

Research Article

Quality Visibility Improvement with Effort Alignment and Cost-Sharing Policies in a Food Supply Chain

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Received 3 June 2020; Revised 13 August 2020; Accepted 18 August 2020; Published 1 September 2020

Academic Editor: Sri Sridharan

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Improving quality visibility along a food supply chain has been considered as a critical driver of quality risk mitigation, safety and security assurance, and performance sustainability. This paper explores the coordination mechanisms in a food supply chain, where the demand and costs are sensitive to the supply chain quality visibility that depends on an upstream supplier and a downstream retailer jointly, and the effort to improve quality visibility is increasingly expensive. After comparing the centralized and decentralized supply chain models to discover an opportunity for Pareto improvement, it is proved that a pure revenue-sharing contract fails to coordinate the supply chain, while the price discount contract with effort alignment policy or effort cost-sharing policy works. The two coordinating contracts' boundary conditions of excluding deviated actions are presented. It is shown that the contract with effort alignment policy is cheaper but more rigid, whereas the cost-sharing one allows us to arbitrarily allocate the supply chain's profits despite more information being collected. The models are applied to a fresh chicken supply chain in order to verify their effectiveness and robustness in reality. The impacts of several specific parameters on supply chain decisions and performances are analyzed, and the results reveal some meaningful managerial implications regarding supply chain quality visibility.

1. Introduction

A series of food recalls and destructions worldwide due to poor quality or safety and security have aroused intensive attention on supply chain vulnerability versus sustainability in food industry and academia. Recently, in July, China Customs detected the novel coronavirus that causes COVID-19 on the packages of frozen South American white shrimp produced by Ecuadorian enterprises and returned or destroyed the batches of risky food soon afterward. Unclear contamination source is attributed to the inadequate quality management and visibility in the producer's supply chain, which brings huge health threats and market losses. Global sourcing and outsourcing stretch supply chains, where quality information becomes opaque, leading to unexpected

supply chain disasters, even if one plant is contaminated [1–3]. Fortunately, it is possible to make supply chains more visible given the prevalence of information technologies such as radio frequency identification (RFID) technology, global positioning system (GPS), quick response (QR) code, and blockchain technology. Increasingly more enterprises consider supply chain visibility as a critical solution to assure product quality and safety, reduce food spoilage and waste [4], enhance operations efficiency, and mitigate supply chain risks [5]. Walmart developed a food traceability initiative with IBM's Food Trust Platform based on blockchain technology and required all his leafy-greens suppliers to use this system starting in September 2019. It allows one to trace a food product back to the farm within seconds, rather than days as before, which will help

Walmart confirm that products are certified in every exchange, thus mitigating the propagation risk of food-borne diseases along the supply chain and avoiding the losses that he and his partners may suffer in food recalls (source: <https://www.nasdaq.com/articles/walmart-embraces-ibms-blockchain-tech-2018-09-25>). The 2017 Supply Chain Worldwide Survey conducted by GEODIS reveals that “Improve end-to-end Supply Chain visibility” has become the third most important supply chain objective behind only two delivery indices [6].

Another stimulus for supply chain quality visibility comes from consumers. The anxiety for quality conditions to be inspected anytime and anywhere via the ubiquitous mobile network and the awareness of sustainable consumption responding to environmental preservation and humanitarian production induce people to request complete quality and health information in order to make sure it meets their exceptions [7]. Specifically, one reviews ingredients, production, and expiration dates on food labels and further wants to know where and how the product was planted or fed, whether the materials involved are organic or environmentally friendly, whether the relevant companies have quality certifications, and whether the product was transported in an uninterrupted cold chain. When it is easy to track these data within seconds, for example, by just scanning the QR code on the package using a smartphone, consumers are willing to buy such high-visibility products with traceable codes or PDO (EU’s Protected Designation of Origin) labels and even pay a considerable premium [8].

In addition, there are pressures from regulation and the public. Food visibility that proves good quality and safety has been a legal requirement or best practice in many regions, referring to US Quality System Regulation (see FDA 21 CFR Part 820 at <https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=820>), EU’s General Food Law (see Regulation (EC) No. 178/2002 at <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32002R0178>), China’s Food Safety Law (see the original version (in Chinese) at http://www.gov.cn/zhengce/2015-04/25/content_2853643.htm. For an unofficial translation version (in English) from the United States Department of Agriculture (USDA), see https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Amended%20Food%20Safety%20Law%20of%20China_Beijing_China%20-%20Peoples%20Republic%20of_5-18-2015.pdf), etc. Comments and complaints about food quality on social networks and the media, sometimes not sent by the target consumers, lead companies to invest more in quality visibility to promote public trust and confidence, not merely legal compliance. More and more food companies are integrating with Alibaba Health’s “Trust on the Code” platform under the guidance of the local government. This platform helps regulators and consumers to identify the authenticity of the provenance and quality of imported foods (see “Trust on the Code” website (<https://www.mashangfangxin.com>), which is initially designed for pharmaceutical traceability but now also available for food traceability).

Although supply chain quality visibility benefits companies in proactive quality risk control, operations efficiency, and consumer trust, the motivation to improve quality visibility is still scant. GEODIS reports that 77 percent of supply chain companies have no or very restricted visibility [6]. The few visibility examples at present mostly appear in apparel companies like H&M and Swiss Heidi who have disclosed their entire supply chain information from the cotton source to the distribution center through the label of each garment [5]. However, in the food domain, there are not so many examples as we might think even it should be more reasonable to disclose information tightly related to health.

Two reasons may explain the status quo. First, technical difficulties and expensive costs of building quality visibility are growing exponentially in food supply chains, often affordable for only large-scale companies. It requires access to more subjects, processes, and items following the “waterfall flow” from farm to table [5] and needs more hard work to collect, standardize, communicate, analyze, store, and visualize quality data, as compared with well-quantified information such as price, demand, and inventory. Besides, the quality of food, especially fresh or perishable food, is always in continuous degradation between two adjacent processing [9], so periodic or real-time monitoring of quality changes is necessary in food supply chains and of course quite expensive. In contrast, product quality is generally constant during each company who gathers quality information only once with a quality inspection in other supply chains. Second, companies’ quality visibility decisions are trapped in “double marginalization” and lack an overall coordination. Companies keep the inertia of saving the expense and protecting private information with the expectation of an advantage in competition or games, and they fail to balance information cost, information confidentiality, and information value. Their decisions tend to maximize one’s own interest, which makes supply chain revenue and quality visibility suboptimal.

Theoretical works surrounding supply chain quality visibility are mostly conceptual, technical, or empirical at present, and the model research ignores the expensive cost of building quality visibility and consumer sensitivity to quality visibility in food supply chains. Therefore, it is quite necessary to further explore the impacts of quality visibility in the food supply chain and use the approach of coordinating supply chain to reduce companies’ cost pressure in quality visibility investment, thus achieving multi-win outcomes for the whole supply chain including the consumer.

This paper seeks to answer the following research questions:

- (1) What are the optimal strategies in the centralized and decentralized food supply chains with demand and cost dependent on quality visibility? Whether the cooperative decision-making benefits the supply chain profit and quality visibility?
- (2) What kind of contracts can coordinate the supply chain? What are their conditions, strengths, and limitations?

- (3) How do the key parameters such as consumers' sensitivity to quality visibility affect the supply chain decisions and performances? What are the effective moves of the managers to improve their profits and quality visibility?

To address these research questions, this study constructs models to investigate the centralized and decentralized decision-making scenarios and the feasibility of a common revenue-sharing contract. Based on that, two modified contracts with effort alignment and cost-sharing policies that coordinate the supply chain with quality visibility effort are proposed. Next, the effectiveness and robustness of the contracts in reality are verified with a practical chicken supply chain case. Finally, suggestions for performance improvement and managerial insights are offered.

The contributions of this paper are mainly manifested in three aspects: (i) We build an analytical model assuming demand and cost are sensitive to quality visibility of the upstream and downstream companies and provide a useful way to capture the optimal price and quality visibility strategies in the food supply chain. (ii) The positive impacts of food quality visibility spectrum on supply chain players are quantitatively demonstrated, and the opportunity for Pareto improvement is revealed, theoretically enabling companies to improve their quality visibility. (iii) Two contract mechanisms based on the price discount contract are designed to address the coordination problem with dual quality visibility efforts. Both contracts align the decision motivations of the supply chain players and show a strong robustness. To the best of our knowledge, there are no other coordination research studies about quality visibility in the supply chain context.

The rest of the paper is arranged as follows. The second section reviews the relevant literature. Afterward, the third section describes the basic model and compares the centralized decision-making supply chain with the decentralized one. In the fourth section, several contracts are discussed to coordinate the supply chain, which is followed by a practical case that applies the model in the fifth section. Finally, this paper concludes with the research limitations and future directions.

2. Literature Review

2.1. Supply Chain Quality Visibility: Concept. Although scholars have focused on supply chain visibility for years, there seems no clear consensus on its definition and position [10]. It is early viewed as the extent of information sharing in the supply chain based on the transparency concept (Lamming et al. [11] and Bartlett et al. [12]) and later described as something similar to traceability based on RFID technology (Holmström et al. [13]), the capacity of the supply chain to have a view of the product life cycle (Musa et al. [14]), or the lower uncertainty of the company's social responsibility effort outcomes based on a CSR perspective (Kraft et al. [15]). In contrast, the definition proposed by Barratt and Oke [16] is more widely accepted: the extent to

which supply chain actors have access to or share key or useful information with mutual benefits to their operations.

