Coordination and Decision of Supply Chain Under:

Price-Dependent Demand and Customer Balking Behavior

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ABSTRACT

In order to investigate supply chain coordination and decision under customer balking and stochastic demand, the article considers a two-echelon supply chain consisting of one manufacturer with risk-neutral and one retailer with risk-neutral and develops two models in a centralized and a decentralized system and the three contracts are designed to coordinate supply chain and the optimal price and customer balking strategies are obtained. The results show that the revenue and cost-sharing contract can coordinate supply chain under customer balking and price-dependent demand and achieve the Pareto-improvement; the expected sales quantity and expected reduced sales quantity are influenced conversely by the threshold of inventory and probability of a sale under customer balking. In addition, numerical analysis is given to verify the effectiveness of revenue and cost-sharing contract and the paper gives some managerial insights and puts forward to the future work at last.

KEYWORDS

Customer Balking Behavior, Newsvendor Model, Price-Dependent Demand, Stackelberg Game, Supply Chain Coordination and Decision

1. INTRODUCTION

The sales of the retailer can be influenced by not only holding inventory but also adjusting the selling price. For example, the retailer can satisfy customer demand by keeping plentiful inventory, but when the item shortage occurs or the item inventory is under a certain threshold which may lead to the customer decision-making: going out the shop directly or continuing to buy alternatives in the shop, there may be customer balking behavior (Moon & Choi, 1995). The models of inventory and customer balking have been developed by some scholars who have derived lots of different conclusions and insights; On the other hand, the selling price is also the important factor influencing item sales and some scholars have studied the applications of the newsvendor model of price-dependent demand

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based on different perspectives. Hence, it can be seen that not only should the inventory be considered, but also the selling price should be considered in the case of analyzing market demand. But from the existing literature, it can be found that market demand is influenced by the single factor or two factors in the newsvendor model and customer balking behavior is not considered. In this paper, we will consider the selling price and customer balking simultaneously and study supply chain coordination in the basis of the extensive newsvendor model.

Based on classical newsvendor model (Scarf, 1957; Pasterncak, 1989; Gallego, 1992), many extensive models are developed and applied and many practical problems have been also solved, so it has been gained more and more attentions by the researchers. It is well known that the price is exogenous in the classical newsvendor model, then it is unrealistic in our daily life: It is obvious that the higher selling price will reduce market demand and the lower selling price will promote market demand for the retailer, so how to set the reasonable price to satisfy market demand is one of our attentions in this paper. In addition, the important content of the newsvendor model is how to set the optimal ordering quantity in order to reduce the cost and risk and decrease customer balking behavior for supply chain. Production quantity is the complex decision-making for the manufacturer: production quantity in excess of market demand will lead to the excessive inventory, otherwise there will be out of stock, which brings the uncertain risk to the manufacturer. How to solve the problems above for the manufacturer and the retailer is important for improving the performance of supply chain.

In the paper, we want to coordinate the supply chain considering the extensive newsvendor model under price-dependent demand and customer balking, then there are some questions remain to be answered: 1) Does the extensive newsvendor model remain to be applicable? 2) How to set the reasonable ordering quantity and selling price? 3) How to design the contracts for coordinating the supply chain and improve the profit of supply chain members.

In order to answer the above-mentioned problems, we develop a two-echelon supply chain with price-dependent demand and customer balking behavior, consisting of one manufacturer with risk-neutral and one retailer with risk-neutral, while market demand is stochastic and influenced by the selling price, the ordering quantity and stochastic variable. In this system, first, we formulate two models of centralized and decentralized supply chain and analyze the available conditions of the optimal ordering quantity and optimal selling price. Next, we analyze the effects of parameters of customer balking on the supply chain, the expected sales quantity and the expected reduced sales quantity and optimize the models developed in the paper. Lastly, we analyze three contracts that are used to coordinate supply chain and compare them to obtain the coordination mechanism of supply chain and test the validity of the models by numerical analysis.

The contributions of this paper are as follows: First, we develop the extensive newsvendor model of price-dependent demand and customer balking behavior and obtain the optimal ordering quantity and selling price in the case of certain parameters of customer balking. Second, the model of the expected reduced sales is applied in coordinating supply chain, which has not been analyzed previously. Last, we obtain that the revenue and cost-sharing contract can coordinate supply chain and analyze the effects of parameters of customer balking on supply chain. In addition, we optimize the models for obtaining the optimal solution and summarize some managerial insights.

