. In addition, we also tried to analyse the impact of t_S on the optimal solutions, but were limited by the fact that each closed-form solution is a higher-order function of t_S and its expression is very complicated. We could only use numerical analysis to explore the sensitivity of the parameter t_S, see Figure 4.

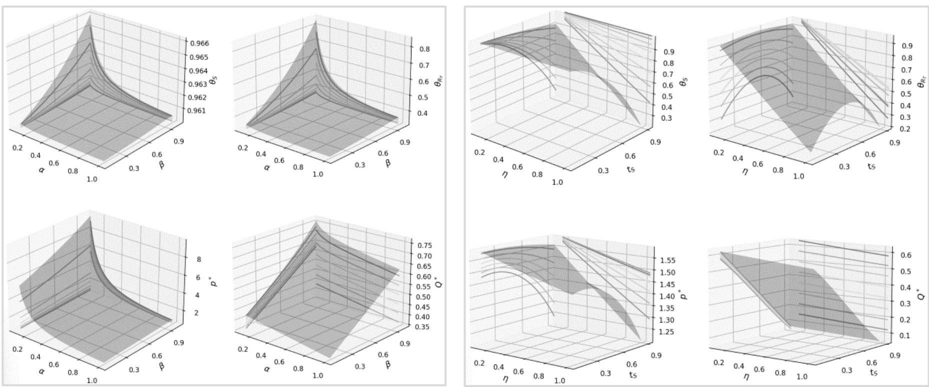

Figure 4. Sensitivity analysis of key parameters to optimal freshness, pricing, and quantity

Source: Authors' own creation.

Furthermore, Corollary 1 shows that the decisions in the game are inefficient. Both firms have lower freshness-keeping levels, and the total channel's available products are relatively small. These eventually lead to both firms' profits being smaller than the integrated optimal profit. The cause of ineffectiveness is that supply chain members are primarily concerned with optimising their profits, and that self-serving focus often results in poor performance (Fang, 2018). However, optimal performance is achievable if firms cooperate by contracting on a set of transfer payments such that each firm's objective becomes aligned with the integrated supply chain's objective (Babaee et al., 2022). Therefore, it is necessary to design a coordination mechanism to incentivize firms to invest in higher freshness-keeping levels, place the optimal quantity, and set the optimal pricing. Cachon (2003) states that a contract mechanism needs coordination, flexibility, and preferences. Proposition 3 shows that a simple wholesale price contract can achieve both firms' actions.

Proposition 3. *Consider the wholesale price with*

$$w = (1-\varphi)\left(p - \frac{C(e_R)}{Q}\right) + \varphi\left(c + \frac{C(e_S)}{Q}\right) \tag{13}$$

and $\varphi \in (0,1)$. *With this contract, the firms' profit functions are*

$$\begin{cases} \hat{\pi}_R = \varphi \Pi(e_S, e_R, p) \\ \hat{\pi}_S = (1-\varphi)\Pi(e_S, e_R, p) \end{cases} \tag{14}$$

Furthermore, $\{e_R^*, p^*\}$ *is the retailer's optimal freshness-keeping effort level and price and* e_S^* *is the supplier's optimal freshness-keeping effort level; i.e., the contract coordinates the supply chain.*

It can be seen that the coordination of wholesale price is a linear combination of the retailer's marginal revenue and the supplier's marginal cost. The value of wholesale price has an extensive range of options. In particular, the supplier obtains the whole optimal profit when the wholesale price is set to $(p^* - C(e_R^*)/Q^*)$. Conversely, the retailer gets the entire channel's optimal profit when the wholesale price is set to $(c + C(e_S^*)/Q^*)$. In practice, each firm may have an outside opportunity to profit, $\pi_i > 0$, that the firm requires to engage in the relationship, i.e., $\hat{\pi}_i \geq \pi_i$ is required to gain firm $i's$ participation. Figure 5 illustrates the lower and upper bounds of the coordination of wholesale prices and the pricing zones. w_L $(or\ w_U)$is calculated by deriving the supplier (or retailer) participation constraint, as shown in subfigures 1, 2, or 4, 5. Meanwhile, these subgraphs also reveal the monotonicity of parameters α, β, η or t_S on coordinated wholesale pricing. In particular, subfigure 3 (or 6) shows the coordinated wholesale pricing zones for the combination of parameters α and β (or parameters η and t_S).

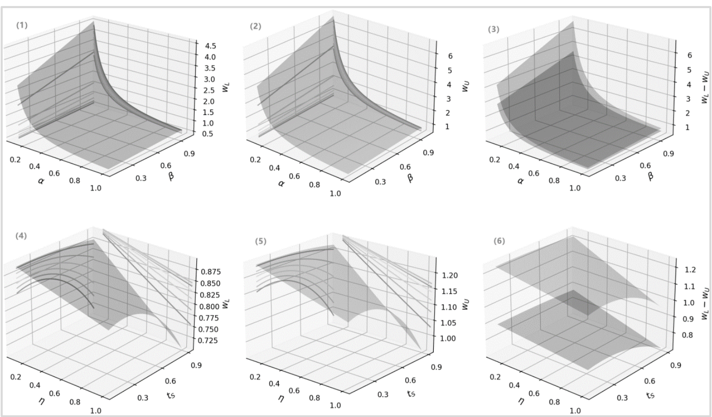

Figure 5. Sensitivity analysis of key parameters to coordinated wholesale pricing

Source: Authors' own creation.

5. Conclusions

This paper investigates the operational optimisation of the fresh food produce supply chain considering the time-varying freshness and consumer utility. An equilibrium under a sequential game is analysed, and then a coordinative contract that facilitates the Pareto improvement for firms is investigated. After combining the sensitivity analysis, the paper has the following main conclusions and management insights.

The first conclusion is that the optimal closed-form solutions uniquely exist. Whether it is a sequential game between firms or an integrated operational optimisation of firms, their decisions are uniquely existent, but the decisions under the sequential game are inferior to the integrated optimal choices. A consequence of this is the existence of a Pareto improvement space, which motivates decision-makers to design a reasonable cooperation mechanism with incentive participation constraints. One obvious management insight is that firms in the fresh supply chain should emphasise cooperation rather than sequential decision-making, i.e., all firms should work together to hedge against the adverse effects of double marginalisation.

The second conclusion is that this paper represents a simple coordination contract. The foundation of business cooperation is that the benefits generated by cooperation are more significant than those of external opportunities, and such benefits need to be guaranteed under a simple cooperation mechanism. This paper represents the wholesale price contract, the simplest cooperation mechanism, where the wholesale price is designed as a linear combination of the supplier's marginal cost and the retailer's marginal revenue. Under this contract, the integrated supply chain's optimal profit can be shared proportionally flexibly, i.e., both firms achieve Pareto improvement. With the backward induction method, fresh food produce retail pricing, the freshness-keeping effort levels, and its cost can be predicted. Therefore, the wholesale price can be easily calculated even with ex-ante contracting for firms.

The following management insights may have positive suggestions for operationalising the fresh food produce supply chain. On the one hand, firms in the fresh food produce supply chain should align their actions with the integrated optimal operations decision, and they will achieve a win-win outcome, which is not less than their outside opportunity to profit. On the other hand, firms can control or adjust some crucial parameters to improve their performance. The monotonicity analysis demonstrates that the consumer's price sensitivity, natural attenuation of the fresh food produce, and the supplier's delivery time have a negative relationship with Pareto improvement space, and the freshness sensitivity positively impacts that. The sensitivity analysis shown in the figure facilitates companies to adjust the direction of the parameters.

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