It is still necessary to distinguish "supply chain visibility" from several intertwined concepts before we discuss its derivative "supply chain quality visibility." Based on the existing discussions, we contend that information sharing among the related companies is a prerequisite for supply chain visibility, and traceability means a visibility of information provenance and dissemination process. Supply chain visibility is considered to meet the information needs of stakeholders internal to the supply chain, and it is named mostly from the perspective of the information user, while supply chain transparency, from the information provider's perspective, comes up only when supply chain companies share or disclose visibility to the external stakeholders [5]. When the consumer is treated as an outsider of the traditional supply chain, supply chain transparency perceived by them can be understood as the minimum of supply chain visibility in terms of information transferred. However, the consumer has been an insider of the modern supply network with engaging more and more in product design, quality supervision, and brand advocacy, etc. Therefore, from the perspective of the whole supply chain, we can use "supply chain visibility" and "supply chain transparency" interchangeably to describe the extent to which the consumer gets the desired information from the upstream supply chain.

Supply chain quality visibility then can be concisely defined as the extent to which supply chain actors have access to high-quality information related to product (service) quality. High-quality information means the information rich in "information quality," i.e., accuracy, timeliness, completeness, trustworthy, usefulness, and ease of use. Information quality represents the level of supply chain visibility [17] and depends on the efforts to collect and integrate relevant information from the upstream and downstream supply chain [5]. Quality information of product or service involves not only inherent characteristics of the product or contents of the service, but also all the processes, operations, and factors that may have an impact. Traceability systems that aim to provide such quality visibility have gradually been opened up to consumers especially in food supply chains. Similar to supply chain transparency [18], supply chain visibility can be categorized into price, demand, quality, cost, inventory, and process visibility by information element. It is noticeable that some process information may contribute to both quality and process visibility, but process visibility prefers information about production, transaction, and management processes for operational or strategic considerations, which is different from quality visibility.

As for measuring supply chain quality visibility, Caridi et al. [19, 20] suggest a structured assessment model of supply chain visibility using a weighted sum of all the node companies' visibility, which is calculated by the geometric mean of three scales: information type, information quantity (which can be regarded as the completeness dimension of information quality), and information quality. Bartlett et al. [12] link information type to the following quality criteria: scrap levels, rework levels, process repeatability, supplier

quality, quality system audit, and continuous improvement. Tse and Tan [17] believe that product quality (risk) visibility comes from the number of product transitions and the disclosure level of suppliers' information that refers to suppliers' conformity, reliability, safety, and quality standards. For the sake of usefulness to the consumer, we summarize and refine the following types: (i) product provenance; (ii) supplier quality, about quality details in production process; (iii) transport conditions; (iv) retailer quality, about quality details in selling process; (v) quality audit and certification, about third-party or self-certification of food and companies; and (vi) product quality, about details on food labels as regulated. Then, their information quality ratings are processed to get the supply chain quality visibility referring to Caridi et al. [19].

2.2. Supply Chain Quality Visibility: Effect. Studies about the impacts of supply chain quality visibility (or supply chain visibility) on the decisions and performances of supply chain companies are relevant. Delen et al. [21] explore the extent of the logistics performance improvement in a supply chain influenced by visibility expressed as RFID data, and they assert that the supply chain visibility could make a company distinctive, just as quality was once the differentiator. Based on the theory of organizational information processing, Williams et al. [22] verify that internal integration can positively regulate the relationship between supply chain visibility (demand, supply, and market visibility) and supply chain responsiveness. Tse and Tan [23] provide quality criteria and a multi-outsourcing decision path for focal companies in supply chains using a marginal incremental analysis (MIA) method. Guo [24] discuss the impact of quality information disclosure on companies' profits in a bilateral monopoly and find that indirect disclosure through the retailer is the optimal form of quality information disclosure. Zhao et al. [25] extend Guo's research to the competitive market, and the results indicate that at equilibrium, the high-quality supply chain chooses not to disclose quality while the low-quality one chooses to disclose quality through the retailer. Wu et al. [26] investigate the quality information-sharing problems in a dual-sourcing supply chain and demonstrate that quality information visibility always benefits the cost-disadvantaged suppliers and the downstream retailer. From a "negative quality" perspective, Piramuthu et al. [27] compare the marginal differences of recall costs at different visibility levels based on the accuracy of contamination source identification and determine the best timing of recall policies in a multistage perishable food supply network.

For consumers, supply chain quality visibility is good up to now. Granados and Gupta [7] elucidate the benefits of quality- and price-related visibility (transparency) to consumers with different product features, industry competition, and regulatory intensity through examples. Ghosh and Galbreth [28] find that a greater proportion of partially informed consumers who capture disclosed quality information can decrease their search behaviour and help companies save disclosure cost and increase profit. Both external visibility initiatives (such as proactive

labelling strategies of voluntary certification and ingredient replacement [29]) and internal visibility initiatives (such as improving environmentally sustainable manufacturing [30]) can spur consumers to purchase products. El Benni et al.'s [8] survey study indicates that affected by the 2008 melamine incident, Chinese consumers are willing to pay an extra CNY 69~109 (equivalent to 30~40% of the retail price) for a 900 g can of infant milk formula with a PDO label, as well as a high premium for anticounterfeiting packaging and a QR traceable code.

We summarize the related literature in Table 1. These studies confirm that supply chain quality visibility can be beneficial to the entire supply chain, downstream companies, and consumers, while the impact on upstream companies is not quite clear [7, 24, 26]. It is because that quality visibility in these studies is provided mainly by suppliers who thus bear quality visibility cost and information leakage risk alone. The mismatch between these disadvantages and slashed revenues handed by downstream companies discourages upstream companies and makes outcomes uncertain. Furthermore, most of the model research studies focus on the information structure transformed by quality information disclosure strategies, also named transparency strategies [18]. They assume quality information is always ready to be shared or not, ignoring the previous processing cost, and few of them are specific to the food supply chain. In fact, every company contributes to the supply chain quality visibility, and everyone needs to pay for it in food supply chains. We thus assume companies' respective quality visibility levels that jointly make up the overall visibility determine their costs, and explore the impacts on supply chain players.

2.3. Supply Chain Coordination Contracts. Asymmetric information in a supply chain often traps the upstream and downstream companies into a double marginalization, which can be dramatically mitigated by supply chain coordination contracts maximizing supply chain profits [31, 32]. This field has accumulated extensive literature. This paper involves several relevant streams, including supply chain coordination with a revenue-sharing contract or a price discount contract, and coordination policies for the supply chain with effort decisions.

The revenue-sharing contract is one of the most common supply chain coordination mechanisms. Cachon and Lariviere [33] conduct a comprehensive analysis of it and illustrate its broad applicability with a single retailer in demand or price certainty/uncertainty settings, or with competing retailers in quantity competition. However, it stops functioning when the supply chain needs to deal with the retailer's costly effort. Xiao et al. [34] examine the impacts of product quality and service quality on demand and obtain the optimal decisions and Pareto conditions of the coordination mechanism using a revenue-sharing contract. Kong et al. [35] discuss the information leakage problem from a supplier in a supply chain where the retailers compete, and their results show that a revenue-sharing contract aligns the motivations of suppliers and retailers better and mitigates the supplier's disclosure risk. Bernstein and Federgruen [36] propose a wholesale price contract with

TABLE 1: Literature related to the effects of supply chain quality visibility.

| Literature | Visibility focused | Objectives | Methods | SC types |
|-----------------------------|---|---|-------------------------------------|------------------------|
| Delen et al. [21] | RFID data | Logistical performance | Case study | Retail |
| Williams et al. [22] | Demand, supply, and market visibility | Supply chain responsiveness | Empirical study | Various including food |
| Tse and Tan [23] | Quality risk visibility | Multi-outsourcing decision | Marginal incremental analysis (MIA) | Common |
| Guo [24] | Quality information disclosure | Company pricing and profit | Mathematical modelling | Common |
| Zhao et al. [25] | Quality information disclosure | Company pricing and profit | Mathematical modelling | Common |
| Wu et al. [26] | Quality information sharing or not | Company profit and market share | Mathematical modelling | Common |
| Piramuthu et al. [27] | Accuracy of contamination source identification | Liability cost, recall timing | Mathematical modelling | Food |
| Granados and Gupta [7] | Quality, price, and features transparency, etc. | Buyer's purchase decision, business, information, and IT strategies | Theoretical development | Common |
| Ghosh and Galbreth [28] | Quality information disclosure | Consumer search and purchase, company pricing, and profit | Mathematical modelling | Common |
| Riganelli and Marchini [29] | Labelling strategies | Consumer demand, company performance | Empirical study | Food |
| Buell and Kalkanci [30] | Internal and external operational transparency | Consumer purchase | Field experiment | Apparel and food |
| El Benni et al. [8] | Authenticity cues | Consumer choice | Survey | Food |
| This paper | Supply chain quality visibility | Company pricing, visibility decision, and SC performance | Mathematical modelling | Food |

a buyback rate, i.e., a price discount contract, that can coordinate the supply chain with uncertain demand, which is proven to be equivalent to a revenue-sharing contract in the price-setting model [33]. Cai et al. [37] demonstrate that in the dual-channel supply chain competition, the price discount contract reduces channel conflict and helps achieve coordination by distributing more profit to the retailer.

