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Managing Food Safety With Pricing, Contracts and Coordination in Supply Chains

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ABSTRACT This study aims to design a safe and sustainable food supply chain with food safety mechanisms so that confidence-dependent demand can be positively affected by centralized, decentralized and combined supply chain contracts. To determine the optimal order quantity, buy-back price, rebate/penalty and sales target with the proposed framework, we derive the optimality conditions of corresponding models and use the results to analyze the lard oil supply chain. It is found that supply chain contracts together with the food safety mechanism can drastically improve food safety, consumer confidence and the resulting profits of a food supply chain. What differentiates our work from earlier research efforts is that only few studies have focused primarily on food safety mechanisms that embed a closed-loop supply chain to benefit all stakeholders of a supply chain and we attempt to bridge the gap. Further improvements can be developed based on the models developed in this study.

INDEX TERMS Food safety, consumer confidence, supply chain contract, coordination, reverse logistics.

I. INTRODUCTION

Over the past few years, a series of food safety issues have arisen in Asian countries. For instance, in 2014, gutter and cooking oil made from recycled restaurant waste caused significant damage to the food industry in Taiwan. Unfortunately, markets around the world seem to lack ideal food safety mechanisms within supply chains, and food safety threats are largely forgotten until the next emergency occurs. According to the World Health Organization [1], the number of deaths occurring due to food safety issues exceeds 2 million each year, which indicates that food safety is an emergent issue that must be addressed. However, in a complex food supply chain, any safety incidents occurring in any link can significantly influence the whole chain and even have an international effect. To draw attention to this issue, World Health Day 2015 was dedicated to “Food Safety” to prioritize this topic on a global scale. Although relevant government agencies and private organizations have developed quality standards and certificates over the past decade, the quality assurance systems that have been developed remain diverse and lack international standards, creating additional burdens

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and sources of inefficiency for those adopting the system [2]. However, apart from control and regulation by government agencies, a food supply chain can actively establish preventive safety mechanisms to reduce risks of food safety incidents. For this reason, the broad stream of supply chain research focused primarily on profit maximization or cost minimization, we propose a supply chain mechanism that addresses food safety.

The food supply chain is unique because food products can be perishable; therefore, managing of the food supply chain can be challenging. The recycling process for food products is another critical issue. In the past, mass production yielding economies of scale was a primary trend; however, the reverse logistics of such products pose another significant challenge. With such trends, rendering food supply chain management sustainable is critical [3].

To establish an analyzable, efficient food supply chain, we extend a basic newsvendor problem and consider the decision making that occurs between a food manufacturer and a retailer that recognizes the importance of consumer confidence in food safety. With the objective of profit maximization, we first evaluate the following three supply chain models of the food industry: centralized, decentralized and combined contract. We then introduce a food safety mechanism while

recognizing that consumers are aware of the importance of food safety and create an incentive for manufacturers to improve food safety. In the proposed model, the manufacturer bears the risk of the loss incurred from returned food products and hence is more willing to invest more in measures relevant to food safety. Next, with the buy-back contract and returned product policy, we incorporate the recycling process and consider the salvage value of food products. With these measures, food manufacturers are able to not only avoid the risk of loss but also strengthen consumer confidence in their food products. As demonstrated by the numerical experiment, the results represent a win-win situation, and the food supply chain can be sustainable.

The remainder of this paper is structured as follows. Section 2 provides a critical overview of related work provided in the literature, and Section 3 presents a mathematical model for the supply chain planning problem. Illustrative examples are summarized in Section 4. The final section offers conclusions and suggestions for future research.

II. LITERATURE REVIEW

Because we hope to build a food supply chain that simultaneously improves food safety and its performance, we review the work published on *food safety*, *supply chain contracts* and *closed loop supply chain* and highlight the differences between our work and past work. Specifically, the literature of food safety includes three parts: sustainable planning, smart scheduling and consumer demand that is affected by confidence level and supply chain stakeholders. As to supply chain contracts, we review the studies regarding coordination contracts, green efforts, and combined contracts respectively. Furthermore, we summarize the details of the buy-back contract and sales rebate and penalty contract that are extended from coordination contracts. Finally, the studies related to closed loop supply chains include reverse logistics, close-loop activity, and green supply chain.

A. FOOD SAFETY

In recent years, food safety issues have drastically affected the food industry and have drawn significant attention to food-safety concerns. Leon-Bravo et al. [4] analyzed sustainability practices adopted in collaboration and identified the sustainability performance of different supply chain stages designed to ensure product safety and quality. Modern food production and advanced logistics increase food safety risks, therefore; Govindan [5] presented patterns of green logistics found in food supply chains to address this issue. Accorsi et al. [6] introduced a framework and a resulting decision-making tool to the sustainable planning of food logistics concerned with safety control and standard compliance.

Moreover, smart scheduling can improve the availability, elasticity, sustainability, and efficiency of supply chain management [7]. Some researchers have developed network models to ensure the quality and safety of food products during delivery. Nakandala et al. [8] proposed a cost-optimization

model to assist suppliers with fresh food industry making cost decisions regarding transportation while maintaining the quality of food products. Amorim et al. [9] developed models to analyze the integrated production and distribution planning of perishable products. Wang and Yin [10] demonstrated a method whereby fresh food can be delivered in time with minimum total cost while maintaining the quality of fresh food to a certain level.

According to Kantar Worldpanel Taiwan [11], an incident involving blended oil products that occurred in Taiwan in 2014 severely damaged consumer confidence in oil products and reduced overall market sales by 4% within a short period of time. The impact of food safety on consumer demand can also be observed from past studies. For instance, Grunert [12] investigated interactions between consumer demand for food quality/safety and showed that the quality/safety of food can significantly impact consumer demand. Bloom [13] demonstrated ways to promote quality food production by introducing food safety standards while maintaining a standardized market. Beske, et al. [14] and Mangla, et al. [15] studied how sustainable supply chain management practices allow companies to control their supply chains and to achieve a competitive advantage with the implementation of dynamic capabilities in the food industry within a context where customers exhibit a growing demand for sustainably produced food and for high levels of food safety. Govindan, et al. [16] stated that food processing industries must apply control and monitoring measures to flows of food products in each stage to ensure food safety and quality, building purchasing confidence in customers and guaranteeing industry growth.

Therefore, consideration of food safety issues in supply chain management can induce customer demand and improve the value of the supply chain. For instance, Wang et al. [17] found consumers to be more willing to pay a higher price for milk that satisfies Hazard Analysis Critical Control Point (HACCP) standards and demonstrated that the willingness to pay can positively affect supply chain profits. To reflect this critical issue, we capture the interaction between consumer demand and food safety with food safety confidence.

Building confidence between a corporation and its customers generates a positive corporate image, which can increase corporate profits through the development of a strong reputation [18], [19]. Food safety confidence is defined as the extent to which consumers view a food product as safe, trustworthy and not threatening to their health. Consumer confidence can be influenced by media coverage of food risks, trust in institutions and concerns about food production [20]. De Jonge et al. [21] and Chen [22] further found that among all supply chain stakeholders, manufacturers and retailers have the strongest effects on consumer confidence in food safety. Based on past studies, we attempt to establish a multi echelon supply chain that includes manufacturers and retailers and that includes a food safety mechanism.

B. SUPPLY CHAIN CONTRACTS

Under stochastic demand that is sensitive to consumer confidence, supply chain members who hope to maximize their profit typically collaborate and coordinate with each other by providing information or incentive measures to improve the overall performance of the supply chain. Among all possible measures, a supply chain contract serves as one form of supply chain coordination and has been researched widely in recent years. Cachon [23] investigated various types of supply chain contracts (e.g., wholesale price, buy-back, revenue-sharing, quantity flexibility, quantity-discount and sales rebate contracts) and analyzed the effects of these different types on supply chain performance.

In a *buy-back contract*, which is examined in the current study, the manufacturer promises to pay the downstream retailer for any unsold product at a price lower than the sales price at the end of the sales season. The risk of products not being sold is reduced for the retailer and is borne by the manufacturer. Such a contract motivates the retailer to ensure the manufacturer a possibly higher chance of selling more products.

Moreover, environmental sustainability has become an important facet of successful supply chain management. Hong and Guo [24] studied several cooperation contracts of green product supply chains and investigated their environmental performance. A buy-back contract can reduce risks to retailers and increase the residual value of unsold products, which is pivotal to the sustainability of a supply chain [25].

However, Emmons and Gilbert [26] found that a buy-back contract will improve supply chain performance only when a retailer can determine a selling price and a stocking quantity before the selling season. Otherwise, a buy-back contract may fail to work. Furthermore, Cachon [23] found that when the demand is price-dependent or relies on wholesalers' sales efforts, a buy-back contract may fail to coordinate the supply chain. In addition, when market demand is inadequate, the corresponding decline in retailer sales performance will expose the retailer to credit risk. At this point, the supplier must undertake the costs of unsold products, which will have negative effects on the supply chain [27]. According to the observations of the abovementioned studies, a buy-back contract is appropriate for the food supply chain considered in the present work. Therefore, buy-back contracts are considered as applicable contracts in our work.

In addition to these common contracts mentioned in Cachon [23], *sales rebate and penalty (SRP) contracts* constitute another supply chain contract option. Based on an SRP contract, a manufacturer sets a sales target for his downstream retailer. Once the retailer's sales number reaches this threshold, the manufacturer offers a certain reward to the retailer. Conversely, a penalty will be incurred when the retailer fails to achieve this goal. This type of contract encourages the retailer to exert more sales effort. Avittathur and Biswas [28] developed the limited clearance sale inventory problem for calculating the optimal order quantity and analyzed supply

chain coordination under wholesale price, buy-back, revenue sharing and sales rebate contracts.

Although contracts are designed to achieve channel coordination, they present some limitations; different types of contracts may not work in specific situations. In recent decades, different contracts have been integrated to further improve supply chain performance. Taylor [29] was the first study to integrate buy-back and target sales-rebate contracts under effort-dependent demand in a supply chain. A target sales-rebate contract is one in which a manufacturer offers rebates for products over the target level. Taylor [29] found that linear rebate, buy-back and target rebate contracts cannot achieve supply chain coordination under a single contract when consumer demand depends on a retailer's sales effort. Only when target rebate and buy-back contracts are simultaneously used can contracts integrate the overall supply chain and improve resulting performance. Following Taylor [29], research efforts have been devoted to examining combined contracts used in supply chains. Relevant studies include [30]–[36].

As the scenario considered in the current work is suited to buy-back and sales rebate and penalty contracts, we integrate these two potential contracts with the food supply chain analyzed in our work.