The remainders of this paper are organized as follows: Section 2 reviews the correlative literature of newsvendor model and customer balking. Section 3 describes assumptions and notations and considers a two-echelon supply chain under customer balking. Section 4 studies the models in centralized and decentralized system and analyze the effects of parameters of customer balking on supply chain. Section 5 studies the revenue sharing-only contract, revenue and cost-sharing contract and revenue sharing contract with sales rebate and penalty to coordinate supply chain and determines the conditions for coordinating supply chain. Section 6 gives numerical analysis with respect to key parameters and puts forward to some managerial insights. Section 7 concludes the work and future research.

2. LITERATURE REVIEW

There are lots of related literature to our work in this paper including different areas such as supply chain coordination, newsvendor model, customer behavior and so on. In this paper, we want to incorporate price-dependent demand and customer balking behavior to build the connection with supply chain coordination.

2.1. Research Related to Coordination With Price-Dependent Demand

Early in the classical newsvendor model, Scarf (1957) began to study the conditions of the stock in the min-max solution and analyzed the results of different distribution, his work was very meaningful and pioneered the study of newsvendor model. Next, some scholars have also done similar studies (Gallego, 1992; Gallego & Moon, 1993, 1994).

In recent years, there are some literature on extensive newsvendor models with price-dependent stochastic demand which are applied in coordinating supply chain. Taylor (2002) investigated coordination of supply chain under sales effort and developed the two models with quantity-only and quantity and sales effort, then they designed the rebate and return contract to coordinate supply chain. The results showed that the sales effort can affect the effectiveness of the contract. Gomez-Padilla (2009) analyzed the supply chain with a supplier and a retailer under stochastic demand and coordinated supply chain by three contracts. The results showed that the quantity flexibility contract and buy back contract could coordinate the supply chain and the wholesale price contract couldn't coordinate supply chain. He et al. (2009) considered a supply chain consisting of a supplier and a retailer and that the demand is influenced by effort and selling price. They developed two models in the centralized and decentralized supply chain by game theory and coordinated the supply chain by return policies and sales rebate and penalty contracts. Xiao et al. (2010) analyzed the coordination of supply chain under consumer return and built the profit models of the manufacturer, retailer and total supply chain. Then, they coordinated the supply chain by buyback contract and markdown money contract and found that the two contracts could coordinate the supply chain under special conditions. Chen et al. (2010) analyzed a supply chain with a supplier and a retailer under reservation capacity and price dependent demand and developed the centralized and decentralized models and they found that the risk and profit-sharing contract can coordinate supply chain under some conditions. Arcelus et al. (2011) analyzed supply chain coordination under a secondary market and applied the return policy to coordinate the manufacturer and the retailer. The results showed that the total profit of supply chain under coordination is greater than that of decentralized supply chain. Egri & Va´ncza (2012) analyzed a two-echelon supply chain with short-dated and asymmetric information and coordinated it by hybrid payment method. It was found that the coordination can reduce the distorting and uncertainty of customer's demand. Wu (2013) investigated supply chain coordination under competition and stochastic demand and built two models by game theory. The conclusions were that the buyback policy could coordinate supply chain and improve the profit of supply chain comparing to non-buyback policy. Zhang et al. (2014) analyzed a supply chain with fuzzy demand and coordinated the supply chain with buyback contract, they also analyzed that how the fuzzy parameters influenced supply chain coordination and shortage cost affected the performance of supply chain. Kusukawa (2014) considered the sales strategies under returns and clearance sales and coordinated supply chain with revenue sharing contract based on developing the centralized and decentralized models. The results showed that the coordination could improve the profit of supply chain stakeholders. Saha and Goyal (2015) considered a two-stage supply chain with one manufacturer and one retailer and developed the model with inventory level and retail price-dependent demand simultaneously. They found that the manufacturer and the retailer didn't accept all the contracts including joint rebate contract, wholesale price discount contract and cost sharing contract because of their preferences and the wholesale price discount contract is the best for the retailer. Zhang and Qin (2016) analyzed an express delivery supply chain with a retailer and a provider under stochastic demand and coordinated the supply chain by option contracts. They found that the option contracts can coordinate the supply chain under special conditions. Wang et al. (2017) considered a supply chain under behavior factors and developed the model with linear utility function, then coordinated the supply chain with five contracts. They found that the wholesale price contract couldn't coordinate supply chain and the other four contract can do it.