To coordinate the supply chain with costly effort, Bhaskaran and Krishnan [38], respectively, assess revenue, investment, and innovation sharing policies in an innovation supply chain. Product innovation revenue only derives from the quality improvement that depends on the innovation effort of both the focal company and the partner company. The results show that although the proposed three mechanisms fail to coordinate the supply chain, they improve supply chain profits compared with the decentralized supply chain when specific conditions are realized. Krishnan et al. [39] pointed out that a single-parameter contract could not correct the distortion caused by the pricing and effort decisions, and they propose effort cost-sharing, unilateral markdown allowances, and constrained buyback mechanisms to address it. Cachon and Lariviere [33] also offer a simple coordinating quantity discount contract based on revenue-sharing. Lambertini [40] extends the traditional two-part tariff contract for quality improvement using a variable linear tariff according to the R&D effort or product quality. For fresh products, Cai et al. [9] consider the impact of distributor's fresh-keeping effort on product freshness and thus on product quality and quantity and develop a price discount sharing contract with compensation contract to make the supply chain coordinated. Extending Cai et al.'s [9] study to the online situation, Gu et al. [41] characterize the online retailer's strategy of fresh-keeping effort under a consumer full-refund policy and present a buyback contract

and a revenue- and cost-sharing contract to achieve the cooperative optimization.

Table 2 provides an overview of the related literature, omitting the wholesale price contract that cannot coordinate the supply chain in each row of the last column. Most of the effort-related studies deal with the single effort of the downstream company, and the revenue-sharing contract or price discount contract works well by extending with an additional parameter. However, when there are multiple decision variables linked to the efforts of the upstream and downstream, more than one parameter needs to be introduced into simple supply chain contracts [38, 40]. Furthermore, there is no model research where the consumer demand is influenced by quality visibility, leaving a missing link between visibility effort and market revenue. In this paper, we consider the demand dependent on supply chain quality visibility and address the coordination problem with dual quality visibility efforts.

3. The Basic Model

3.1. Model Settings. We examine a two-tier food supply chain consisting of a supplier and a retailer who faces a consumer market. At the start of a selling season, the supplier sets a wholesale price w and its own quality visibility level v_s . Then the supplier invests in quality visibility as it claims and begins to produce after receiving the retailer's order. Once the delivery is ready, the retailer determines a retail price p and its own quality visibility level v_r . Subsequently, the retailer invests in quality visibility and sells the food. The consumer observes the price and the overall quality visibility provided by both companies and decides to buy or not, finally making revenue realize. The timeline of events is outlined in Figure 1.

TABLE 2: Literature related to supply chain coordination contracts.

| Literature | Demand (or other) depends on | Main decision variable | Contract types (coordination or not) |
|--|---|---|---|
| Cachon and Lariviere [33] | (Inverse demand) quantity | Price, order quantity | Revenue-sharing (Y), buyback (Y), quantity flexibility (Y), sales rebate (Y), etc. |
| Xiao et al. [34] | Price, product quality, service quality | Price, service quality | Revenue-sharing (Y) |
| Kong et al. [35] | (Inverse demand) quantity | Price, order quantity, leakage decision | Revenue-sharing (Y) |
| Bernstein and Federgruen [36] | Price | Price, order quantity | Price discount (Y) |
| Cai et al. [37] | Price | Price | Price discount (Y) |
| <i>Supply chain with costly effort</i> | | | |
| Cachon and Lariviere [33] | (Inverse demand) quantity, retailer effort | Retail effort, order quantity | Revenue-sharing (N), quantity discount with revenue-sharing (Y) |
| Bhaskaran and Krishnan [38] | (Quality depends on) innovation effort of focal and partner firms | Innovation level of focal firm and partner firm | Revenue-sharing (N), investment sharing (N), innovation sharing (N) |
| Krishnan et al. [39] | Promotional effort | Price, order quantity, retailer promotional effort | Buyback (N), buyback with three mechanisms (Y) |
| Lambertini [40] | Price, quality | Price, R&D effort of the upstream and downstream | Two-part tariff (N), control-linear two-part tariff (Y), state-linear two-part tariff (Y) |
| Cai et al. [9] | Price, freshness | Price, order quantity, distributor's fresh-keeping effort | Price discount sharing with compensation (Y) |
| Gu et al. [41] | Customer returns | Price, order quantity, fresh-keeping effort | Buyback (Y), revenue-sharing (N), revenue- and cost-sharing (Y) |
| This paper | Price, SC quality visibility | Price, quality visibility (effort) of the upstream and downstream | Revenue-sharing (N), price discount with effort alignment (Y), with cost-sharing (Y) |

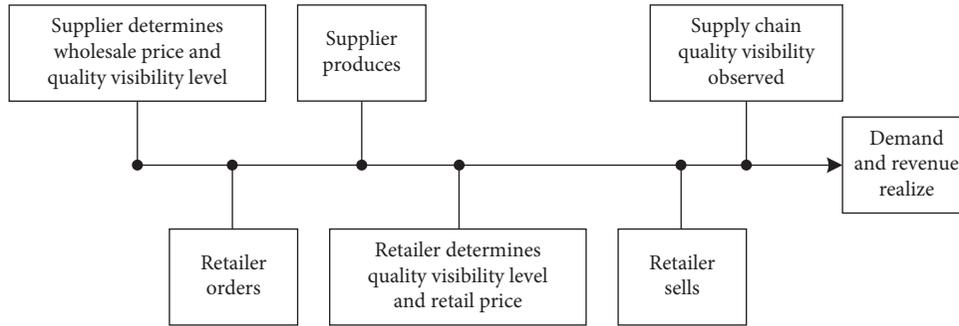


FIGURE 1: Timeline of events under consideration.

3.1.1. Demand Function with Quality Visibility.

Consumers are assumed sensitive to food price and supply chain quality visibility, $d(p, v_{sc}) = \theta - \lambda p + \alpha v_{sc}$, where θ is the largest potential demand, λ and α are sensitivity coefficients, $\lambda, \alpha > 0$, and $\theta > \lambda p > 0$. Refer to the supply chain visibility assessment method of [19], $v_{sc} = \sum \omega_i v_i$ ($i = s, r$), where the weight ω_i measures the importance of the quality visibility provided by company i to consumers. We suppose $\omega_s = \omega_r = (1/2)$, indicating equal importance. The demand sensitive to quality visibility is reasonable mostly in food supply chains where consumers are willing to pay a significant premium [8].

3.1.2. Cost Function with Quality Visibility.

The visibility effort cost of the upstream or downstream company is $c(v_i) = \beta_i v_i^2$, a most widely used effort cost function [33, 38, 40], where $\beta_i > 0$. The square reflects the diseconomy of

visibility systems due to the increased information capacity, efficacy requirement, and management complexity brought by a higher visibility level [42]. The diseconomy occurs in every company no matter upstream and downstream, characterizing the food supply chain. In contrast, except for the focal company, quality visibility cost of the partner company is generally fixed or linear in other types of supply chains. For example, a quality inspection instruction is usually enough for mobile phone components, and the mobile phone retailer rarely needs to invest in quality visibility.

The related notations and variables are defined as follows. $i = sc, s, r$ are the subscripts that represent the whole supply chain, the supplier, and the retailer, respectively. $j = C, D, R, E, B$ are the subscripts that represent scenarios of centralized decision-making, decentralized decision-making, a revenue-sharing contract, a price discount contract with effort alignment, and a price discount contract with cost-sharing, respectively.

w is the wholesale price of a food unit
 p is the retail price of a food unit
 v_i is the food quality visibility provided by the supply chain or company i
 d is the market demand
 θ is the largest potential demand
 λ is the price sensitivity coefficient of demand
 α is the quality visibility sensitivity coefficient of demand
 β_i is company i 's cost coefficient of the quality visibility effort

In this supply chain setting, the supplier's profit is as follows:

$$\pi_s = w(\theta - \lambda p + \alpha v_{sc}) - \beta_s v_s^2. \quad (1)$$

The retailer's profit is given by

$$\pi_r = (p - w)(\theta - \lambda p + \alpha v_{sc}) - \beta_r v_r^2, \quad (2)$$

and the profit of the whole supply chain is given by

$$\pi_{sc} = \pi_s + \pi_r = p(\theta - \lambda p + \alpha v_{sc}) - (\beta_s v_s^2 + \beta_r v_r^2). \quad (3)$$

The channel costs of the supplier and the retailer are omitted; however, by replacing w and p with $w - c_s$ and $p - c_r$, respectively, we have the intact costs, where c_s is the supplier's production cost per unit and c_r is the retailer's retail cost per unit.

3.2. Centralized Supply Chain. The supplier and the retailer are integrated when making decisions in the centralized supply chain. Although their own visibility systems are also expected to be integrated into one, the system integration costs and benefits are quite slight compared to the visibility input cost, namely, the effort cost. This is partly because the amounts and types of quality metadata collected from the upstream and the downstream are rarely the same, and thus, the two parts of the integrated visibility system are regarded as still working separately. The profit function of the centralized supply chain is obtained from equation (3):

$$\pi_{sc,C}(p_C, v_{s,C}, v_{r,C}) = p_C \left[\theta - \lambda p_C + \frac{\alpha(v_{s,C} + v_{r,C})}{2} \right] - \beta_s v_{s,C}^2 - \beta_r v_{r,C}^2. \quad (4)$$

The profit function (4) always has second continuous partial derivatives. In order to avoid not making sense, the function is assumed to have a maximum value in its definition domain $\theta/\lambda > p_C > 0$ and $v_{i,C} > 0$. Therefore, its Hesse

matrix $\mathbf{H} = \begin{bmatrix} -2\lambda & \alpha/2 & \alpha/2 \\ \alpha/2 & -2\beta_s & 0 \\ \alpha/2 & 0 & -2\beta_r \end{bmatrix}$ is set to be negative definite.

Let $\Delta_1 = 16\lambda\beta_s\beta_r - \alpha^2\beta_s - \alpha^2\beta_r$ and then we have $\Delta_1 = -2|H| > 0$ and $16\lambda\beta_i - \alpha^2 > 16\lambda\beta_j - \alpha^2 (\beta_i/\beta_j) > 0 (i, j \in \{s, r\} \text{ and } i \neq j)$.