C. CLOSED LOOP SUPPLY CHAIN

Under a buy-back contract, when the manufacturer buys the unsold product from the retailer at the end of the season, reverse logistics must be considered. Reverse logistics concerns all relevant operations involved in transporting goods from the final destination for remanufacturing/refurbishing/recycling [37], [38] and can occur in various forms (i.e., direct recalls from manufacturers, through retailers and via third-party logistics companies). Savaskan et al. [39] found that the most efficient approach involves retailers that are positioned close to customers. With mounting concerns over environmental sustainability, advancements in supply chain management and the rise of consumer awareness have rendered reverse logistics the focus of supply chain management [40]–[43]. Van Hillegersberg et al. [44] proposed a closed-loop supply chain and identified how forward and reverse supply chains interact. Through recycling and maintenance, such supply chains can benefit both supply chain and environmental performance. Yang et al. [45] described a model of a general closed-loop supply chain network that includes a forward logistics chain (i.e., raw material suppliers, manufacturers, retailers and customers) and reverse logistics chain (i.e., customers, recovery centers and manufacturers). Cannella et al. [46] studied the inventory and order flow dynamics of a closed-loop supply chain and analyzed relationships between facets of reverse logistics (i.e., return rates of recycled products, reverse order policies, and the number of supply chain tiers). Shaharudin et al. [47] developed a research model based on the natural resource-based view to

TABLE 1. Summary of the literature review.

Papers	Contracts	Pricing	Sales effort	Consumer confidence	Recycling process
Wang, et al. [17]	-	-	-	V	-
De Jonge, et al. [20]	-	-	-	V	-
De Jonge, et al. [21]	-	-	-	V	-
Chen [22]	-	-	-	V	-
Hong and Guo [24]	CSC + POC	V	-	-	-
Wang, et al. [25]	BBC	V	-	-	-
Emmons and Gilbert [26]	BBC	V	-	-	-
Taylor [29]	BBC + SRC	V	V	-	-
He, et al. [30]	RPC + RC	V	V	-	-
Chiu, et al. [31]	RRC	V	-	-	-
Hu, et al. [32]	OPR + RSC	V	-	-	-
Pang, et al. [34]	RSC	V	V	-	-
Meng, et al. [36]	BBC + RSC	V	-	-	-
Savaskan, et al. [39]	-	V	-	-	V
Banasik, et al. [49]	-	V	-	-	V
Gao, et al. [50]	-	V	V	-	V
Gan, et al. [51]	-	V	-	-	V
Chen, et al. [52]	-	V	V	-	-
Taleizadeh, et al. [53]	TTC + CAC	V	V	-	V
Modak, et al. [54]	TTC	V	-	-	-
Panda, et al. [55]	RSC	V	-	-	V
Cachon and Lariviere [56]	RSC	V	-	-	-
Our paper	BBC + RPC	V	V	V	V

Note: CSC: Cost sharing contract; POC: Price-only contract; BBC: Buy-back contract; SRC: Sales-rebate contract; RC: Returns contract; RPC: Rebate and penalty contract; RRC: Rebates and return contract; RSC: Revenue sharing contract; OPRC: Order penalty and rebate contract; TTC: Two-part tariff contract; CAC: Cooperative advertising contract.

study the effectiveness of reverse supply chains when influenced by levels of firms' closed-loop supply chain activity. Manzini and Accorsi [48] introduced a conceptual framework that applies a closed-loop control system to integrate a food supply chain and focused on the control of the safety, quality, sustainability and eco-efficiency of an integrated food supply chain. Banasik et al. [49] investigated closed loops of a mushroom supply chain and developed a multiobjective mixed integer programming model to quantify trade-offs between economic outcomes and sustainability.

There has been a growing consensus on the need to manage closed-loop supply chains in ways that integrate supply and reverse-supply chains efficiently, and processes used to recycle and reuse products to reduce waste have led to the adoption of green supply chain management (GSCM). A comprehensive review of GSCM can be found in [57]–[60].

Reverse logistics is particularly critical for the food industry, which consumes large amounts of natural resources and which faces ever-increasing demands. In particular, in achieving economies of scale through mass production, food waste

and loss pose a significant challenge. Therefore, we designed a closed-loop supply chain in which the returned product can be recycled or be used in an alternative way (i.e., as fertilizer or biofuel). With this study, to contribute to the literature, we propose a closed-loop supply chain model in which the returned or unsold product can be recycled into fertilizer or biofuel to establish a sustainable and safe food supply chain.

In Table 1, we provide a list of the reviewed literature that illustrates the contributions of this paper. To summarize, the current work differs from earlier studies in the following respects. (1) Unlike past studies that have investigated supply chain coordination from the supply side (analyzing consumer demand based on product prices and sales efforts), we attempt to study supply chain coordination from the consumer's side by assuming that consumer demand can be influenced by consumer confidence in food safety. (2) Past studies on supply chain coordination have focused more on the two-echelon model, which addresses the relationship between a manufacturer and a retailer. In this paper, we further consider the recycling process and incorporate consumer confidence into

a conventional supply chain contract model in which we integrate buy-back and sales rebate and penalty contracts with the food supply chain in our work based on Cachon [23] and Taylor [29]. (3) To reassure consumers of the safety of the food supply chain, a new food safety mechanism is introduced to promote better manufacturer performance and to improve safety in food industries. The proposed model applies a closed-loop supply chain based on Savaskan et al. [39] with a food safety mechanism and can result in the benefit of all parties. The mathematical formulation together with numerical analyses are presented in the following sections.

III. MATHEMATICAL FORMULATION

In this section, we present a mathematical model for supply chain planning that considers the issue of food safety by applying various supply chain strategies.

A. PROBLEM STATEMENT

We aim to design a safe and sustainable food supply chain such that confidence-dependent demand can be positively affected by various supply chain contracts. The goal is to determine the optimal order quantity, buy-back price, rebate/penalty and sales target. A food safety mechanism is introduced into the model through recycling procedures to benefit all stakeholders. Because concerns regarding food safety and environmental sustainability are mounting, we develop a framework that can be applied to the food supply chain to help the food industry become more reliable and efficient.

B. ASSUMPTIONS

To support our in-depth analysis of the underlying problem, we impose certain assumptions.

1. We propose a model based on the newsvendor problem that considers a single-period and single-product inventory model in which a manufacturer creates orders before the sales season. Unlike the conventional newsvendor problem, we extend the base model to a multi echelon supply chain model. In the model, we consider a retailer, a manufacturer and raw material suppliers who can take advantage of a product's salvage value, creating new value from recycling and thus manufacturer's production costs. We also consider interactions between consumer perceptions and demand. Without compromising generality, we assume that demand is influenced by consumer confidence in food safety.
2. The sale price p_0 , manufacturing cost c_1 , unit purchasing cost of a retailer c_2 and salvage value v are assumed to be exogenous. The return price m , rebate/penalty δ , and sales target T are assumed to be endogenous. To render the model more realistic, we assume that the present price $p(t)$ decreases over time.
3. Generally, a greater investment in promotion results in a product that is more attractive to consumers and that

therefore sells more quickly. In this study, we assume that the promotion cost $w(t)$ (i.e., cost for commercials and improving food safety) is a function of time t based on the following relationship: $w(t) = Ip_0 = \frac{1}{t^2}p_0 + \varphi \geq 0$. In this function, I is the ratio of the retailer's investment in promotion to the product price and is the inverse function of t^2 , and φ is the parameter of function $w(t)$ and can be adjusted according to $w(t)$. Note that the function can be modified without affecting the conclusions drawn in later sections.

4. As noted in Piggott and Marsh [61], in conventional demand modeling, the effect of food safety concerns on consumer demand is less pronounced than that of product prices and consumer income. However, once a food safety issue arises, demand can immediately and significantly decrease. Rimal et al. [62] found a discrepancy between consumer concerns for food safety and actual consumption habits. Thus, it is possible to influence consumption habits with food safety policies, planning and education to minimize this discrepancy. To incorporate the influence of policy into the current study, we extend the work of Taylor [29] by specifying the demand function as $x(Cd) = \mu + \theta Cd + \varepsilon$ where μ is mean demand, θ is a parameter characterizing the relationship between the food safety confidence index and consumer demand, Cd is the food safety confidence index, and ε is a normally distributed random variable. It is assumed that market demand is stable under long-term market mechanisms and does not vary over time (i.e., the value of θCd can be considered one part of mean demand μ over the long term when Cd remains unchanged). Furthermore, to obtain an analyzable closed form function, we assume that retailers' efforts do not affect demand distributions and that the mean total number of demanded products is fixed over the planning horizon. When a retailer exerts more effort in selling a product, only the amount of time required to sell this product is shortened while the volume demanded remains unchanged. Unless a food safety issue arises, new food safety policies from the manufacturer are adopted, or food safety regulations are imposed, average demand remains stable.

Based on our problem statement and assumptions, we introduce the notation used throughout the paper, followed by a detailed description of the model.

C. NOTATION

Cd Index of consumer confidence in food safety, an index used to measure a consumer's confidence in food safety. Note that we consider confidence-dependent demand, which can be affected by various factors (e.g., the safety, quality, nutritional value, brand image and trustworthiness of food).