In the deterministic demand, Qi et al. (2004) developed a two-period model with demand disruptions and analyzed the decision-making in the centralized and decentralized supply chain in the case of demand disruptions; they found that the supply chain could be coordinated by the wholesale quantity discount. Pan (2010) considered one manufacturer and two retailers with price-dependent demand and analyzed how to coordinate the supply chain by the wholesale price contract and the revenue sharing contract; they found that the revenue sharing contract is perfect to coordinate the supply chain, their research is different from the previous literature because they designed the two channels. Maihami et al. (2012) considered a deterministic demand with jointly price and time and derived the optimal price, replenishment schedule and order quantity when the profit is maximum and provided the optimal solution by the algorithm; they found that it is an improvement for total profit from the non-instantaneously deterioration products. Liu et al. (2012) considered a supply chain with multi-period and price-dependent demand and analyzed two models of centralized and decentralized supply chain, then they obtained the optimal price and ordering quantity and the different effects of price protection on supply chain. Avinadav et al. (2014) developed two models with price and inventory age dependent demand which includes two forms and analyzed the effects of two forms on demand and the optimal conditions for the price and inventory age. it was obtained that there was one form suitable for the model that was built in their paper and the optimal properties were dependent on the type of the model. Ghosh and Shah (2015) considered one manufacturer and one retailer with price and green improvement level dependent demand and analyzed how to coordinate the supply chain by cost sharing contract, their research was a new field of green supply chain and provided a meaningful research interest. Bai et al. (2017) analyzed a sustainable supply chain with promotional effort, sustainable level, selling price and time dependent demand and coordinated the supply chain with revenue and promotional cost-sharing contract and two-part tariff contract, they found that the two-part tariff contract is more robust than the revenue and promotional cost-sharing contract. Wei et al. (2015) and Maiti et al. (2017) also studied the coordination of supply chain under price-dependent demand.

From the above-mentioned literature, the contents of research are jointly incorporated price-dependent demand with other factors whether stochastic demand or deterministic demand, which makes the models more complex and more difficult. The extensive newsvendor model with single factor can't meet the needs of the development of modern theory and the interdisciplinary application of the theory is getting more and more attention.

2.2. Research on Customer Balking Behavior

The research on customer balking behavior was derived from the application of queuing theory, with the development of theory, the customer balking behavior is applied in the newsvendor model. The newsvendor model with balking began in the late 1980's (Pasterncak, 1989), Moon and Choi (1995) extended the model of Pasterncak (1989) based on the distribution and fixed ordering cost under balking behavior and found that the optimal ordering rule existed in the condition of giving certain mean and variance of demand and proved that the free distribution of newsvendor model is robust. Liao et al. (2011) also analyzed the extensive classic newsvendor model with customer balking and a linear shortage penalty cost and their work proved the improvement of inventory performance and provided some useful insights. Lee & Jung (2014) modified the newsvendor model with balking and proved the inapplicability of previous literature under customer balking, then analyzed the effects of uncertain parameters of customer balking on the retailer. Cheong and Kwon (2013), Hu and Zhai (2014) also studied the extension to the classical model with two uncertain parameters under customer balking. Feng (2015) studied the newsvendor model with customer balking and coordinated the supply chain, which was a meaningful extension and was merely studied. Lan (2017) analyzed a VMI supply chain with customer balking and promotional efforts and coordinated supply chain by the wholesale price contract. Zhang et al. (2018) proposed a supply chain with customer balking and asymmetric information and designed the transfer payment contract to coordinate the supply chain.

It can be seen that the extensive newsvendor models are only improved in the theory and rarely analyzed in the practical application from above-mentioned analysis. Comparing other applications, the research on the newsvendor model with customer balking are only a few. In the paper, we will study the application of newsvendor model with customer balking based on the previous research in order to find different insights.