Proposition 1. Given the assumption $8\lambda\beta_s\beta_r - \alpha^2\beta_s - \alpha^2\beta_r > 0$, in the centralized supply chain, the optimal retail price is $p_C^* = (8\beta_s\beta_r\theta/\Delta_1)$, and the quality visibility levels offered by the supply chain are $v_{s,C}^* = (2\alpha\beta_r\theta/\Delta_1)$, $v_{r,C}^* = (2\alpha\beta_s\theta/\Delta_1)$, and $v_{sc,C}^* = (\alpha\theta(\beta_s + \beta_r)/\Delta_1)$; the supply chain realizes the maximum profit $\pi_{sc,C}^* = (4\beta_s\beta_r\theta^2/\Delta_1)$.

Proof. Solve three first-order conditions of equation (4) jointly, as follows:

$$\begin{cases} \frac{\partial \pi_{sc,C}}{\partial p_C} = -2\lambda p_C + \theta + \frac{1}{2}\alpha(v_{s,C} + v_{r,C}) = 0, \\ \frac{\partial \pi_{sc,C}}{\partial v_{s,C}} = -2\beta_s v_{s,C} + \frac{1}{2}\alpha p_C = 0, \\ \frac{\partial \pi_{sc,C}}{\partial v_{r,C}} = -2\beta_r v_{r,C} + \frac{1}{2}\alpha p_C = 0. \end{cases} \quad (5)$$

The optimal retail price $p_C^* = (8\beta_s\beta_r\theta/\Delta_1)$, the optimal quality visibility level of the upstream $v_{s,C}^* = (2\alpha\beta_r\theta/\Delta_1)$, and the optimal quality visibility level of the downstream $v_{r,C}^* = (2\alpha\beta_s\theta/\Delta_1)$ can be easily derived. Then, substituting them into equation (4) and $v_{sc} = \sum \omega_i v_i$ simultaneously, we have the optimal supply chain profit $\pi_{sc,C}^* = (\alpha\theta(\beta_s + \beta_r)/\Delta_1)$ and maximal supply chain quality visibility $\pi_{sc,C}^* = (4\beta_s\beta_r\theta^2/\Delta_1)$ in the centralized supply chain.

The assumption $8\lambda\beta_s\beta_r - \alpha^2\beta_s - \alpha^2\beta_r > 0$ ensures that the optimal price exists in the domain by $\theta - \lambda p_C^* = ((8\lambda\beta_s\beta_r - \alpha^2\beta_s - \alpha^2\beta_r)\theta/\Delta_1) > 0$, and it is more strict than the negative definite assumption of Hesse matrix. \square

Corollary 1. $(\partial K/\partial \lambda) < 0$, $(\partial K/\partial \alpha) > 0$, $(\partial K/\partial \beta_s) < 0$, and $(\partial K/\partial \beta_r) < 0$, where $K \in \{p_C^*, v_{s,C}^*, v_{r,C}^*, v_{sc,C}^*, \pi_{sc,C}^*\}$.

From Corollary 1, we can find that the more sensitive consumers are to quality visibility, the greater the incentives that supply chain companies have to improve their quality visibility related to the foods in each stage so that the supply chain can charge a higher retail price and gain a bigger supply chain profit. Conversely, more price-sensitive consumers and a greater marginal cost of the visibility system prevent the previous process.

3.3. Decentralized Supply Chain. In a decentralized decision-making supply chain, the supplier firstly determines its own quality visibility level and supplies the retailer at a wholesale price according to the pure wholesale price contract. The retailer then decides its own quality visibility level after receiving the delivery and sells foods at a retail price.

The profit function of the retailer is given by

$$\pi_{r,D}(p_D, v_{r,D}) = (p_D - w_D) \left[\theta - \lambda p_D + \frac{\alpha(v_{s,D} + v_{r,D})}{2} \right] - \beta_r v_{r,D}^2, \quad (6)$$

and the profit function of the supplier is as follows:

$$\pi_{s,D}(w_D, v_{s,D}, p_D, v_{r,D}) = w_D \left[\theta - \lambda p_D + \frac{\alpha(v_{s,D} + v_{r,D})}{2} \right] - \beta_s v_{s,D}^2. \quad (7)$$

Let $\Delta_2 = 32\lambda\beta_s\beta_r - 2\alpha^2\beta_s - \alpha^2\beta_r$. Through the backward induction of a Stackelberg game, it is easy to find that the Hessian matrixes of equations (6) and (7) are negative definite with $16\lambda\beta_r - \alpha^2 > 0$ and $\Delta_2 = 2\Delta_1 + \alpha^2\beta_r > 0$, which reveals that there exists a maximum solution set of the decentralized supply chain.

Proposition 2. *In the decentralized supply chain, the optimal wholesale price of the supplier is $w_D^* = (\beta_s\theta(16\lambda\beta_r - \alpha^2)/\lambda\Delta_2)$, the optimal quality visibility is $v_{s,D}^* = (2\alpha\beta_s\theta/\Delta_2)$, and the optimal profit is $\pi_{s,D}^* = (4\beta_s\beta_r\theta^2/\Delta_2)$. The optimal retail price of the retailer is $p_D^* = (\beta_s\theta(24\lambda\beta_r - \alpha^2)/\lambda\Delta_2)$, the optimal quality visibility is $v_{r,D}^* = (2\alpha\beta_s\theta/\Delta_2)$, and the optimal profit is $\pi_{r,D}^* = (4\beta_s^2\beta_r\theta^2(16\lambda\beta_r - \alpha^2)/\Delta_2^2)$. Furthermore, the supply chain realizes the optimal quality visibility $v_{sc,D}^* = (\alpha\theta(\beta_s + \beta_r)/\Delta_2)$ and the optimal profit $\pi_{sc,D}^* = (4\beta_s\beta_r\theta^2(48\lambda\beta_s\beta_r - 3\alpha^2\beta_s - \alpha^2\beta_r)/\Delta_2^2)$.*

Proof. Given w_D and v_s , the retailer's optimal retail price and quality visibility are acquired by the first-order conditions of equation (6) as follows:

$$\begin{cases} p_D^*(w_D, v_{s,D}) = \frac{8\beta_r\theta + 8\lambda\beta_r w_D + 4\alpha\beta_r v_{s,D} - \alpha^2 w_D}{16\lambda\beta_r - \alpha^2}, \\ v_{r,D}^*(w_D, v_{s,D}) = \frac{2\alpha\theta + \alpha^2 v_{s,D} - 2\alpha\lambda w_D}{16\lambda\beta_r - \alpha^2}. \end{cases} \quad (8)$$

We substitute them into equation (7)

$$\pi_{s,D}(w_D, v_{s,D}) = \frac{4\beta_r\lambda w_D(\alpha v_{s,D} + 2\theta - 2\lambda w_D)}{16\lambda\beta_r - \alpha^2} - \beta_s v_{s,D}^2, \quad (9)$$

and similarly obtain the supplier's optimal wholesale price w_D^* and quality visibility $v_{s,D}^*$ by solving the first-order conditions of equation (9). Then, it is easy to get p_D^* and $v_{r,D}^*$ by a substitution into equation (8) and thus the optimal performance variables by a few further substitutions. \square

Corollary 2

- (i) $\pi_{sc,C}^* - \pi_{sc,D}^* = (4\beta_s^3\beta_r\theta^2(16\lambda\beta_r - \alpha^2)^2/\Delta_1\Delta_2^2) > 0$
- (ii) $\pi_{s,D}^* - \pi_{r,D}^* = (4\beta_s\beta_r\theta^2\Delta_1/\Delta_2^2) > 0$
- (iii) $v_{sc,C}^* - v_{sc,D}^* = (\alpha\beta_s\theta(16\lambda\beta_r - \alpha^2)(\beta_s + \beta_r)/\Delta_1\Delta_2) > 0$
- (iv) $p_C^* - p_D^* = -((\beta_s\theta(16\lambda\beta_r - \alpha^2)(8\lambda\beta_s\beta_r - \alpha^2\beta_s - \alpha^2\beta_r))/\lambda\Delta_1\Delta_2) < 0$

Under the optimal equilibriums, by comparing the overall supply chain profits in the two decision-making

contexts, Corollary 2 (i) indicates that the overall profit of the decentralized supply chain is strictly less than those of the centralized supply chain. Since the supply chain's revenue completely comes from the retailer, to coordinate the supply chain, the optimal solution $\{p_C^*, v_{r,C}^*\}$ of integrated decisions should be optimal for the retailer, and it must satisfy

$$\begin{cases} \frac{\partial \pi_{r,D}(p_C^*, v_{r,C}^*)}{\partial p_D} = 0, \\ \frac{\partial \pi_{r,D}(p_C^*, v_{r,C}^*)}{\partial v_{r,D}} = 0. \end{cases} \quad (10)$$

Then, we have $w_D = 0$ and $v_{s,D} = v_{s,C}^*$, which mean that the supplier receives nothing from charging a production cost, but bears its own quality visibility cost. Therefore, the simple wholesale price contract cannot coordinate the supply chain, which is consistent with many previous researches. From Corollary 2 (ii), the supplier's profit is larger than the retailer's, which verifies the supplier's great first-move advantage in the Stackelberg game.

In addition, Corollary 2 (iii) and (iv) show that the overall quality visibility level in the decentralized supply chain is lower than that in the centralized one, but the former retail price is higher than the latter. It implies that the centralized supply chain realizes not only greater profit and higher food quality visibility, but also greater consumer surplus, which leads to more social welfare, thus realizing a win-win between the supply chain and consumers.

Corollary 3. $(\partial K/\partial\lambda) < 0$, $(\partial K/\partial\alpha) > 0$, $(\partial K/\partial\beta_s) < 0$, and $(\partial K/\partial\beta_r) < 0$, where $K \in \{w_D^*, p_D^*, v_{i,D}^*, \pi_{i,D}^*\}$ ($i = s, r, sc$).