x	Market demand, a random variable that can be influenced by a consumer's food safety confidence index Cd .	c_1	The unit production cost of a food manufacturer
$f(x Cd)$	The probability density function of market demand x given Cd .	c_2	The unit purchasing cost of a retailer when the retailer places an order with a manufacturer
$F(x Cd)$	The cumulative density function of market demand x given Cd . In this study, we assume that this function is continuous and differentiable.	v	The salvage value of unsold food
$M(Q)$	The expected sales function of food. We assume that this function is greater than zero so that the retailer is willing to sell the product. Q is the order quantity from a retailer. Modified from Cachon and Lariviere [56], the function can be expressed as $M(Q) = \int_0^\infty \min(x, Q)f(x Cd)dx$. $M(Q)$ can be simplified as $Q - \int_0^Q F(x Cd)dx$. (See APPENDIX I for a detailed derivation.)	v_0	The new value from recycling resources
$L(Q)$	The expected shortage function of a retailer. Again, Q is the order quantity of a retailer. We establish the function as $L(Q) = \int_Q^\infty (x - Q)f(x Cd)dx$	h	The unit expected unsold inventory cost of a food product at the end of the selling period. Note that at the end of the selling period, unsold products can remain. The expected total inventory cost is $K(Q) \cdot h$.
$K(Q)$	The expected leftover inventory function of a food retailer. Similarly, Q is the order quantity of a retailer. The function is expressed as $K(Q) = Q - M(Q) = \int_0^Q F(x Cd)dx$	a	The unit shortage cost of a food product
$Y(Cd)$	The retailer's cost of achieving food safety confidence Cd (e.g., food safety mechanism or testing lab establishment). We assume that the function is expressed as $Y(Cd) = \frac{\theta Cd^2}{2}$, and it is convex and strictly increasing.	m	The unit return price of a food manufacturer. The cost must reflect a manufacturer's buy-back policy and should be greater than a product's salvage value.
t	Time index. Because food products are perishable, we must introduce a time index so that the model can reflect the food product life cycle with more fidelity.	δ	The rebate or penalty term imposed on a retailer when it succeeds in or fails to achieve the sales target T agreed upon in an SRP contract.
p_0	The initial market price.	$P(Q, t, Cd)$	The total profit function of the centralized supply chain.
r	The smoothing factor of product price fluctuation	$P_R^d(Q_R^d, t_d, Cd)$	The retailer's profit function in a decentralized supply chain.
$p(t)$	The present price function of the food product. The price can typically decrease over time and therefore the price is a function of time. Extending the work of Guide et al. [63], the function is expressed as $p(t) = rp_0g(t) + (1 - r)p_0$. $g(t)$ is the decreasing function of a price that must satisfy (1) $g(0)=1$, (2) $\lim_{t \rightarrow \infty} g(t) = 0$, and (3) $g'(t) < 0$ (4) $g''(t) > 0$. In the current study, we use $g(t) = \exp(-\lambda t)$, where λ is the price decay rate.	$P_M^d(Q_R^d, t_d, Cd)$	The manufacturer's profit function in a decentralized supply chain.
$w(t)$	The unit extra sale cost from a retailer. A retailer can invest more funds in promotion and shorten the amount of time required to sell all products, thereby incurring more costs. The extra cost is expressed as a function of time to reflect the time-varying nature of the cost.	$P^d(Q_R^d, t_d, Cd)$	The total profit function of a decentralized supply chain.
		$P_R^C(Q_R^C, t_C, Cd)$	The retailer's profit function under a buy-back contract.
		$P_M^C(Q_R^C, t_C, Cd)$	The manufacturer's profit function under a buy-back contract.
		$P^C(Q_R^C, t_C, Cd)$	The overall supply chain profit achieved under a buy-back contract.

D. FOOD SUPPLY CHAIN CONSIDERING CONTRACTS AND FOOD SAFETY CONFIDENCE

Based on the notation presented above, we propose centralized and decentralized supply chain models and consider a decentralized model with contracts. The models determine the optimal order quantity, return price and rebate required to maximize supply chain performance. Furthermore, a food safety mechanism and a closed-loop supply chain model are introduced in an attempt to create universally beneficial conditions for the supply chain.

1) CENTRALIZED FOOD SUPPLY CHAIN MODEL

In a centralized supply chain model, a manufacturer and retailer can be considered one entity, and the entity determines the sales cost, order quantity and sales period to improve overall supply chain performance. Specifically, the stakeholders involved have the same goal and hope to maximize supply chain profits. The overall supply chain

profit can be expressed as

$$P(Q, t, Cd) = \left[\frac{\int_0^t p(y) dy}{t} - w(t) \right] \times M(Q) + (v-h)K(Q) - a \times L(Q) - c_1 \times Q - Y(Cd) \tag{1}$$

In such a scenario, the food manufacturer and retailer are considered one entity; therefore, the objective function must only incorporate a manufacturer’s unit product cost c_1 . To maximize supply chain profits, we take the partial derivative with respect to Q , t , and Cd and set the result to zero. The optimal solution, if it exists, satisfies the first-order conditions. By letting $\bar{p} = \frac{\int_0^t p(y) dy}{t}$, we can determine Equations (2), (3) and (4). (See APPENDIX II for the specific derivation).

$$\frac{\partial P(Q^*, t^*, Cd^*)}{\partial Q} = [\bar{p} - w(t)] \times [1 - F(Q^* | Cd) - 0] + (v-h)F(Q^* | Cd) - a[F(Q^* | Cd) - 1] - c_1 = 0 \tag{2}$$

$$\frac{\partial P(Q^*, t^*, Cd^*)}{\partial t} = \left[\frac{p(t^*)t^* - \int_0^{t^*} p(y) dy}{t^{*2}} - w'(t^*) \right] \times \left[Q^* - \int_0^{Q^*} F(x | Cd) dx \right] = 0 \tag{3}$$

$$\frac{\partial P(Q^*, t^*, Cd^*)}{\partial Cd} = [\bar{p} - w(t^*)] \times \frac{\partial M(Q^*)}{\partial Cd} + (v-h) \times \frac{\partial K(Q^*)}{\partial Cd} - a \times \frac{\partial L(Q^*)}{\partial Cd} - Y'(Cd^*) = 0 \tag{4}$$

The optimal value t^* must satisfy $\frac{p(t^*)t^* - \int_0^{t^*} p(y) dy}{t^{*2}} - w'(t^*) = 0$, whereas Cd must achieve the optimal level (see APPENDIX II for the result) so that Equation (2) can be zero.

Note that the integrated supply chain’s profit function need not be concave or unimodal [23]. We assume the existence of finite optimal quantity-time-confidence and derive the first-order derivatives for three key decision variables. The supply chain achieves coordination when it is able to satisfy the first-order conditions at Q^* , t^* , and Cd^* (but these conditions are not necessarily sufficient).

To find the optimal order quantity Q^* solution for a given t and Cd , we also determine that

$$\frac{\partial^2 P(Q, t, Cd)}{\partial Q^2} = [-\bar{p} + w(t) + (v-h) - a] \times F'(Q | Cd) < 0 \tag{5}$$

Therefore, $\frac{\partial^2 P(Q, t, Cd)}{\partial Q^2}$ is concave in Q .

According to He et al. [30], we also apply the second-order derivative with t and Cd to ensure the optimal solution.

$$\frac{\partial^2 P(Q, t, Cd)}{\partial t^2} = \left[\frac{[p'(t)t - \int_0^t p(y) dy] - 2[p(t)t - \int_0^t p(y) dy]}{t^3} \right] \times \left[Q - \int_0^Q F(x | Cd) dx \right] < 0 \tag{6}$$

$$\frac{\partial^2 P(Q, t, Cd)}{\partial Cd^2} = [-\bar{p} + w(t) + (v-h)] \times \frac{\partial^2 \int_0^Q F(x | Cd) dx}{\partial Cd^2} - a \times \frac{\partial^2 L(Q)}{\partial Cd^2} - Y''(Cd) < 0 \tag{7}$$

(See APPENDIX III for the derivation.)

Therefore, from Equation (2), we have

$$F(Q^* | Cd) = \frac{\bar{p} - w(t^*) + a - c_1}{\bar{p} - w(t^*) + a + h - v} \tag{8}$$

The optimal order quantity Q^* is then

$$Q^* = F^{-1} \left(\frac{\bar{p} - w(t^*) + a - c_1}{\bar{p} - w(t^*) + a + h - v} \mid Cd \right) \tag{9}$$

The integrated supply chain’s expected profit is as follows:

$$P(Q^*, t^*, Cd^*) = [\bar{p} - w(t^*)] \times \left[Q^* - \int_0^{Q^*} F(x | Cd) dx \right] + (v-h) \int_0^{Q^*} F(x | Cd) dx - a \left[\int_Q^\infty (x - Q^*) f(x | Cd) dx \right] - c_1 \times Q^* - Y(Cd) \tag{10}$$

2) DECENTRALIZED FOOD SUPPLY CHAIN MODEL

In a decentralized supply chain model, the manufacturer and retailer do not collaborate with one another; rather, they pursue their own maximum benefit rather than considering the benefit of the entire supply chain. Hence, decentralization can result in double marginalization [64], a well-known phenomenon whereby both upstream and downstream members independently set prices above their marginal cost to optimize their profit margins, thereby creating inefficiency in the supply chain. In this section, we devise the individual profit functions of the manufacturer and retailer and analyze the effects of such a self-benefitting philosophy on supply chain performance. First, the retailer’s objective function is

$$P_R^d(Q_R^d, t_d, Cd) = \left[\frac{\int_0^{t_d} p(y) dy}{t_d} - w(t_d) \right] \times M(Q_R^d) + (v-h)K(Q_R^d) - a \times L(Q_R^d) - c_2 \times Q_R^d - Y(Cd) \tag{11}$$

To maximize profits, we similarly take the partial derivative of Equation (11) with respect to Q_R^d , t_d and Cd and set the result as zero. Let $\bar{p} = \frac{\int_0^{t_d^*} p(y) dy}{t_d^*}$; the optimal order quantity is

$$Q_R^{d*} = F^{-1}\left(\frac{\bar{p} - w(t_d^*) + a - c_2}{\bar{p} - w(t_d^*) + a + h - v}\right) | Cd \quad (12)$$

The retailer's maximum profit is then

$$\begin{aligned} P_R^d(Q_R^{d*}, t_d^*, Cd^*) &= [\bar{p} - w(t_d^*)] \\ &\times \left[Q_R^{d*} - \int_0^{Q_R^{d*}} F(x|Cd) dx \right] \\ &+ (v - h) \int_0^{Q_R^{d*}} F(x|Cd) dx \\ &- a \left[\int_{Q_R^{d*}}^\infty (x - Q_R^{d*}) f(x|Cd) dx \right] \\ &- c_2 \times Q_R^{d*} - Y(Cd^*) \end{aligned} \quad (13)$$

A food manufacturer's optimal profit function is

$$P_M^d(Q_R^{d*}, t_d^*, Cd^*) = (c_2 - c_1) \times Q_R^{d*} \quad (14)$$

Therefore, the overall supply chain profit is

$$\begin{aligned} P^d(Q_R^{d*}, t_d^*, Cd^*) &= P_R^d(Q_R^{d*}, t_d^*, Cd^*) + P_M^d(Q_R^{d*}, t_d^*, Cd^*) \\ &= \left[\frac{\int_0^{t_d^*} p(y) dy}{t_d^*} - w(t_d^*) \right] \times M(Q_R^{d*}) \\ &+ (v - h) K(Q_R^{d*}) \\ &- a \times \left[\int_{Q_R^{d*}}^\infty (x - Q_R^{d*}) f(x|Cd) dx \right] \\ &- c_1 \times Q_R^{d*} - Y(Cd^*) \end{aligned} \quad (15)$$

Generally, $c_2 > c_1$ and $t_d^* = t^*$. Thus, $\frac{\bar{p} - w(t_d^*) + a - c_2}{\bar{p} - w(t_d^*) + a + h - v} < \frac{\bar{p} - w(t^*) + a - c_1}{\bar{p} - w(t^*) + a + h - v}$.