In this paper, there are some differences from the above-mentioned literature as follows: First, we build the model with price-dependent demand and customer balking, which is rare and more complex. Second, we analyze the application of expected reduced sales quantity which differs from the existing literature and the contract mechanism is designed to coordinate supply chain. Finally, the effects of uncertain parameters of customer balking on supply chain are analyzed.

3. MODEL DESCRIPTIONS

3.1. Notations and Assumptions

In the section, we consider a two-echelon supply chain consisting of a risk-neutral manufacturer and a risk-neutral retailer with a single period. In the system, the manufacturer provides a certain type of items for the retailer at the wholesale price w and has no inventory, the retailer sells items to customers at the price p and second purchasing is not allowed. The structure of supply chain is shown in Figure 1.

The main parameters and notations are described in Table 1 and the other assumptions are shown as following:

1. Letting $F\left(D\right)$ be the distribution of demand and be increasing and $F\left(0\right)=0$;
2. For a given p, it is assumed that the demand decreased in price and $\partial F\left(D\middle|p\right)\big/\partial p>0$;
3. The values of parameters a and b are known;
4. We assume that the salvage value of the item is negligible. The fixed ordering cost is assumed to be zero because the retailers can order items by internet with negligible cost and there is no shortage of items;
5. The information symmetry exists among the manufacturer, the retailer and the customer in this paper.

Figure 1. The structure of supply chain

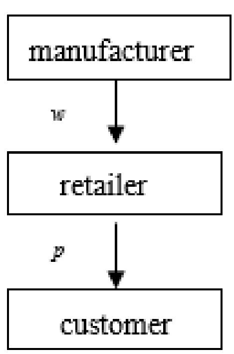


Table 1. The main parameters and notations

Parameters	Notations
α	Unit lost cost due to customer balking
c	Unit cost of item, c<p
D	The item's random demand
q	The ordering quantity, $q > K$
$F(D)$	The cumulative distribution function of D
$f(D)$	The density function of D
L	The probability of a sale under customer balking, $0 < L < 1$
K	The threshold of inventory under customer balking, $0 < K < q$

3.2. The Models With Customer Balking

In this section, we develop the model of the expected sales quantity $S\left(q,p\right)$ in the case of customer balking and there are three stages shown in Equation (1) (Lee & Jung, 2014):

$$S\left(q,p\right) = \int_0^{q-K} Df\left(D\middle|p\right)dD + \int_{q-K}^{q-K+K/L}\left[q-K+L\left(D-q+K\right)\right]f\left(D\middle|p\right)dD \\ +\int_{q-K+K/L}^{\infty} qf\left(D\middle|p\right)dD \tag{1}$$

In Equation (1), the first part represents the expected sales quantity when the demand is between 0 and $q-K$ units, customer balking doesn't occur because the inventory is beyond the threshold of inventory K. The second part means the expected sales quantity if market demand is between $q-K$ and $q-K+K/L$ units, then the probability of a sale becomes L when customer balking occurs. Customer balking behavior affects $\left(1\text{-}L\right)\left[D\text{-}\left(q-K\right)\right]$ units among total demand. So the quantity of sales is $q-K+L\left[D-\left(q-K\right)\right]$. The last part is the quantity of expected sales when the demand goes beyond $q-K+K/L$.

Based on the basis of Lee and Jung (2014), $S\left(q,p\right)$ can be simplified as follows:

$$S\left(q,p\right) = q - \int_0^{q-K} F\left(D\middle|p\right)dD - L\int_{q-K}^{q-K+K/L} F\left(D\middle|p\right)dD \tag{2}$$

And the function of expected reduced sales quantity $g(q,p)$ due to customer balking is shown as following (Lee & Jung,2014):

$$g\left(q,p\right) = L\int_{q-K}^{q-K+K/L} F\left(D\middle|p\right)dD - \int_{q-K}^{q} F\left(D\middle|p\right)dD \tag{3}$$

where:

0<L<1 且 K>0

4. DECISION MODELS

4.1. Centralized Decisions

In the section, the centralized supply chain with customer balking behavior is analyzed. In the case, the objective of supply chain is to set the optimal product supply (q) and optimal selling price (p) to maximize the total profit. The profit function of centralized supply chain $\pi_c\left(q,p\right)$ is as follows:

$$\pi_c\left(q,p\right) = pS\left(q,p\right) - cq - \alpha g\left(q,p\right) \tag{4}$$

In Equation (4), the first term is the sales revenue of centralized supply chain, the second term is purchasing cost, the third term is the reduced sales cost of customer balking.