The inspirations from Corollary 3 are similar to those from Corollary 1, i.e., consumers' sensitivity to quality visibility positively influences the prices and performances of the decentralized supply chain, as opposed to the price sensitivity and visibility cost coefficients. Nevertheless, it seems that the extent of the influences they have is less significant than that in the centralized supply chain due to the double marginalization, which will be recognized more intuitively in the subsequent practical case. This finding indicates that a centralized or coordinated food supply chain is more efficient than a decentralized one in performance improvement. Therefore, it is necessary to explore a coordination contract if there is no chance to integrate this food supply chain to a centralized one.

4. Supply Chain Coordination

4.1. Revenue-Sharing Contract. The revenue-sharing contract is one of the most used coordination contracts. Suppose that the supplier and the retailer agree on the following ex-ante revenue-sharing contract: the supplier charges a lower wholesale price w_R and receives $1 - \varphi$ ($0 < \varphi < 1$) percent of

the retailer's revenue. Assuming $\varphi = 1$, the contract becomes a pure wholesale price contract; and if $w_R = 0$, it is equivalent to a price discount contract with $w = (1 - \varphi)p$. Therefore, for a crisp wholesale price contract and a price discount contract, there is always an equivalent revenue-sharing contract.

The retailer's profit function is given by

$$\pi_{r,R}(p_R, v_{r,R}) = (\varphi p_R - w_R) \left[\theta - \lambda p_R + \frac{\alpha(v_{s,R} + v_{r,R})}{2} \right] - \beta_r v_{r,R}^2. \quad (11)$$

Similarly, by solving the first-order conditions

$$\begin{cases} \frac{\partial \pi_{r,R}(p_C^*, v_{r,C}^*)}{\partial p_R} = 0, \\ \frac{\partial \pi_{r,R}(p_C^*, v_{r,C}^*)}{\partial v_{r,R}} = 0, \end{cases} \quad (12)$$

we have $w_R = (\varphi - 1)p_C^* < 0$ and $v_{s,R} = v_{s,C}^*$. This means that if the supply chain is coordinated, the supplier needs to subsidize the retailer $(1 - \varphi)p_C^*$ for each unit of food; however, the revenue that the supplier receives from the retailer is equal to the total subsidy. Just like in the wholesale price contract, the supplier in the revenue-sharing contract does not realize any revenue but experiences the losses due to his own quality visibility cost. The revenue-sharing contract, as Cachon and Lariviere [33] assert, cannot coordinate the supply chain with costly effort decisions.

4.2. Effort Alignment Policy. The contracts with a single parameter could correct the distortion in the pricing decisions of the upstream and downstream supply chain, but they do not address the dual-effort and pricing decisions. Two or more parameters need to be included to align the relevant decision variables, making the profit function of the last-move decision-maker an affine transformation of the profit function of the whole supply chain. In this paper, the profit function of the retailer who plays as the last-mover depends on the effort decisions, that is, the quality visibility decisions of both the supplier and the retailer. Given that effort can be observed, it is feasible to align the supplier's effort with the retailer's, similar to the wholesale price aligned with the retail price in a pure price discount contract.

Theorem 1. *The following price discount contract with effort alignment (E) can coordinate the supply chain: the supplier charges a wholesale price $w_E = (\beta_r / (\beta_s + \beta_r))p_E$ and offers quality visibility $v_{s,E} = (\beta_r / \beta_s)v_{r,E}$. Then, the retailer's profit function is $\pi_{r,E} = \varphi \pi_{s,C}$ and the supplier's profit function is $\pi_{s,E} = (1 - \varphi)\pi_{s,C}$. $\{w_E^* = (1 - \varphi)p_C^*, v_{s,C}^*; p_C^*, v_{r,C}^*\}$ is the optimal solution set of the supply chain, where $\varphi = (\beta_s / (\beta_s + \beta_r))$.*

Proof. Substitute $w_E = (\beta_r / (\beta_s + \beta_r))p_E$ and $v_{s,E} = (\beta_r / \beta_s)v_{r,E}$ into the retailer's profit function (2):

$$\begin{aligned} \pi_{r,E}(p_E, v_{r,E}) &= [p_E - (1 - \varphi)p_E] \left[\theta - \lambda p_E + \frac{\alpha(v_{s,E} + v_{r,E})}{2} \right] \\ &\quad - \beta_r v_{r,E}^2 \cdot \frac{\varphi(\beta_s + \beta_r)}{\beta_s} \\ &= \varphi p_E \left[\theta - \lambda p_E + \frac{\alpha(v_{s,E} + v_{r,E})}{2} \right] \\ &\quad - \varphi(\beta_r v_{r,E}^2 + \beta_s v_{s,E}^2), \end{aligned} \quad (13)$$

i.e., $\pi_{r,E}(p_E, v_{r,E}) = \varphi \pi_{s,C}(p_E, v_{s,E}, v_{r,E})$, and then $p_E^* = p_C^*$, $v_{s,E}^* = v_{s,C}^*$, $v_{r,E}^* = v_{r,C}^*$, and $w_E^* = (1 - \varphi)p_C^*$. The supplier's profit function is $\pi_{s,E} = \pi_{s,C} - \pi_{r,E} = (1 - \varphi)\pi_{s,C}$. \square

Theorem 1 shows that the price discount contract allocates the supply chain profit to the supplier and the retailer at proportions of $1 - \varphi$ and φ , respectively, and coordinates the supply chain. The proportion φ is a fixed value dependent on the quality visibility cost coefficients of both sides. Since the quality visibility cost function is nonlinear, φ has a unique value in order to ensure a linearly affine transform of the profit functions in a three-parameter contract (w, v_s, φ) . According to the contract, the supplier loses his decision autonomy on quality visibility, which is anchored to that of the retailer via a fixed rate (β_r / β_s) . The bigger the rate is, the greater the gap between the supplier and retailer regarding price, quality visibility, and profit. Although the contract does not allow them to freely negotiate on the profit allocation rate, it is cheaper and less tedious under specified conditions due to a reduction of one contract parameter in the determination.

Proposition 3. *The incentive compatibility conditions of the contract (E) are $16\lambda\beta_r^2 - 16\lambda\beta_s\beta_r + \alpha^2\beta_s \geq 0$ for the supplier and $(3\beta_s - \beta_r)\Delta_2^2 + (\beta_s + \beta_r)\alpha^4\beta_r^2 \geq 0$ for the retailer when there is an alternative opportunity profit by a pure wholesale price contract.*

Proof. In order to avoid any deviated actions, it must satisfy $\pi_{s,E}^* = (1 - \varphi)\pi_{s,C}^* \geq \pi_{s,D}^*$ for the supplier and $\pi_{r,E}^* = \varphi\pi_{s,C}^* \geq \pi_{r,D}^*$ for the retailer. Simplifying them, the conditions are given by

$$\varphi \in [\varphi_{\min}, \varphi_{\max}], \quad (14)$$

where $\varphi_{\max} = (\beta_s(16\lambda\beta_r - \alpha^2)/\Delta_2)$ and $\varphi_{\min} = (\beta_s(16\lambda\beta_r - \alpha^2)\Delta_1/\Delta_2^2)$.

We substitute $\varphi = (\beta_s / (\beta_s + \beta_r))$ into equation (14) and simplify it to $16\lambda\beta_r^2 - 16\lambda\beta_s\beta_r + \alpha^2\beta_s \geq 0$ for the supplier and $(3\beta_s - \beta_r)\Delta_2^2 + (\beta_s + \beta_r)\alpha^4\beta_r^2 \geq 0$ for the retailer. \square

The two inequations in Proposition 3 guarantee that the effort alignment policy is Pareto superior to the decentralized decision-making, and thus, it can strictly coordinate the supply chain coordination.

4.3. Effort Cost-Sharing Policy. The price discount contract with an effort alignment policy may not always match the negotiation power and profit appeal of the two supply chain players because it is unable to arbitrarily allocate supply chain profit, and whether its rigid incentive compatibility conditions could be realized with extreme parameters is doubtful. In order to relax these restrictions and thus enhance companies' motivations for quality visibility, effort cost-sharing is introduced into the price discount contract, where the supplier and retailer proportionately share the total costs of quality visibility.

Theorem 2. *A price discount contract with cost-sharing (B) can coordinate the supply chain: the retailer pays the supplier a wholesale price $w_B = (1 - \varphi)p_B$ and shares the total quality visibility cost of the supply chain at a proportion φ (the supplier shares $1 - \varphi$ and $0 < \varphi < 1$). Then, the retailer's profit function is $\pi_{r,B} = \varphi\pi_{sc,C}$, and the supplier's profit function is $\pi_{s,B} = (1 - \varphi)\pi_{sc,C}$. Furthermore, $\{w_B^* = (1 - \varphi)p_C^*, v_{s,C}^*, p_C^*, v_{r,C}^*\}$ is the optimal decision set of the supply chain.*

Proof. With cost-sharing, the retailer's profit function is

$$\pi_{r,B}(p_B, v_{r,B}) = (p_B - w_B)(\theta - \lambda p_B + \alpha v_{sc,B}) - \varphi(\beta_r v_{r,B}^2 + \beta_s v_{s,B}^2). \quad (15)$$

We substitute $w_B = (1 - \varphi)p_B$ into it to get $\pi_{r,B}(p_B, v_{r,B}) = \varphi\pi_{sc,C}(p_B, v_{s,B}, v_{r,B})$ and $\pi_{s,B} = (1 - \varphi)\pi_{sc,C}$. \square

Compared with contract (E), the feasible range of φ under contract (B) covers the whole interval (0, 1), and it is determined by the bargaining power of the supplier and the retailer. The stronger the retailer's power is, the greater the φ . When φ equals 0 or 1, the supply chain turns into a centralized one. Similarly, the incentive compatibility conditions (14) must be satisfied when a wholesale price contract is an option. In addition, the information of both contracts (B) and (E) need to include the retail price and the retailer's quality visibility level, while contract (B) needs to include the supplier's quality visibility level as well. The difference in the required information sets dominates the applicability of the two contracts, and the higher information cost of contract (B) contributes to the arbitrarily profit allocation to some extent.