Because $F(x|Cd)$ is strictly monotonically increasing, $F^{-1}\left(\frac{\bar{p} - w(t_d^*) + a - c_2}{\bar{p} - w(t_d^*) + a + h - v}\right) | Cd < F^{-1}\left(\frac{\bar{p} - w(t^*) + a - c_1}{\bar{p} - w(t^*) + a + h - v}\right) | Cd$.

Finally, we determine that $Q_R^{d*} < Q^*$.

Therefore, $P^d(Q_R^{d*}, t_d^*, Cd^*) < P(Q^*, t^*, Cd^*)$ (see APPENDIX IV for the proof). In such cases, decentralized supply chains yield lower overall profits.

3) CONTRACT MODEL

In a decentralized supply chain, each stakeholder pursues his or her own maximum benefit, which typically results in an inefficient use of resources. It has been suggested that forming a contract and the resulting coordination mechanism can address this inefficiency (i.e., [65]). However, as reported in published studies (i.e., [29], [23], [66]), a single contract may fail to achieve this goal when consumer demand is affected by exogenous factors. In the current study, consumer

demand is affected by the confidence index. When we only introduce a buy-back contract into a decentralized supply chain, a retailer's objective function is written as follows:

$$\begin{aligned} P_R^C(Q_R^C, t_C, Cd) &= \left[\frac{\int_0^{t_C} p(y) dy}{t_C} - w(t_C) \right] \times M(Q_R^C) \\ &+ m \times K(Q_R^C) - a \times L(Q_R^C) \\ &- c_2 \times Q_R^C - Y(Cd) \end{aligned} \quad (16)$$

To determine the maximum profit, we take the derivative of Equation (16) with respect to Cd as follows:

$$\begin{aligned} \frac{\partial P_R^C(Q_R^C, t_C, Cd^*)}{\partial Cd} &= [\bar{p} - w(t_C^*)] \times \frac{\partial M(Q_R^{C*})}{\partial Cd} + m \\ &\times \frac{\partial K(Q_R^{C*})}{\partial Cd} - a \times \frac{\partial L(Q_R^{C*})}{\partial Cd} \\ &- Y'(Cd^*) = 0 \end{aligned} \quad (17)$$

In comparing Equations (17) and (4), we find that optimality can only be established when $m = (v - h)$. However, the buy-back cost m is typically greater than the salvage value v ; the optimality condition cannot be established under such a scenario. Therefore, we conclude that a buy-back contract cannot drive supply chain performance to its system optimum.

To address this situation, based [29] and [67], we further incorporate SRP together with buy-back contracts. The primary difference here is that we select the confidence index as a critical factor for the analysis of supply chain performance. We denote δ as the penalty or reward that results when a retailer fails to meet a sales target T , which will encourage the retailer to sell more products. The retailer's objective function is then

$$\begin{aligned} P_R^C(Q_R^C, t_C, Cd) &= \left[\frac{\int_0^{t_C} p(y) dy}{t_C} - w(t) + \delta \right] \times M(Q_R^C) \\ &+ m \times K(Q_R^C) - \delta T - a \times L(Q_R^C) \\ &- c_2 \times Q_R^C - Y(Cd) \end{aligned} \quad (18)$$

The following calculation is performed to determine the optimal solution

$$\begin{aligned} \frac{\partial P_R^C(Q_R^C, t_C, Cd^*)}{\partial Q_R^C} &= [\bar{p} - w(t_C^*) + \delta] \\ &\times [1 - F(Q_R^{C*} | Cd)] \\ &+ mF(Q_R^{C*} | Cd) \\ &- a [F(Q_R^{C*} | Cd) - 1] - c_2 = 0 \end{aligned} \quad (19)$$

$$\begin{aligned} \frac{\partial P_R^C(Q_R^C, t_C, Cd^*)}{\partial t_C} &= \left[\frac{p(t_C^*) t_C^* - \int_0^{t_C^*} p(y) dy}{t_C^{*2}} - w'(t_C^*) \right] \\ &\times \left[Q_R^{C*} - \int_0^{Q_R^{C*}} F(x|Cd) dx \right] = 0 \end{aligned}$$

$$\frac{\partial P_R^C(Q_R^{C*}, t_C^*, Cd^*)}{\partial Cd} = [\bar{p} - w(t_C^*) + \delta] \times \frac{\partial M(Q_R^{C*})}{\partial Cd} + m \times \frac{\partial K(Q_R^{C*})}{\partial Cd} - a \times \frac{\partial L(Q_R^{C*})}{\partial Cd} - Y'(Cd^*) = 0 \quad (20)$$

$$(21)$$

When we compare Equations (2), (3) and (4) and solve the resulting simultaneous equations, we can determine the optimal reward/penalty δ as

$$\delta = m - v + h \quad (22)$$

To secure optimal profits from the supply chain, let $Q_R^{C*} = Q^*$. In other words, $\frac{\bar{p}-w(t_c)+\delta+a-c_2}{\bar{p}-w(t_c)+\delta+a-m} = \frac{\bar{p}-w(t)+a-c_1}{\bar{p}-w(t)+a+h-v}$. Because $\delta=m-v+h$, the optimal buy-back contract m is

$$m = v - h + c_2 - c_1 \quad (23)$$

The optimal profit function for a food manufacturer is

$$P_M^C(Q_R^{C*}, t_C^*, Cd^*) = (c_2 - c_1) \times Q_R^{C*} + (v - h - m) K(Q_R^{C*}) - \delta \times M(Q_R^{C*}) + \delta T \quad (24)$$

Because the buy-back and rebate/penalty happen within the supply chain, the overall supply chain profit can be expressed as

$$P^C(Q_R^{C*}, t_C^*, Cd^*) = P_R^C(Q_R^{C*}, t_C^*, Cd^*) + P_M^C(Q_R^{C*}, t_C^*, Cd^*) = \left[\frac{\int_0^{t_C^*} p(y) dy}{t_C^*} - w(t_C^*) \right] \times M(Q_R^{C*}) + (v - h) K(Q_R^{C*}) - a \times \left[\int_{Q_R^{C*}}^{\infty} (x - Q_R^{C*}) f(x|Cd) dx \right] - c_1 \times Q_R^{C*} - Y(Cd^*) \quad (25)$$

To incorporate a measure for preventing food safety incidents, we introduce a new mechanism into the supply chain contract model. In such a model, a manufacturer accepts all returned products should a food safety incident occur. Under the protection of such a mechanism, consumers should have a higher confidence index. Let the increase in the confidence index be ΔCd and let the resulting marginal increase of demand be $\theta \Delta Cd$. Therefore, the new sales function $M'(Q)$ is

$$M'(Q) = Q - \int_0^Q F(\mu + \theta \Delta Cd + \varepsilon | Cd) dx \quad (26)$$

On the manufacturing side, the returned product can be recycled or be used in an alternative way (i.e., as fertilizer or biofuel). Therefore, we assume that the production cost can be lowered. Suppose that the recycled product yields a value

of v_0 ; the new production cost is then $c'_1 = c_1 - v_0$. The resulting food manufacturer's optimal profit function is

$$P_M^C(Q_R^{C*}, t_C^*, Cd') = \beta \left[(c_2 - c'_1) \times Q_R^{C*} + (v - h - m) K(Q_R^{C*}) - \delta \times M'(Q_R^{C*}) + \delta T \right] + \gamma \left[(v - c'_1) \times Q_R^{C*} - N \right] \quad (27)$$

Under normal conditions, there are no food safety concerns. Therefore, $(\beta, \gamma) = (1, 0)$ under such a scenario. $\beta = 1$ indicates that a manufacturer can obtain a normal profit and is profitable. However, when food safety incidents occur, some countermeasures should be applied to address these incidents. One of the measures involves letting $(\beta, \gamma) = (0, 1)$. $\beta = 0$ indicates that a manufacturer accepts all returned products and loses all original profits from the sale of these products. $\gamma = 1$ indicates that with the exception of lost profits, a manufacturer may incur additional losses apart from those resulting from unsold products. Although the unsold/returned product may have salvage value v , it is assumed to be lower than the production cost c'_1 , and the manufacturer still cannot achieve a profit. Moreover, N represents a penalty, fine, compensation or cost of a product recall. In such cases, the manufacturer has a negative total profit and must bear the potential loss of invested production costs.

Under such a food safety mechanism, a manufacturer will attempt to improve the quality of food products to prevent a potential loss incurred from food safety incidents. Based on this mechanism, similar to that applied in the earlier derivation, the overall supply chain profit is

$$P^C(Q_R^{C*}, t_C^*, Cd') = P_R^C(Q_R^{C*}, t_C^*, Cd') + P_M^C(Q_R^{C*}, t_C^*, Cd') = \left[\frac{\int_0^{t_C^*} p(y) dy}{t_C^*} - w(t_C^*) \right] \times M'(Q_R^{C*}) + (v - h) K(Q_R^{C*}) - a \times \left[\int_{Q_R^{C*}}^{\infty} (x - Q_R^{C*}) f(x|Cd) dx \right] - c'_1 \times Q_R^{C*} - Y(Cd') \quad (28)$$

Because the recycling production cost is less than the original production cost ($c'_1 < c_1$) and as consumers have more confidence in food safety measures applied under such a food safety mechanism, sales $M'(Q)$ increase. Consequently, the difference between Equations (28) and (25) becomes positive, and the overall supply chain profit increases by $[\bar{p} - w(t_C^*) - (v - h)] \times [M'(Q_R^{C*}) - M(Q_R^{C*})] + (c_1 - c'_1) \times Q_R^{C*} + [Y(Cd^*) - Y(Cd')]$. We can then conclude that the overall profit is higher than that of the model presented in Section III-D3.

IV. NUMERICAL EXPERIMENT

In this section, we present numerical analyses conducted to gain further insight into food supply chain coordination

under confidence-dependent demand and then illustrate the effect of introducing a food safety mechanism and closed loop into the supply chain. In 2014, the gutter oil scandal in Taiwan inflicted severe damage on food businesses. In light of this, we apply the new supply chain model proposed in this paper to the market for lard oil to ensure cooking oil safety for consumers in Taiwan. To further understand the impacts of parameters used in the food supply chain formulation, we apply the sensitivity analysis described in Section IV-F and summarize the results.

A. DATA AND PARAMETERS

Assume that demand has a mean of $\mu = 100$ and a standard deviation of $\sigma = 30$ and that the cost of exerting food safety confidence is small and negligible (i.e., $\theta \approx 0$). The basic parameters are assumed to be as follows: smoothing factor of product price fluctuation $r = 0.5$, price decay rate $\lambda = 0.03$, and $\pi = 0.9$, which is the target percentage of the order quantity Q promised by the retailer for sale. The sensitivity analysis will be performed using these values. According to the published price of I-MEI FOODS COMPANY LTD. [68], p_0 is set as NT\$ 140/kg. c_1 and c_2 are set as NT\$ 47.5/kg and NT\$ 73/kg, respectively, based on a report by the Council of Agriculture, E. Y., R.O.C. [69]. According to data from the Environmental Protection Administration, R. O. C. [70], the value of v and v_0 are NT\$ 6.1 /kg and NT\$ 11 /kg, respectively. Finally, h and a represent 20% and 40% of c_2 , respectively [71], and they are therefore have valued at NT\$ 14.6 /kg and NT\$ 29.2 / kg, respectively.