Proposition 1: The optimal selling price p_c^* in the centralized supply chain satisfies Equation (5):

$$S\left(p^*,q\right) + p^* \frac{\partial S\left(q,p^*\right)}{\partial p} - \alpha \frac{\partial g\left(q,p^*\right)}{\partial p} = 0 \tag{5}$$

Proof: Please see Appendix.

Proposition 1 shows that there exists the optimal selling price which can maximize the profit of supply chain when customer balking occurs.

Proposition 2: The optimal ordering quantity q_c^* for the retailer satisfies Equation (6):

$$\left(1-L\right)\left(p+\alpha\right)F\left(\left(q-k\right)\middle|p\right) + L\left(p+\alpha\right)F\left(\left(q-K+K/L\right)\middle|p\right) - \alpha F\left(q\middle|p\right) = p - c \tag{6}$$

Proof: Please see Appendix.

It can be seen from Proposition 2 that the optimal ordering quantity exists and can maximize the total profit of supply chain under customer balking.

4.2. Decentralized Decisions

In this section, the manufacturer and the retailer make their own decisions separately to maximize their own profit when supply chain is decentralized. We consider this scenario to be a Stackelberg game with the manufacturer as the leader. The manufacturer first sets the wholesale price and the retailer determines the order quantity and selling price based on the manufacturer's announced decisions. Next, we use the backward sequential decision-making approach to analyze the optimal response function. The profit function of the retailer $\pi_r\left(q,p\right)$ is as follows:

$$\pi_r\left(q,p\right) = pS\left(q,p\right) - wq - \alpha g\left(q,p\right) \tag{7}$$

In Equation (7), the first term is the sales revenue of the retailer, the second term is purchasing cost of the retailer, the last term is the reduced sales cost with customer balking.

The profit function of the manufacturer is as follows:

$$\pi_m\left(q,p\right)=wq-cq \tag{8}$$

In Equation (8), the first term is the sales revenue of the manufacturer and the second term is the production cost of the manufacturer.

Proposition 3: For any given ordering quantity q, the optimal selling price p_d^* satisfies Equation (9) in the decentralized supply chain:

$$S\left(q,p^*\right)+p\frac{\partial S\left(q,p^*\right)}{\partial p}-\alpha\frac{\partial g\left(q,p^*\right)}{\partial p}=0 \tag{9}$$

Proof: Please see Appendix.

From Proposition 3, it shows that there exists the optimal selling price which can maximize the retailer's profit.

Proposition 4: For any given selling price p, the optimal ordering quantity q_d^* should satisfy:

$$\frac{\partial \pi_r\left(q^*,p\right)}{\partial q}=p\frac{\partial S\left(q^*,p\right)}{\partial q}-w-\alpha\frac{\partial g\left(q^*,p\right)}{\partial q}=0 \tag{10}$$

Proof: Please see Appendix.

Form Proposition 4, we can find that:

$$\frac{\partial \pi_r\left(q^*,p\right)}{\partial q}\neq\frac{\partial \pi_c\left(q^*,p\right)}{\partial q}$$

then, if the second condition of supply chain coordination is satisfied, it should be:

$$\frac{\partial \pi_r\left(q^*,p\right)}{\partial q}=\frac{\partial \pi_c\left(q^*,p\right)}{\partial q}$$

then, $w=c$, but in the decentralized supply chain, the profit of the manufacturer is zero, so it is unrealistic.

In the decentralized supply chain, the manufacturer, as a leader, may be increase the wholesale price in order to gain more profit. However, the retailer may reject the scenario, because the retailer must increase the selling price to maximize the profit, which may lead to decrease the sales. Hence, it is important for the manufacturer to design the contract mechanism to coordinate the decentralized system influenced by customer balking behavior. In order to solve the problem, we will analyze three contracts to coordinate the supply chain under customer balking behavior.

4.3. The Effects of Customer Balking on Centralized Decisions

Proposition 5: In the centralized supply chain, the profit function is strictly concave and increasing in the probability of a sale under customer balking when $0 < L < 1$ and other parameters are fixed.
Proof: Please see Appendix.