5. Practical Case

5.1. Data Collection. We collect data from a practical fresh chicken supply chain, where a fresh retailer orders to its partner farm base. Fresh chicken is not the dominant meat in the local market, and its demand is elastic. The retailer submits the order plan to the farm base regularly. After receiving the plan, the farm base slaughters all the planned chickens and cools them to 0 to 4 degree centigrade in packages for chilled freshness. The fresh retailer is in charge of the delivery using its own whole-process cold chain system from the farm base to all its fresh supermarkets.

Consumers can scan the QR traceable code on the package to obtain the quality visibility from the chicken feeding to the shelf reported by the farm base and the fresh supermarket, and the completeness and accuracy of the available quality information depend on the visibility systems of the two companies. Figure 2 shows the quality visibility displayed on a type of packaging for fresh chicken.

First, we operationalize the supply chain quality visibility assessment model suggested by Caridi et al. [19]. We ignore the mandatory information such as ingredients, product date, shelf life, and quality certification as shown in Figure 2 and focus on the changing quality information linked to QR code and sale scene instead, i.e., the four information types listed at the end of Section 2.1 except the fifth one. Information quality is rated and quality visibility is calculated in (0, 5). The 5 of quality visibility represents that consumers could get all the quality-related knowledge if they want, and this knowledge has an almost perfect quality. The 0 indicates consumers hardly get any additional information except what is on the package.

Second, the value of each parameter is derived based on the sales statistics of the fresh retailer during a quarter in 2019. When the price remains the same for a few days and there is a change in the information system, we obtain the sensitivity coefficient of the demand to quality visibility and the potential market demand using linear fitting; similarly, the sensitivity coefficient of demand to price is obtained when the information system is constant and the price fluctuates. Two sensitivity coefficients of cost to quality visibility are derived by quadratic fitting. Historical records of several other quarters are used as a reference for correction.

For simplicity, we use the integers close to these parameters for case analysis, and the sensitivity analysis in Section 5.3 proves that a slight parameter deviation does not affect the validity of the results. Finally, we have the potential market demand $\theta = 5000$ in the quarter, the sensitivity coefficient of demand to price $\lambda = 100$, the sensitivity coefficient of demand to quality visibility $\alpha = 700$, the supplier's quality visibility cost coefficient $\beta_s = 1900$, and the retailer's quality visibility cost coefficient $\beta_r = 2500$.

5.2. Contract Discussion. The optimal decisions and performances of the supply chain in different scenarios are presented in Table 3. In this case, it is obvious that the price discount contract with effort alignment (E) or cost-sharing (B) coordinates the supply chain to an integrated one. In contrast, the total quality visibility and profit of the supply chain in the decentralized supply chain (D) are far lower than those in the other scenarios because of severe double marginalization. It is presumed a higher revenue per unit with an increased retail price and a lower visibility cost with a decreased visibility effort in (D); however, they inhibit consumers' demand, which dominates both companies' profit functions. Therefore, there are strong practical interests for both the farm base and fresh retailer, driving them



FIGURE 2: Quality visibility about the fresh chicken on shelf.

TABLE 3: Optimal solution sets in different scenarios.

| j | v_s^* | v_r^* | v_{sc}^* | w^* | p^* | π_s^* | π_r^* | φ | π_{sc}^* |
|-----|---------|---------|------------|-------------|-------|---------------------|---------------------|-----------|--------------|
| C | 3.21 | 2.44 | 2.83 | — | 34.90 | — | — | — | 87,252.02 |
| D | 1.44 | 1.10 | 1.27 | 27.53 | 43.21 | 39,214.07 | 21,589.91 | 0.36 | 60,803.98 |
| E | 3.21 | 2.44 | 2.83 | 19.83 | 34.90 | 49,575.01 | 37,677.01 | 0.43 | 87,252.02 |
| B | 3.21 | 2.44 | 2.83 | 26.26~15.69 | 34.90 | 65,662.11~39,214.07 | 21,589.91~48,037.95 | 0.25~0.55 | 87,252.02 |

to seek supply chain integration or coordinated decision-making.

The outcomes under contract (E) are as good as a centralized supply chain, but the contract distributes supply chain profit at a fixed proportion because it requires a correlation of the visibility efforts between the supplier and the retailer, similar to the pricing. It applies to two companies of similar size with stable partnership, since it does not require integrating the visibility systems of the two companies, leaving them largely independent instead. However, contract (B) applies to a closer partnership because it requires upstream and downstream firms to integrate visibility systems and share effort costs. In this sense, the two contracts are in the middle of the vertical integration spectrum where the decentralized and centralized scenarios are at opposite ends.

Further consider that when the profit allocation rate φ is slightly lower than the lower threshold 0.25 (or slightly higher than the upper threshold 0.55), the fresh retailer (or the farm base) obtains a slightly smaller profit under contract (B) than that under contract (D). It seems that there is no reason for the fresh retailer (or the farm base) to deviate from contract (D) in terms of profit, but his and his partner's quality visibility levels would be significantly improved if they used contract (B). Furthermore, the reduced retail price and higher supply chain visibility offered by

contract (B) lead to increased food sales and consumer welfare, as well as predictable improvements in business management and goodwill, which to some extent spur the fresh retailer and the farm base to change their minds. We conclude that there is a strong stability with contract (B). There are some existing practices in which retailers or brand owners ally with suppliers to jointly bear the costs of visibility systems. As mentioned earlier, Walmart is believed to accept a large part of the R&D costs of the Food Trust Platform in cooperation with IBM while the leafy-greens suppliers just pay a service fee of 100~10000 dollars monthly according to their scales.

5.3. Sensitivity Analysis. Figures 3–6 show the influence of price sensitivity, quality visibility sensitivity, and visibility cost coefficients on supply chain performances and contract parameters. The shadow in each figure represents the Pareto improvement space in the decentralized supply chain.

It is easy to find that increased quality visibility sensitivity leads to a higher price (in Figure 4(a)), higher quality visibility (in Figure 4(b)), and greater profit (in Figure 4(c)), regardless of the supply chain or the companies in it, while the other three parameters have the opposite effect (in Figures 3, 5, and 6). Therefore, when the negotiating cost of a coordination contract is too high or the supply chain has

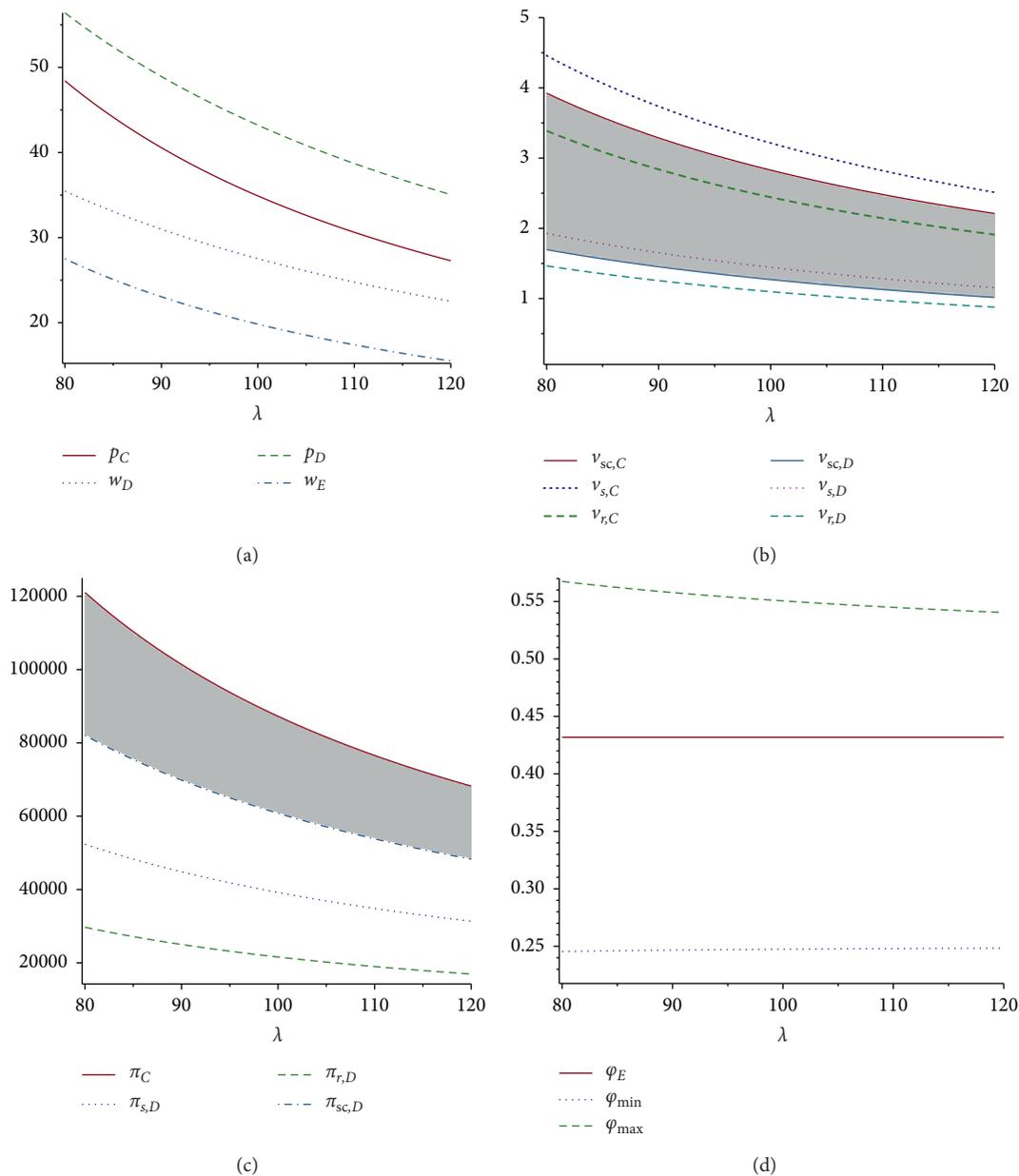


FIGURE 3: The impacts of price sensitivity. (a) Prices. (b) Quality visibility. (c) Profits. (d) Allocation rates.