B. CENTRALIZED/DECENTRALIZED MODEL

We first analyze the differences between centralized and decentralized models. The results are summarized in Figure 1. Note that a higher σ value implies more uncertain demand.

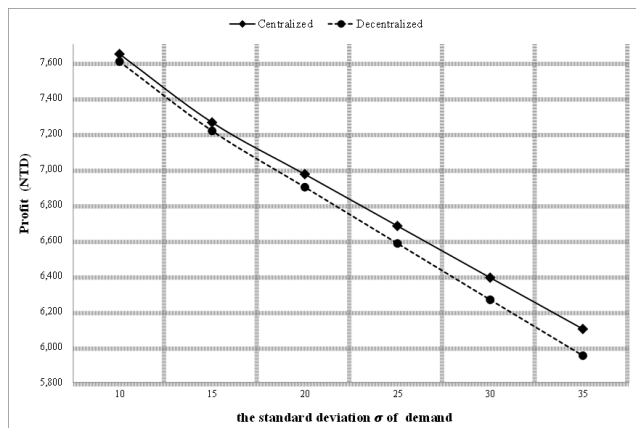


FIGURE 1. Comparison of centralized and decentralized models.

As is shown in Figure 1, sales performance is adversely affected by demand uncertainty. The result is a decrease in overall profits generated with an increase in demand uncertainty. However, the centralized model always outperforms

the decentralized one, and this trend becomes even more apparent as demand uncertainty increases. We can then conclude that the centralized model is more stable and is affected less by demand uncertainty. The stability of the centralized model can be attributed to the fact that within this model, stakeholders coordinate and collaborate more with channel partners and can therefore reduce risks of demand uncertainty through strategic partnerships while in the decentralized model they fail to do so.

C. DECENTRALIZED MODEL WITH THE SRP AND BUY-BACK CONTRACTS

To address the inefficiency of the decentralized food supply chain model, we introduce SRP and buy-back contracts. The results are shown in Figure 2. Note that it is assumed that consumer demand can be affected by consumer confidence in food safety. That is, an increase in average demand indicates a corresponding increase in consumer confidence in food safety. A decrease in average demand can be interpreted in the same manner.

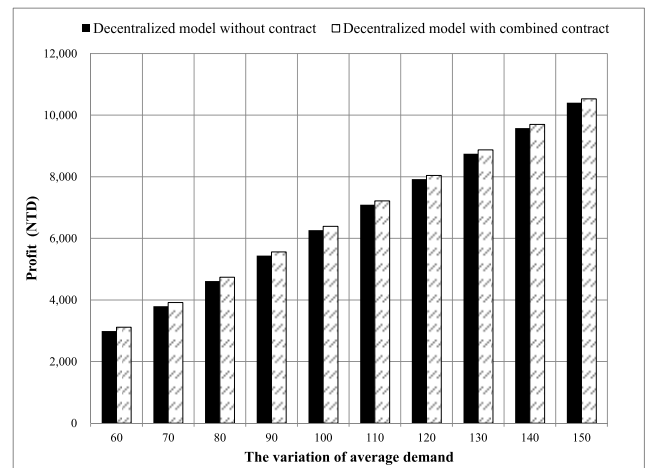


FIGURE 2. Effect of contracts on profits under confidence-dependent demand.

Figure 2 shows that the decentralized model benefits from the introduction of contracts through coordination because the model with contracts generates higher supply chain profits. The model also shows that profits of the entire supply chain are enhanced by an increase in consumer food safety confidence. In contrast, as the confidence level declines, profits decrease accordingly. For this reason, we conclude that when the stakeholders of a food supply chain can improve food quality and safety to increase/rebuild consumer confidence, the whole food supply chain can benefit from such improvements.

Next, we examine profit sharing between the manufacturer and retailer under a combined contract. Note that π is the target percentage of the order quantity Q that the retailer promises to sell through contracts. A higher π leads to a higher sales target T .

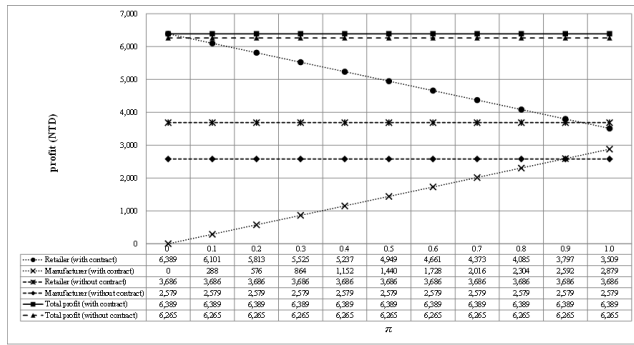


FIGURE 3. Allocation of profit between the manufacturer and retailer.

As is shown in Figure 3, various sales targets T lead to varied profit allocation between the two parties. When sales targets T increase, the manufacturer’s profit increases, whereas the retailer’s profit decreases because the retailer’s profits are shared by the manufacturer. When π increases to more than 0.8955, the manufacturer secures more profits than when there is no contract. When π increases to over 0.9385, the retailer generates less profits than when a contract is not used. Therefore, when π is 0.8955-0.9385, the two parties generate more profits than without a contract, resulting in a universally beneficial outcome.

D. FOOD SAFETY CONFIDENCE

Based on assumption 4 described in Section III-B, demand is affected by the index of food safety confidence. In this section, to examine this effect, we assume that the demand function is written as $x(Cd) = \mu + \theta Cd + \varepsilon$. As noted above, θ is the parameter that characterizes the relationship between the food safety confidence index and consumer demand. The effects of interactions between a different parameter θ and a different rate of confidence decline are depicted in Figures 4 and 5, respectively. A higher θ denotes that demand is more sensitive to variation in consumer confidence.

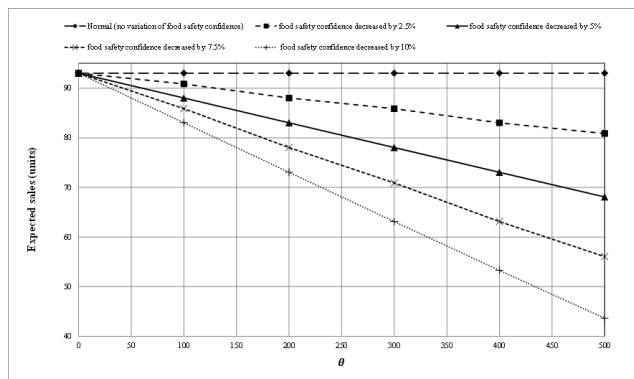


FIGURE 4. Impact of parameter θ on expected sales.

As is shown in Figure 4, when the consumer confidence index Cd decreases, the sales number decreases accordingly

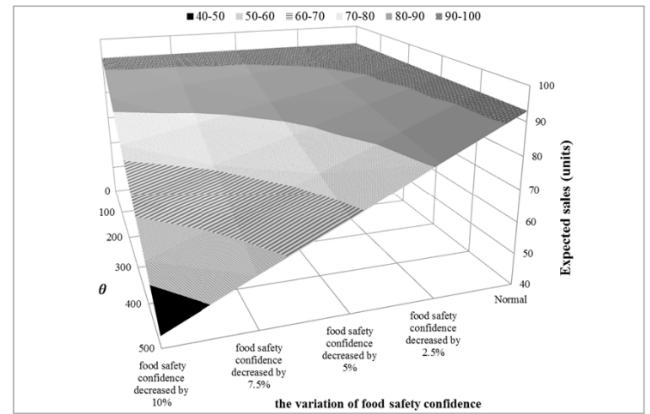


FIGURE 5. Effect of interactions between parameter θ and confidence Cd on expected sales.

due to consumer loss of confidence in the food product. The trend is more apparent with higher values of θ . We can observe this more clearly in Figure 5. Cd and θ interact with one another and have a synergic effect. Thus, higher values of Cd and θ result in a more decline in rapid sales.

E. RECYCLING AND FOOD SAFETY MECHANISM

Introducing a new food safety mechanism into a supply chain contract mode under confidence-dependent demand can increase consumer confidence in food safety and thus induce more demand for a given food product. With this experiment, we evaluate models that are (1) decentralized, (2) decentralized with contracts, (3) decentralized with contracts and food safety mechanisms and (4) decentralized with contract, food safety mechanisms and closed-loop supply chains. The numerical results are shown in Figure 6. For this experiment, we apply a value of $\theta = 100$. Furthermore, we assume that the implementation of a food safety mechanism can increase consumer confidence by 10% and that there is no penalty, fine, compensation or product recall cost (namely, $N = 0$).

Figure 6 shows that with more measures (i.e., contracts, food safety mechanisms and closed-loop supply chains) introduced into the food supply chain, the profits of the supply chain increase accordingly. Furthermore, when no food safety incidents occur (i.e., $(\beta, \gamma) = (1, 0)$), consumers are more confident in food products (i.e., food safety confidence Cd increases) and thus are more willing to purchase more products. Therefore, overall profits are higher than they are without the food safety mechanism. When we introduce a closed-loop supply chain into the model, due to lower production costs resulting from recycling, profits increase further. However, when food safety outbreaks occur (i.e., $(\beta, \gamma) = (0, 1)$), the retailer returns all products and the manufacturer bears all of the loss. In such a model, the manufacturer will be more cautious about food safety concerns to prevent significant profit losses. Additionally, when the manufacturer can ensure food safety, overall profits can

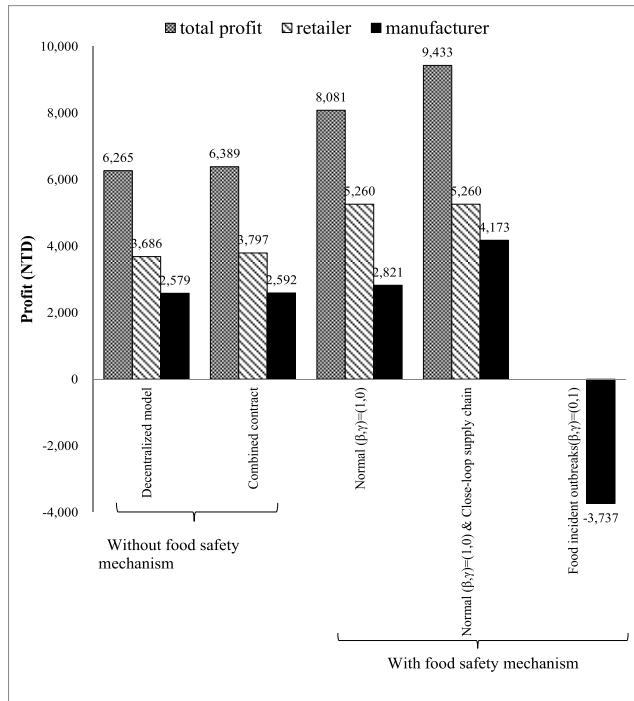


FIGURE 6. Effects of different frameworks on profits.

increase even more than they can through a supply chain without these measures, and the supply chain can in turn become more stable.