Proposition 5 shows that the probability of a sale under customer balking can increase the profit of centralized supply chain when $0 < L < 1$ and other parameters are fixed.

Proposition 6: The profit function of centralized supply chain is strictly concave and decreasing in the threshold of inventory under customer balking when $K > 0$.
Proof: Please see Appendix.

From Proposition 6, it can be seen that the threshold of inventory under customer balking can maximize the profit of supply chain when $K > 0$.

From Proposition 5 and 6, we can know that the parameters of customer balking lead to the disruption of the profit of supply chain, so we should consider the effects of the parameters of customer balking on the supply chain when the supply chain coordination is studied.

Lemma 1: The expected sales quantity is strictly concave and increasing in the probability of a sale when customer balking occurs.
Proof: Please see Appendix.

From Lemma 1, we can find that the probability of a sale when customer balking occurs can increase the expected sales quantity when $0 < L < 1$ and other parameters are fixed.

Corollary 1: The expected sales quantity has a positive correlation with *L*.
Lemma 2: The expected sales quantity is strictly concave and decreasing in the threshold of inventory under customer balking when $K > 0$.
Proof: Please see Appendix.

From Lemma 2, we can see that the threshold of inventory under customer balking can maximize the expected sales quantity when $K > 0$ and other parameters are fixed, but decreases as the threshold of inventory increases when customer balking occurs, so the expected sales quantity is maximum when *K* is minimum.

Corollary 2: The expected sales quantity has a negative correlation with *K*.

From Lemma 1 and 2, we can find that both the parameters of customer balking affect the expected sales, so the expected sales quantity is affected by not only the selling price and ordering quantity but also the parameters of customer balking.

Lemma 3: The expected reduced sales quantity is strictly convex and decreasing in the probability of a sale under customer balking.

Proof: Please see Appendix.

Lemma 3 shows that increasing the probability of a sale under customer balking can decrease the reduced sales quantity.

Corollary3: The relationship between the expected reduced sales and *L* is negative.
Lemma 4: The expected reduced sales quantity is strictly convex and increasing in the threshold of inventory *K* under customer balking.
Proof: Please see Appendix.

From Lemma 4, we can find that the expected reduced sales quantity is minimum when *K* is minimum, which means that the smaller is the threshold of inventory under customer balking, the smaller the expected reduced sales quantity is. Hence, we can reduce the threshold of inventory under customer balking in order to decrease the expected reduced sales quantity which is caused by customer balking.

Corollary4: The relationship between the expected reduced sales and *K* is positive.

5. COORDINATING SUPPLY CHAIN WITH THREE CONTRACTS

5.1. Coordination With Revenue Sharing-Only Contract

With revenue sharing-only contract, the manufacturer charges *w* per unit purchased for the retailer and the retailer sells the item *p* per unit, let ϕ be the quota of supply chain revenue that the retailer at the end of selling period, the retailer gives (1- ϕ) to the manufacturer. Then, the profit of the retailer π_r^1 and the profit of the manufacturer π_m^1 are shown as follows respectively:

$$\pi_r^1\left(q,p\right)=\varphi pS\left(q,p\right)-wq-\alpha g\left(q,p\right) \tag{11}$$

$$\pi_m^1\left(q,p\right)=\left(w-c\right)q+\left(1-\varphi\right)pS\left(q,p\right) \tag{12}$$

Proposition 7: Supply chain coordination can't be achieved by revenue sharing-only contract under customer balking and price-dependent demand.
Proof: Please see Appendix.

Because the retailer undertakes the total reduced cost of customer balking, but only gains a fraction of supply chain revenue, so the retailer only selects the lower selling price. The revenue sharing-only contract can't coordinate the supply chain, which had been proved by Cachon and Lariviere (2005), then, a better contract should be used to coordinate supply chain. Next section, we will propose the revenue and cost-sharing contract for coordinating supply chain.