been coordinated, for more profits and quality visibility, the companies may consider (i) promoting food positioning and acquiring more price-insensitive consumers, such as by launching “organic chicken” or minipackaging for one meal by the farm base and locating in luxury communities or office buildings for the fresh retailer; (ii) advocating for the traceable and trackable whole-chain quality and safety from farm to table in order to attract consumers focused on quality visibility; and (iii) purchasing or renting a more popular cost-effective visibility system, and improving the interfaces and compatibility of visibility systems.

As shown in Figures 4(a)–4(c), when consumers pay more attention to quality visibility, the company’s visibility investment increases demand, which compensates for the demand reduction caused by price inflation. In this respect, higher quality visibility sensitivity rapidly increases the optimal retail price in the supply chain, that is, consumers’ willingness to pay for a high-quality visibility food. In this case, for a unit increase in quality visibility, consumers are willing to pay an extra 7 CNY (α/λ) as the food premium for high-quality visibility.

The increased quality visibility sensitivity also leads to a broader range of the profit allocation rate (increased

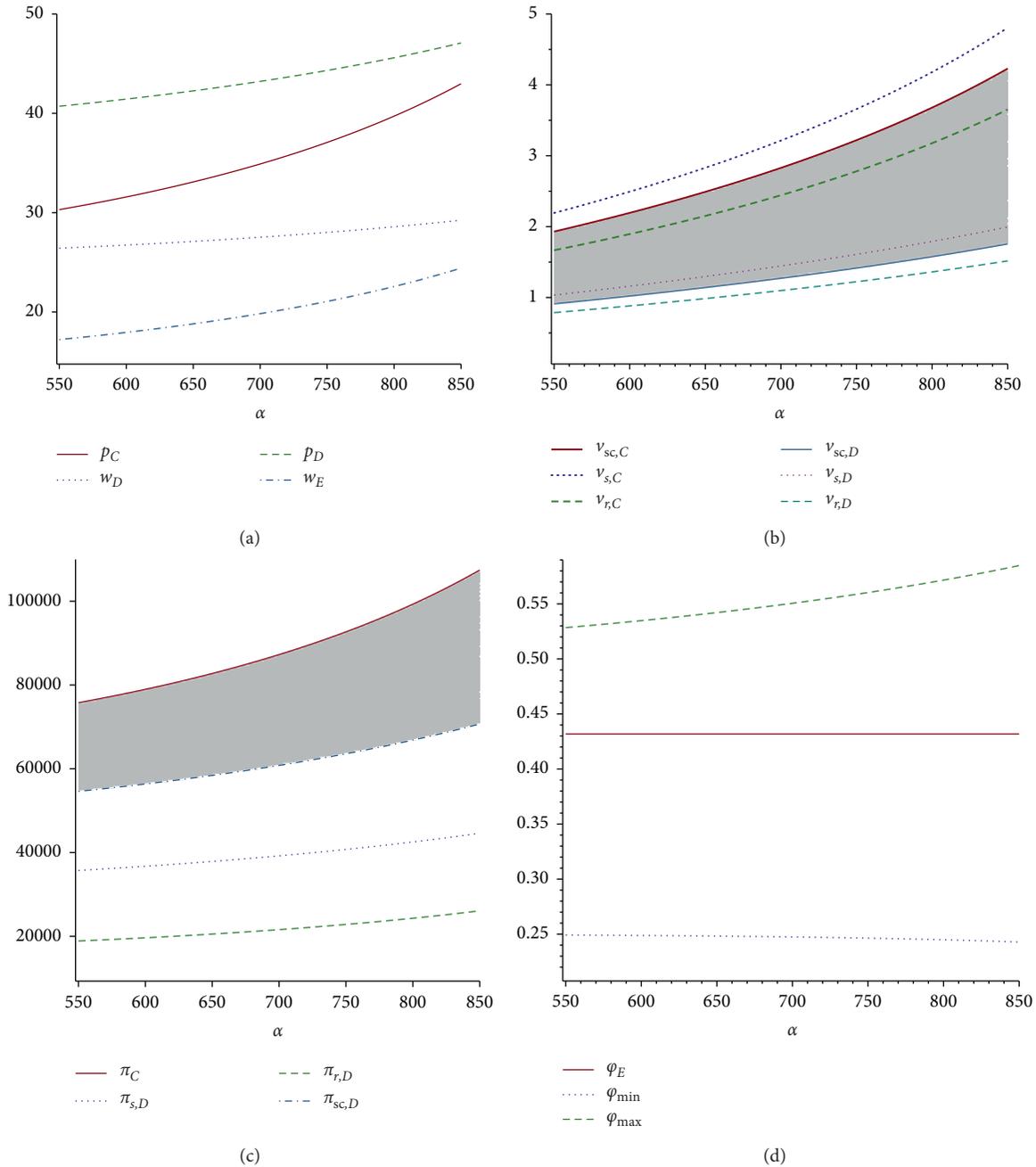


FIGURE 4: The impacts of quality visibility sensitivity. (a) Prices. (b) Quality visibility. (c) Profits. (d) Allocation rates.

φ_{max} and decreased φ_{min}) from Figure 4(d), while the other three parameters still have the opposite effect and narrow the range. Therefore, it is easier to realize supply chain coordination with a high visibility sensitivity, low price sensibility, or low-quality visibility cost coefficient.

In addition, a significant impact of the visibility cost coefficient on the contract (E) is observed in Figures 5(d) and 6(d). The fresh retailer (or the farm base) seizes a larger share of the supply chain profit with its own lower cost

coefficient or a higher cost coefficient of the other party. Moreover, a large part of the φ_E curve is below 0.5 (by $\beta_s = \beta_r$), which suggests that it is prone to contract (E) when the visibility cost coefficient of the fresh retailer is far beyond that of the farm base, according to incentive compatibility conditions in Section 4.2. Indeed, more and more retailers source directly from farms and transport using self-built logistics to mitigate supply risk and quality risk, which makes the retailer's visibility cost coefficient often greater

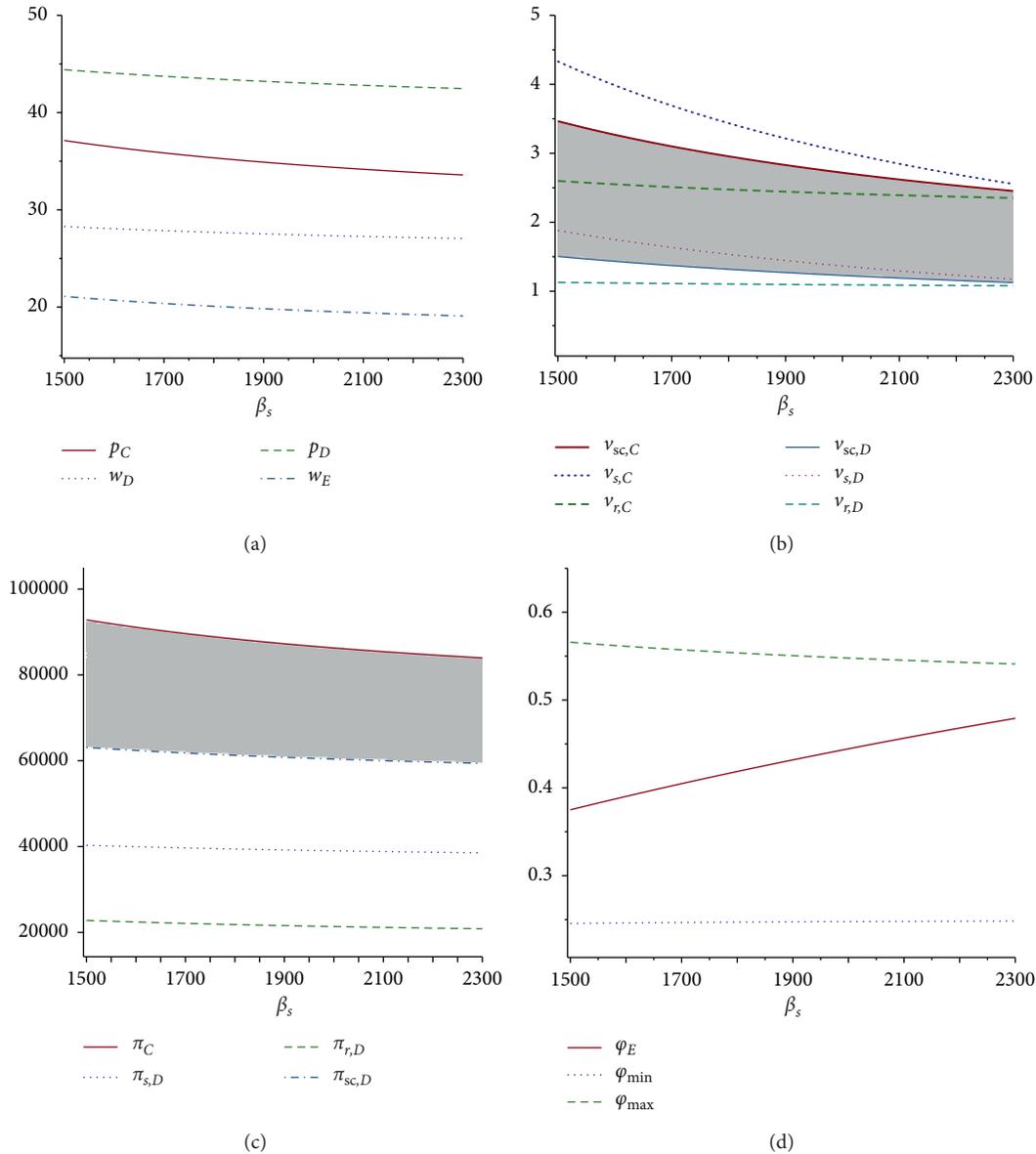


FIGURE 5: The impacts of the supplier's visibility cost coefficient. (a) Prices. (b) Quality visibility. (c) Profits. (d) Allocation rates.

than the supplier's, and thus, it is more likely to coordinate the supply chain with contract (E).