F. SENSITIVITY ANALYSIS

1) ANALYSES OF SMOOTHING FACTOR r AND PRICE DECAY RATE λ

Note that, as described in Section III-C, $p(t) = rp_0g(t) + (1 - r)p_0$ where $g(t) = \exp(-\lambda t)$. To study the effects of important parameters on the performance of a food supply chain, we conduct sensitivity analyses of smoothing factor r and price decay rate λ . Through this analysis, we obtain further insight into the effects of these parameters on the optimal policy of a supply chain. Relationships between the sales period and parameters are shown in Figures 7 and 8, respectively. The results of different levels of supply chain performance are provided in Tables 2 and 3.

In the present study, smoothing factor r determines the correlation between the sales time and price, i.e., r is larger when it is more relevant and thus causes the value of products to deteriorate more rapidly over time. As is shown in Figure 7, the optimal sales period decreases with an increase in r , as product prices are more sensitive to time and decrease more rapidly when r is a larger value. Therefore, when r is a larger value, a retailer must sell the product faster before the product loses its value. Furthermore, from Table 2, an increase in r decreases supply chain profits because the retailer must devote more effort to selling a product facing a more rapid decline in product prices over a shorter period.

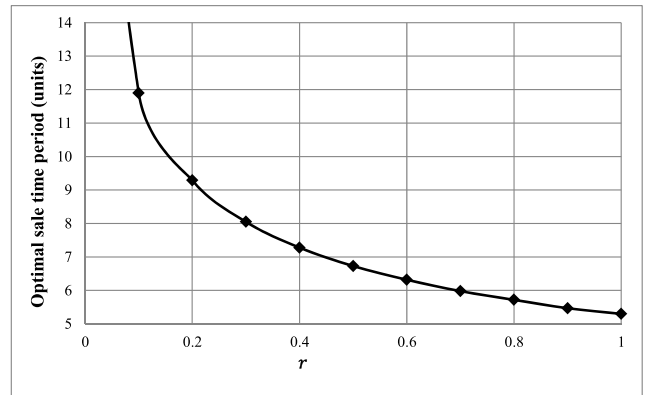


FIGURE 7. Relationship between the optimal food product life cycle and smoothing factor r .

TABLE 2. Sensitivity analysis of parameter r .

r	t	$w(t)$	\bar{p}	Q^*	Retailer's Profit	Manufacturer's Profit	Total Profit
1.00	5.30	4.98	129.44	86.94	1,937	2,952	4,889
0.90	5.47	4.68	130.20	87.12	2,022	2,958	4,980
0.80	5.72	4.28	130.92	87.31	2,110	2,964	5,075
0.70	5.98	3.91	131.71	87.51	2,112	2,971	5,083
0.60	6.32	3.51	132.52	87.71	2,208	2,978	5,185
0.50	6.73	3.09	133.39	87.92	2,309	2,985	5,294
0.40	7.28	2.64	134.31	88.14	2,419	2,992	5,411
0.30	8.05	2.16	135.31	88.38	2,537	3,001	5,538
0.20	9.29	1.62	136.44	88.65	2,573	3,010	5,583
0.10	11.90	0.99	137.77	88.95	2,731	3,020	5,751
0.01	29.71	0.16	139.55	89.35	2,940	3,033	5,974
0.005	132.40	0.01	139.95	89.43	2,985	3,036	6,021

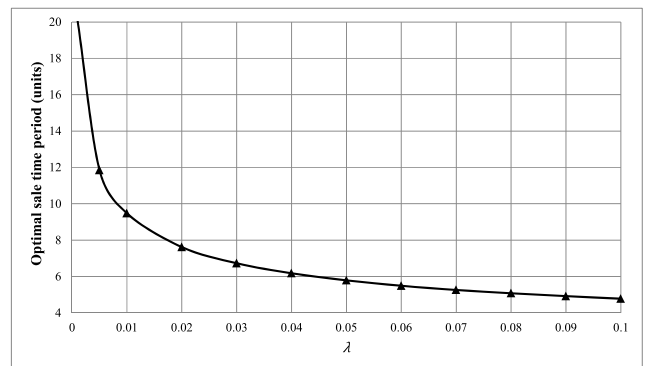


FIGURE 8. Relationship between the optimal food product life cycle and price decay rate λ .

An increase in λ indicates that the product price declines more per unit of time. As is shown in Figure 8, the optimal sales period is shortened with an increase in λ . This is the case because within the same period, the price of the product decreases more rapidly when λ is larger. Therefore, a retailer dedicates more effort to selling products faster to earn more profit. As is shown in Table 3, a higher value of λ is associated with lower supply chain profits because the supply chain must invest more in promoting the product in response to a shorter sales period.

TABLE 3. Sensitivity analysis of parameter λ .

λ	t	$w(t)$	\bar{p}	Q^*	Retailer's Profit	Manufacturer's Profit	Total Profit
0.1	4.78	5.9	125.42	86.06	1,634	2,922	4,556
0.09	4.92	5.78	126.56	86.29	1,733	2,929	4,663
0.08	5.08	5.43	127.52	86.52	1,752	2,937	4,690
0.07	5.26	5.06	128.56	86.77	1,862	2,946	4,808
0.06	5.49	4.64	129.64	87.03	1,980	2,955	4,935
0.05	5.79	4.18	130.78	87.31	2,107	2,964	5,072
0.04	6.18	3.67	132.02	87.6	2,156	2,974	5,130
0.03	6.73	3.09	133.39	87.92	2,309	2,985	5,294
0.02	7.62	2.41	134.93	88.28	2,486	2,997	5,484
0.01	9.48	1.56	136.78	88.71	2,606	3,012	5,618
0.005	11.86	1	137.96	88.98	2,746	3,021	5,767
0.001	20.11	0.35	139.3	89.28	2,905	3,031	5,936

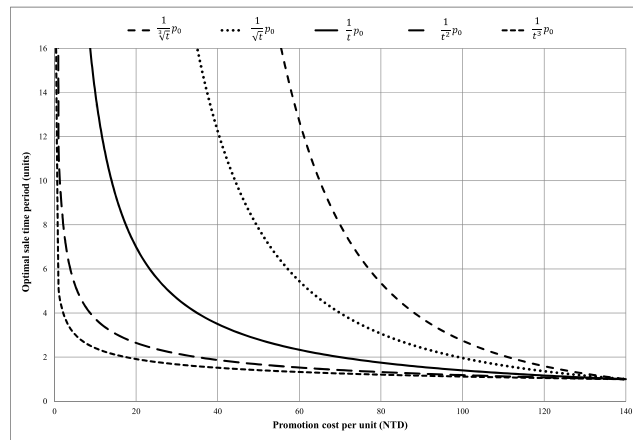


FIGURE 9. Relationship between the optimal sale time period and promotion costs for different types of functions.

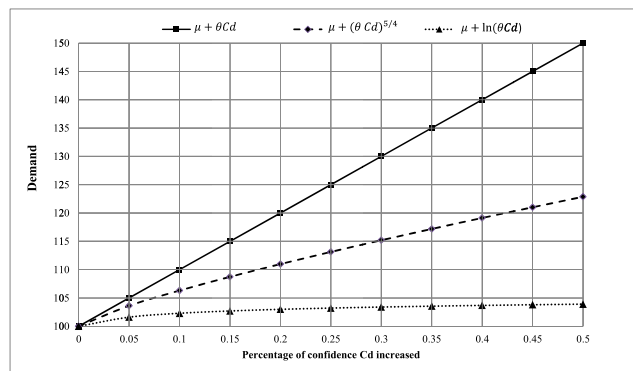


FIGURE 10. Different forms of the demand function.

2) ANALYSES OF DIFFERENT TYPES OF PROMOTION COST FUNCTIONS $w(t)$

With assumption 3 shown in Section III-C, we assume that the promotion cost $w(t)$ is a function of sales time t (i.e., $w(t) = Ip_0 = \frac{1}{t^2}p_0 + \varphi$), indicating that investments made in promotion by a retailer can shorten the sales period. To evaluate the effect of this function, we test it with different functions and summarize the results in Figure 9.

When the function is $w(t) = Ip_0 = \frac{1}{\sqrt{t}}p_0 + \varphi$, the sales time and promotion cost are more directly related. However, when the function is of a higher power (i.e., $\frac{1}{t^2}$ or $\frac{1}{t^3}$), only a minor investment is required to shorten the optimal sales period.

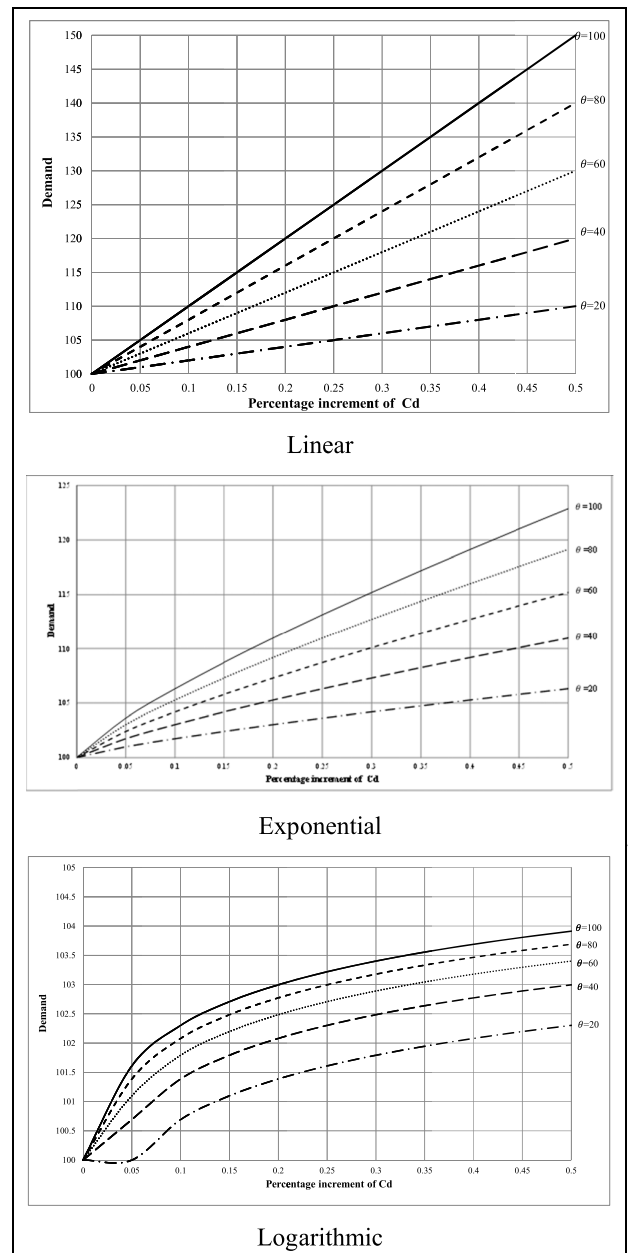


FIGURE 11. Impact of θ on demand based on various functional forms.

For instance, investing 10 NTD per unit in promotion can decrease the sales period from approximately 16 or longer to 3.7 units of time when $w(t) = Ip_0 = \frac{1}{t^2}p_0 + \varphi$. Under this scenario, investing more does not create a significant benefit and a retailer may not invest more in promotion. Therefore, determining the ideal function form of $w(t)$ for different markets and investing accordingly is the appropriate strategy for a food supply chain to adopt.

3) ANALYSES OF DIFFERENT FORMS OF DEMAND FUNCTION $x(Cd)$

Based on assumption 4 given in Section III-C, the demand function $x(Cd)$ is of linear form ($x(Cd) = \mu + \theta Cd + \varepsilon$), which can occasionally be unrealistic in practice. To investigate the effect of this function, we conduct a sensitivity

analysis on various function forms (i.e., linear, exponential, and logarithmic) and show the results in Figure 10.

As is shown in the figure, we observe a similar trend, but the magnitude is slightly different when different functional forms are used. The nonlinear forms (i.e., exponential and logarithmic functions) are concave and increasing functions. Therefore, demand increases relatively slowly for these two function forms, and the marginal effectiveness of confidence is decreasing.

Furthermore, we can adjust parameter θ of Cd according to the elasticity of consumer demand. The value of θ is higher when consumers place more weight on food safety, which thus leads to more variation of demand with an increase/decrease in Cd . We test different values of θ with different functional forms and present the results in Figure 11.

Thus, we can adopt different function forms of demand and adjust parameter θ to different markets to render the model more appropriate and realistic. Suppose that we have five products with identical conditions that only differ in terms of θ values (i.e., $\theta = 20, 40, 60, 80, \text{ and } 100$). Under this scenario, consumers are less sensitive to the safety of a product with $\theta = 20$. Because consumers are more concerned with the safety of food products than that of other products, parameter θ for food products will be higher.

V. CONCLUSION AND FUTURE RESEARCH

In a heavily globalized world, the food supply chain is becoming more complex. Thus, safety incidents that occur in any link can significantly affect the entire chain, even on an international scale. Unsafe food leads to health issues and to greater difficulties in the food business. Hence, food safety issues are an important and serious public concern. Against the backdrop of such trends, this paper incorporates consumer food safety confidence into a conventional supply chain contract model and then presents a mathematical model for supply chain planning. We also compare centralized and decentralized models and find that the centralized model outperforms the decentralized one due to effective coordination and collaboration among channel partners. To address inefficiencies of the decentralized model of the food industry, we introduce combined SRP and buy-back contracts. By determining the optimal order quantity Q_R^{C*} , return cost m , rebate/penalty δ , and sales target T , the supply chain can achieve coordination and therefore improve performance. Specifically, a combined contract can distribute risks of uncertain demand between a manufacturer and retailer so that the supply chain can perform more effectively and generate more profits.

To incorporate measures for preventing food safety incidents, a food safety mechanism is introduced into the contract model so that all stakeholders of the food industry can benefit. The food safety mechanism can rebuild consumer confidence in food products and improve the quality and safety of the food supply chain. The core premise of this mechanism is to increase levels of risk faced by the manufacturer; that is, the manufacturer must bear all of the loss incurred when there

is an incident involving food safety. By contrast, when the manufacturer can provide food that is safer, the overall profit can be even higher, which can increase confidence through the mechanism. Through this mechanism, the food manufacturer will more carefully ensure food quality and safety to prevent any significant profit losses and to further increase total profits. In light of growing concerns about sustainable production in the food industry, a closed-loop supply chain is also proposed in this paper. A contract model with a food safety mechanism leads to reverse logistics, and in turn some returned or leftover products are returned to the manufacturer. Under a closed-loop framework, the food manufacturer can lower production costs by recycling, increasing profits further.

To illustrate the analytical results, the proposed models are applied to the lard oil industry in Taiwan. Our illustrative examples verify that the centralized model performs better than the decentralized one and shows that an SRP with a buy-back contract can effectively coordinate upstream and downstream supply chain members within a decentralized model. We study also illustrate the effects of consumer confidence on demand and show that sales numbers change more when concerns about food safety are raised. We then discuss the effects of different frameworks proposed in this paper and find supply chain profits increase when more measures are introduced into the food supply chain. Managerial insights derived from our results are as follows. To mitigate risk and improve the performance of a supply chain with uncertain confidence-dependent demand, stakeholders can coordinate and collaborate with one another through joint SRP with buy-back contracts. Furthermore, the conceptual framework of food safety and sustainability offers references to the food industry on the condition that the model can effectively prevent the production of unsafe food and maximize the use of product value. Under such a framework, the food supply chain can achieve efficiency, safety and sustainability.

Although interesting insights can be gleaned from the proposed models, this study is not without limitations. In this paper, we focus our analysis on the effects that food safety has on the food supply chain and therefore assume that consumer confidence in food safety is the only critical factor that shapes demand. However, customer demand can be more stochastic and diverse due to various complex factors (i.e., price, preferences, time and effort). Future research can consider additional factors to provide greater fidelity to the results in reflecting consumer behavior. Furthermore, the study only considers a single period, manufacturer and retailer. However, retailers and manufacturers can have competitors, particularly when a longer time is considered. Customer demand is shared by retailers/manufacturers in the market. A decrease in customer demand due to food safety incidents for one party can mean an increase in customer demand for others. Based on the proposed model, future research can analyze competition and cooperation with respect to food products in the market to better understand the effects of food safety

concerns on the food industry over various time periods. Finally, as demand for seasonal products may fluctuate, future studies may investigate issues of seasonality.

APPENDIX I: DERIVATION OF THE EXPECTED SALES FUNCTION

$$M(Q) = \int_0^\infty \min(X, Q)f(x|Cd)dx$$

$$= \begin{cases} \int_Q^\infty Qf(x)dx, x \geq Q \\ [x \int_0^x f(x) dx]_0^Q - \int_0^Q [\int_0^x f(x)dx]dx \\ = Q \int_0^Q f(x) dx - 0 - \int_0^Q F(x) dx, 0 < x < Q \end{cases}$$

In integrating the above two equations, we obtain the following equation

$$M(Q) = Q \times \left[\int_0^Q f(x|Cd) dx + \int_Q^\infty f(x|Cd) dx \right] - \int_0^Q F(x|Cd) dx$$

$$= Q - \int_0^Q F(x|Cd) dx \blacksquare$$

APPENDIX II: THE OPTIMAL SOLUTION OF THE CENTRALIZED MODEL

We take the partial derivative of Equation (1) with respect to Q , t , and Cd and set it as zero to determine the optimal solution of the centralized model. $\frac{\partial P(Q^*, t^*, Cd^*)}{\partial Q}$, shown at the bottom of this page.

Note that

$$\frac{\partial \int_Q^\infty (x - Q^*)f(x|Cd) dx}{\partial Q} = \frac{\partial \int_Q^\infty xf(x|Cd) dx}{\partial Q} - \frac{\partial \int_Q^\infty Q^*f(x|Cd) dx}{\partial Q}$$

$$= \lim_{n \rightarrow \infty} \left[\frac{\partial \int_Q^n xf(x|Cd) dx}{\partial Q} - \frac{\partial \int_Q^n Qf(x|Cd) dx}{\partial Q} \right]$$

$$\frac{\partial P(Q^*, t^*, Cd^*)}{\partial Q} = \frac{\partial [\bar{p} - w(t)] \times M(Q^*) + (v - h)K(Q^*) - a \times L(Q^*) - c_1 \times Q^*}{\partial Q}$$

$$= \frac{\partial [\bar{p} - w(t^*)] \times [Q^* - \int_0^{Q^*} F(x|Cd) dx] + (v - h) \int_0^{Q^*} F(x|Cd) dx - a \left[\int_Q^\infty (x - Q^*)f(x|Cd) dx \right] - c_1 \times Q^*}{\partial Q}$$

$$= [\bar{p} - w(t^*)] \times [1 - F(Q^*|Cd) - 0] + (v - h)F(Q^*|Cd) - a[F(Q^*|Cd) - 1] - c_1 = 0$$

$$\frac{\partial P(Q^*, t^*, Cd^*)}{\partial t} = \frac{\partial \left[\frac{\int_0^{t^*} p(y)dy}{t^*} - w(t^*) \right] \times M(Q^*) + (v - h)K(Q^*) - a \times L(Q^*) - c_1 \times Q^*}{\partial t^*}$$

$$= \left[\frac{p(t^*)t^* - \int_0^{t^*} p(y) dy}{t^{*2}} - w'(t^*) \right] \times \left[Q^* - \int_0^{Q^*} F(x|Cd) dx \right] = 0$$

$$= \lim_{n \rightarrow \infty} \left\{ \frac{\partial [x \int_0^x f(x|Cd) dx]_{Q^*}^n - \int_{Q^*}^n \int_0^x f(x|Cd) dx dx}{\partial Q} - \frac{\partial \int_{Q^*}^n Qf(x|Cd) dx}{\partial Q} \right\}$$

$$= - \int_0^{Q^*} f(x|Cd) dx - Q^*f(Q^*|Cd) + F(Q^*|Cd) - \int_{Q^*}^\infty f(x|Cd) dx + Q^*f(Q^*|Cd)$$

$$= F(Q^*|Cd) - 1$$

Thus, $Q^* = F^{-1}(\frac{\bar{p} - w(t^*) + a - c_1}{\bar{p} - w(t^*) + a + h - v} | Cd)$, $\frac{\partial P(Q^*, t^*, Cd^*)}{\partial t}$, shown at the bottom of this page.