It is also meaningful to examine the sensitivity of each constraint condition to each parameter. The assumption in Proposition 1 is the condition to ensure a profitable supply chain coordination, denoting as Cdt1, while the incentive compatibility conditions in Proposition 3 guarantees the companies' participation, denoting as Cdt2 for the supplier and Cdt3 for the retailer, respectively. We can get the interval of each parameter with other parameters fixed (the strictest condition where the number is derived is in the parentheses): $\lambda > 56.74$ (Cdt1), $(Cdt1) 929.32 > \alpha > 0$, $(Cdt2) 2849.00 > \beta_s > 811.26$ (Cdt1), $(Cdt3) 5677.35 > \beta_r > 903.88$ (Cdt1). The result shows that as long as Cdt1 is met, what

stops the company is its own cost coefficient of quality visibility. Therefore, it could be the most important thing to reduce the unit cost of visibility efforts, and a number of companies good at information systems are working on that. For example, Frigga launches a low-cost real-time and an ultra-low-cost USB temperature recorder for cold chain logistics, and both of them are disposable and can be used for more than 90 days (see its website: <https://www.friggatech.com>).

Finally, from the perspective of the overall supply chain or the regulators, it is good for improving quality visibility to promote IT innovation, upgrade industries and consumption, and create a conducive environment for sign a contract.

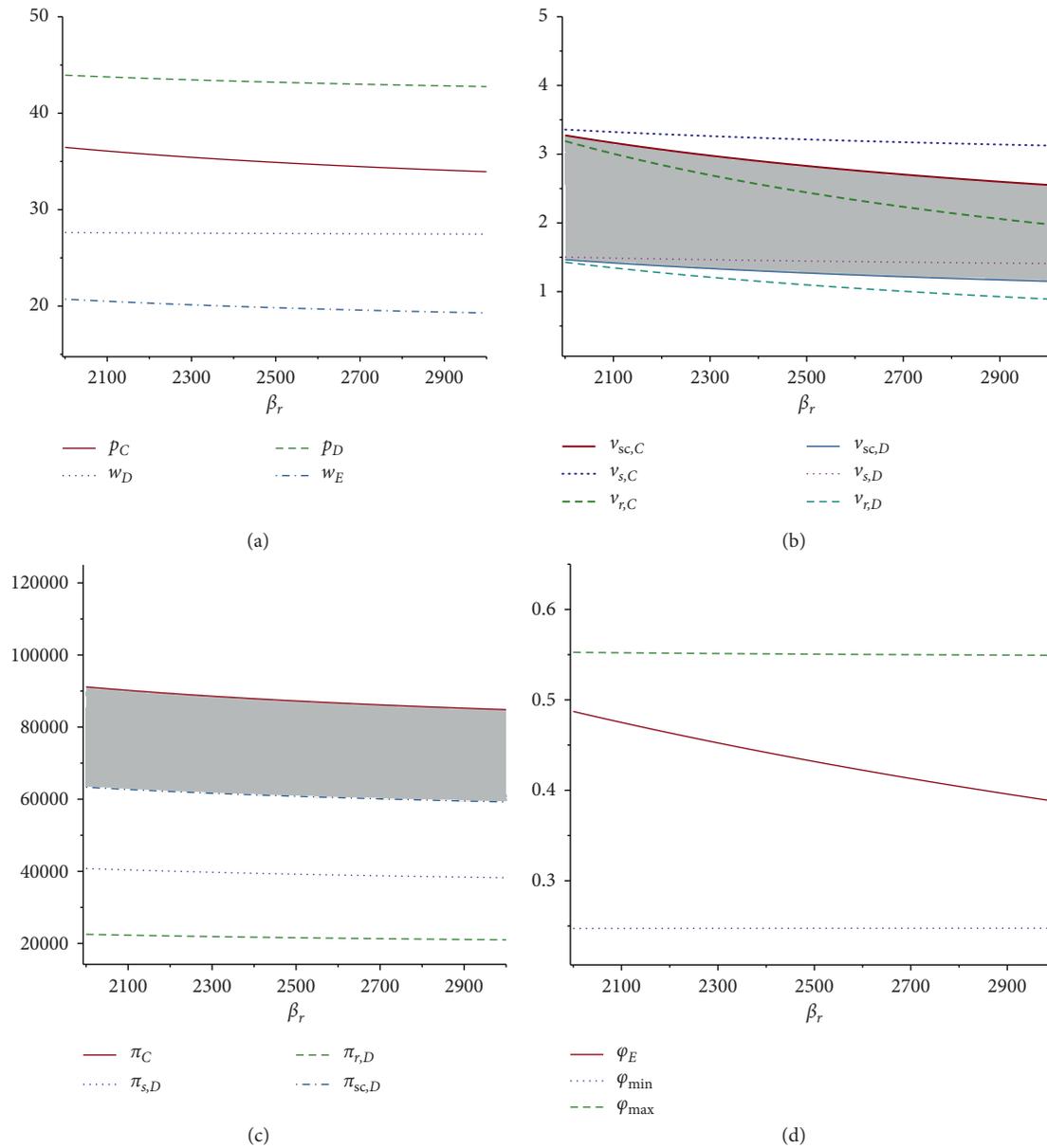


FIGURE 6: The impacts of the retailer's visibility cost coefficient. (a) Prices. (b) Quality visibility. (c) Profits. (d) Allocation rates.

6. Conclusions

This paper examines a food supply chain decision-making problem in which both the supplier and the retailer determine prices and quality visibility, and both demand and costs depend on each company's quality visibility. We propose two price discount contracts with effort alignment and with cost-sharing to coordinate the supply chain. After discovering a Pareto improvement opportunity by comparing the supply chain performances under the centralized and decentralized (wholesale price contract) situations, we demonstrate that the two modified contracts other than a common revenue-sharing contract could coordinate the supply chain, and we give their boundary conditions excluding the deviated actions. Their strengths and limitations

are presented, as well as their feasibility and stability, which are confirmed by a practical case of a chicken supply chain. Sensitivity analysis is conducted to reveal the impacts of four exogenous coefficients on the decisions and performances of the supply chain, which provide some meaningful managerial implications related to supply chain quality visibility.

The results prove that the decentralized supply chain is far inferior to the centralized supply chain in terms of both quality visibility and profit due to the existence of double marginalization. Both the supplier and the retailer have enough incentives to realize supply chain coordination from an inefficient wholesale price contract. However, other simple contracts are also invalid unless more than one parameter is introduced when the profit functions of all the players depend on the prices and efforts of both the

upstream and downstream supply chains in this model, which is different from most of the existing studies. The effort alignment and cost-sharing policies correct the distortions in the decisions on multiple layers. The former is simpler at a fixed profit allocation rate, whereas the latter can arbitrarily allocate supply chain profits to the supplier and retailer despite a larger information set being needed. In reality, considering that the quality visibility marginal costs of fresh retailers are relatively high, the incentive compatibility condition of the retailer seems to be more easily satisfied when an opportunity profit exists. Furthermore, since the coordination contracts improve everyone's quality visibility considerably, there is still a good chance for the companies to pursue coordination even if either's profit is slightly eroded, which guarantees the practical applicability of the two contracts.

Supply chain coordination not only provides opportunities to improve the performance of supply chain companies, but it also increases sales and consumer welfare at a lower retail price, which implies potential benefits such as higher brand awareness and goodwill. It may be effective to improve supply chain profit and quality visibility using improved food positioning, publicity for quality assurance, or a more cost-effective visibility system. Furthermore, IT innovation, industries and consumption upgradation, and contracting convenience also help from the holistic point of view.

Our study has limitations that lead to further research suggestions. The demand function in the model is classically linear, which may be applicable for foods with elastic demand and within certain ranges of price and quality visibility. However, daily consumption products except necessities generally have high elasticities and so do each of the competing brands in the same category of necessities. It would be interesting to discuss different demand functions and pricing models and examine the effects of revenue-sharing, buyback, quantity flexibility, and quantity/price discount contracts in the case that quality visibility effort is not observed. Another research direction in the future is to study the quality visibility strategies in the multisupplier, multiretailer, or multistage supply chain.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (grant numbers 71390330 and 71371151), Major Program of National Fund of Philosophy and Social Science of China (grant number 15ZDB150), and National Key Research and Development Program of China (grant number 2019YFB1704103).

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