Therefore, the optimal value t^* must satisfy $\frac{p(t^*)t^* - \int_0^{t^*} p(y)dy}{t^{*2}} - w'(t^*) = 0$ so that the equation holds.

$$\frac{p(t^*)t^* - \int_0^{t^*} p(y) dy}{t^{*2}} - w'(t^*) = \frac{[\gamma p_0 g(t^*) + (1 - \gamma)p_0]t^* - \int_0^{t^*} \gamma p_0 g(y) + (1 - \gamma)p_0 dy}{t^{*2}} + \frac{2p_0}{t^{*3}}$$

$$= \frac{\gamma p_0 [e^{-\lambda t^*} t + \frac{1}{\lambda} e^{-\lambda t^*} - \frac{1}{\lambda}] + 2p_0}{t^{*2}} = 0$$

Therefore, $t^* \left[\lambda e^{-\lambda t^*} t + e^{-\lambda t^*} - 1 \right] = -\frac{2\lambda}{\gamma}$

Because the values of parameters (i.e., λ , e and γ) are known, we can solve the equation and obtain the optimal $t^* = \frac{\partial P_R^C(Q^*, t^*, Cd^*)}{\partial Cd}$, shown at the bottom of the next page.

Assuming that $Y(Cd) = \frac{\theta Cd^2}{2}$ where $\theta > 0$, θ can be interpreted as the cost of applying food safety confidence level Cd .

In turn, we can obtain the optimal

$$Cd^* = \frac{a\theta [F(Q^*|Cd) - 1] - [v - h - \bar{p} + w(t^*)] \theta f(Q^*|Cd)}{\theta} \blacksquare$$

APPENDIX III: SECOND-ORDER DERIVATIVES FOR Q, t, AND Cd

The product price is typically greater than the promotion cost and salvage value; therefore, $\bar{p} > w(t) + v$. Because $h \geq 0$ and $a \geq 0$, $-\bar{p} + w(t) + v - h - a \leq 0$. Furthermore, $F'(Q|Cd) > 0$ for $F(Q|Cd)$ is strictly monotonically increasing. Hence,

$$\begin{aligned} &= \frac{\partial \theta f(Q|Cd)}{\partial x} \cdot \frac{\partial x}{\partial Cd} \\ &= \theta f(Q|Cd) \end{aligned}$$

$$\frac{\partial^2 P(Q, t, Cd)}{\partial Q^2} = [-\bar{p} + w(t) + v - h - a] \times F'(Q|Cd) < 0. \blacksquare$$

Because $p(t) = \gamma p_0 g(t) + (1 - \gamma)p_0$, $g(t) = \exp(-\lambda t)$, $M(Q) > 0$ and $g'(t) < 0$, then

$$\begin{aligned} \frac{\partial^2 P(Q, t, Cd)}{\partial t^2} &= \left[\frac{t^2 p'(t) t - 2t \left[p(t) t - \int_0^t p(y) dy \right]}{t^4} \right. \\ &\quad \left. - w''(t) \right] \times M(Q) \\ &= \left[\frac{t^2 \gamma p_0 g'(t) - 2p(t) t + 2 \int_0^t \gamma p_0 g(t) + (1 - \gamma) p_0 dy}{t^3} \right. \\ &\quad \left. - w''(t) \right] \times M(Q) \\ &= \left[\frac{t^2 \gamma p_0 g'(t) - 2\gamma p_0 g(t) - (1 - \gamma) p_0 t - 2\gamma \left(\frac{1}{\lambda} e^{-\lambda t} + \frac{1}{\lambda} \right)}{t^3} \right. \\ &\quad \left. - w''(t) \right] \times M(Q) < 0 \end{aligned}$$

Because $g'(t) < 0$ and $t^2 \gamma p_0 \geq 0$, $t^2 \gamma p_0 g'(t) \leq 0$. Furthermore, $2\gamma p_0 g(t) \geq 0$, $(1 - \gamma) p_0 t > 0$, $2\gamma \left(\frac{1}{\lambda} e^{-\lambda t} + \frac{1}{\lambda} \right) > 0$, and $\frac{t^2 \gamma p_0 g'(t) - 2\gamma p_0 g(t) - (1 - \gamma) p_0 t - 2\gamma \left(\frac{1}{\lambda} e^{-\lambda t} + \frac{1}{\lambda} \right)}{t^3} < 0$. Given $w''(t) > 0$ and $M(Q) > 0$, we establish the above result. \blacksquare

Finally, by applying the chain rule, the second-order partial derivative of $\frac{\partial^2 \int_0^Q F(x|Cd) dx}{\partial Cd^2}$ is as follows

$$\frac{\partial^2 \int_0^Q F(x|Cd) dx}{\partial Cd^2} = \frac{\partial}{\partial Cd} \left[\frac{\partial \int_0^Q F(x|Cd) dx}{\partial x} \cdot \frac{\partial x}{\partial Cd} \right]$$

$$\begin{aligned} \frac{\partial P_R^C(Q^*, t^*, Cd^*)}{\partial Cd} &= [\bar{p} - w(t^*)] \times \frac{\partial M(Q^*)}{\partial Cd} + (v - h) \times \frac{\partial K(Q^*)}{\partial Cd} - a \times \frac{\partial L(Q^*)}{\partial Cd} - Y'(Cd^*) \\ &= \frac{\partial [\bar{p} - w(t^*)] \times \left[Q^* - \int_0^{Q^*} F(x|Cd) dx \right] + (v - h) \int_0^{Q^*} F(x|Cd) dx - a \left[\int_{Q^*}^{\infty} (x - Q^*) f(x|Cd) dx \right]}{\partial Cd} \\ &\quad - Y'(Cd^*) \\ &= \frac{\partial [v - h - \bar{p} + w(t^*)] \int_0^{Q^*} F(x|Cd) dx - a \left[\int_{Q^*}^{\infty} (x - Q^*) f(x|Cd) dx \right]}{\partial Cd} - Y'(Cd^*) \\ &= [v - h - \bar{p} + w(t^*)] \theta f(Q|Cd) - a \theta [F(Q^*|Cd) - 1] - Y'(Cd^*) = 0 \end{aligned}$$

Furthermore,

$$\begin{aligned} \frac{\partial^2 L(Q)}{\partial Cd^2} &= \lim_{n \rightarrow \infty} \frac{\partial^2 (n-Q) F(n) - \int_Q^n F(x|Cd) dx}{\partial Cd^2} \\ &= \lim_{n \rightarrow \infty} \frac{\partial}{\partial Cd} \left[\frac{\partial (n-Q) F(n) - \int_Q^n F(x|Cd) dx}{\partial x} \cdot \frac{\partial x}{\partial Cd} \right] \\ &= \lim_{n \rightarrow \infty} \frac{\partial \theta [(n-Q) f(n|Cd) - F(n|Cd) + F(Q|Cd)]}{\partial x} \cdot \frac{\partial x}{\partial Cd} \\ &= \theta^2 f(Q|Cd) \end{aligned}$$

Therefore,

$$\begin{aligned} \frac{\partial^2 P_R^C(Q, t, Cd)}{\partial Cd^2} &= [-\bar{p} + w(t) + (v - h)] \\ &\quad \times \frac{\partial^2 \int_0^Q F(x|Cd) dx}{\partial Cd^2} - a \\ &\quad \times \frac{\partial^2 L(Q)}{\partial Cd^2} - Y''(Cd^*) \\ &= [-\bar{p} + w(t) + (v - h)] \times \theta^2 f(Q|Cd) \\ &\quad - a \theta^2 f(Q|Cd) - Y''(Cd^*) \end{aligned}$$

Because $-\bar{p} + w(t) + (v - h) < 0$, $\theta^2 f(Q|Cd) \geq 0$ and $Y''(Cd^*) > 0$ ($Y(\cdot)$ is convex and strictly increasing), $[-\bar{p} + w(t) + (v - h)] \times \theta^2 f(Q|Cd) - a \theta^2 f(Q|Cd) - Y''(Cd^*) < 0$. \blacksquare

APPENDIX IV: CENTRALIZED AND DECENTRALIZED MODEL PROFIT COMPARISONS

Because centralized and decentralized models have the profit functions of $P(Q^*, t^*, Cd^*)$ and $P^d(Q_R^{d^*}, t_d^*, Cd^*)$, respectively,

$$\begin{aligned} P(Q^*, t^*, Cd^*) - P^d(Q_R^{d^*}, t_d^*, Cd^*) &= [\bar{p} - w(t^*)] \\ &\quad \times \left[Q^* - Q_R^{d^*} + \int_0^{Q^*} F(x|Cd) dx - \int_0^{Q_R^{d^*}} F(x|Cd) dx \right] \\ &\quad + (v - h) \times \left[\int_0^{Q^*} F(x|Cd) dx - \int_0^{Q_R^{d^*}} F(x|Cd) dx \right] \end{aligned}$$

$$\begin{aligned}
 & -a \left[\int_{Q^*}^{\infty} (x - Q^*) f(x|Cd) dx - \int_{Q_R^{d*}}^{\infty} (x - Q_R^{d*}) f(x|Cd) dx \right] \\
 & -c_1 \times (Q^* - Q_R^{d*}) \\
 & = [\bar{p} - w(t^*) - c_1] \times (Q^* - Q_R^{d*}) + [\bar{p} - w(t^*) + v - h] \\
 & \times \left[\int_0^{Q^*} F(x|Cd) dx - \int_0^{Q_R^{d*}} F(x|Cd) dx \right] \\
 & -a \left[\int_{Q^*}^{\infty} (x - Q^*) f(x|Cd) dx - \int_{Q_R^{d*}}^{\infty} (x - Q_R^{d*}) f(x|Cd) dx \right] \\
 & > 0
 \end{aligned}$$

Because the product price is typically greater than the promotion cost, production cost and expected unsold inventory cost so that the retailer does not bear losses, $\bar{p} - w(t) - c_1 > 0$ and $\bar{p} - w(t^*) + v - h > 0$.

Furthermore, $a \geq 0$, $Q^* > Q_R^{d*}$, $\int_0^{Q^*} F(x|Cd) dx > \int_0^{Q_R^{d*}} F(x|Cd) dx$, and $\int_{Q_R^{d*}}^{\infty} (x - Q_R^{d*}) f(x|Cd) dx > \int_{Q^*}^{\infty} (x - Q^*) f(x|Cd) dx$ for $F(x|Cd)$ are strictly monotonically increasing.

Because $P(Q^*, t^*, Cd^*) - P^d(Q_R^{d*}, t_d^*, Cd^*) > 0$, we can conclude that $P(Q^*, t^*, Cd^*) > P^d(Q_R^{d*}, t_d^*, Cd^*)$. ■

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