5.2. Coordination With Revenue and Cost-Sharing Contract

In the section, the manufacturer not only shares the revenue of the retailer but also shares the cost of the retailer. Let ϕ be the fraction of revenue the retailer keeps and (1- β) be the fraction of cost under customer balking which the retailer keeps, then the expected profit of the retailer π_r^2 and the manufacturer π_m^2 are respectively:

$$\pi_r^2\left(q,p\right)=\varphi pS\left(q,p\right)-wq-\left(1-\beta\right)\alpha g\left(q,p\right) \tag{13}$$

$$\pi_m^2\left(q,p\right)=\left(w-c\right)q+\left(1-\varphi\right)pS\left(q,p\right)-\beta\alpha g\left(q,p\right) \tag{14}$$

Proposition 8: Supply chain can be coordinated when the coefficient of revenue and cost-sharing and the wholesale price satisfy Equations (15) and (16):

$$\varphi+\beta=1 \tag{15}$$

$$w=\varphi c \tag{16}$$

Proof: Please see Appendix.

From Proposition 8, we can find that the revenue and cost-sharing contract can coordinate the supply chain and the wholesale price is a constant fraction of production cost and less than production cost. Next section, we will analyze another mixed contract and compare the effectiveness of the contracts.

5.3. Coordination With Revenue Sharing Contract With Sales Rebate and Penalty (SRP)

In the section, the revenue sharing contract with SRP will be applied to coordinate supply chain in order to find the suitable contract for coordinating supply chain because the revenue sharing-only contract can't achieve coordination.

In the case of revenue sharing contract with SRP, the manufacturer sets up the goal of sales *T* and the retailer will obtain a rebate (τ) if the retailer sales quantity is greater than *T*, otherwise, the retailer will accept a penalty (τ). Then, the profit function of the retailer π_r^3 is:

$$\pi_r^3=\varphi pS\left(q,p\right)-wq-\alpha g\left(q,p\right)+\tau\left(S\left(q,p\right)-T\right) \tag{17}$$

where the term $\tau\left(S\left(q,p\right)-T\right)$ means that the retailer receives a reward when $S\left(q,p\right)\geq T$, otherwise, the retailer obtains a penalty.

Proposition 9: The revenue sharing contract with SRP can't coordinate supply chain.
Proof: Please see Appendix.

From Proposition 9, it can be seen that the revenue sharing contract with SRP can't coordinate supply chain which is the same as revenue sharing-only contract, but it is known that the revenue and cost-sharing contract can do it, that's because the revenue of the retailer is shared and the reduced cost due to customer balking is only undertaken by the retailer, so there is no equilibrium for the retailer if the cost can't be shared.

From the above coordination, it can be found that the revenue and cost-sharing contract can coordinate supply chain when there exists the cost for the retailer and the traditional contracts can't coordinate supply chain in the case.

6. MODEL OPTIMIZATION AND ANALYSIS

It is difficult to obtain the general solutions because there are implicit functions that have been built in above-mentioned models. Then, we want to find that the optimal ordering quantity and selling price exist in the models and analyze the effects of them on supply chain by numerical analysis.

In order to prove the applicability of the above models, we will optimize the models that have been built and prove the existing of the optimal solutions. In the section, we select the only additive demand model of price-dependent demand (Yu et al., 2013) and make them to easily analyze. It is obviously that the demand is a decreasing function of the selling price *p*. Next, we assume that the customer demand *x(p)* is in the following form:

$$x\left(p\right) = y\left(p\right) + \varepsilon$$

where *y(p)* reflects the effect of the selling price and is a decreasing and deterministic function of selling price, ε is a non-negative random variable defined on the range [A, B]. And it is assumed that $y\left(p\right) = a - bp$, where *a* is the item's potential demand and *b* is the sensitivity coefficient of selling price and ε is the random variable of the demand function and has the uniform distribution.

6.1. Analysis of Certain Parameters of Customer Balking

In this example, we assume that c = 6, *L* = 0.8, *K* = 20, $\alpha = 3$, a = 500, b = 6, ε~uniform [0,100].

In the centralized system, using Equation (4) and (6), we can prove that the selling price *p* can maximize the profit of supply chain and there is the optimal selling price when the profit of supply chain is maximum. Then, we derive that $p^* = 48.7$, $q^* = 295$, $\pi_c^{\max} = 10722.2$.

In the decentralized supply chain with coordination, using the coordination condition of $p^* = 48.7$ and $q^* = 295$, we assume that *w* and β are known when ϕ is known, the profits of supply chain members are shown in Table 2.

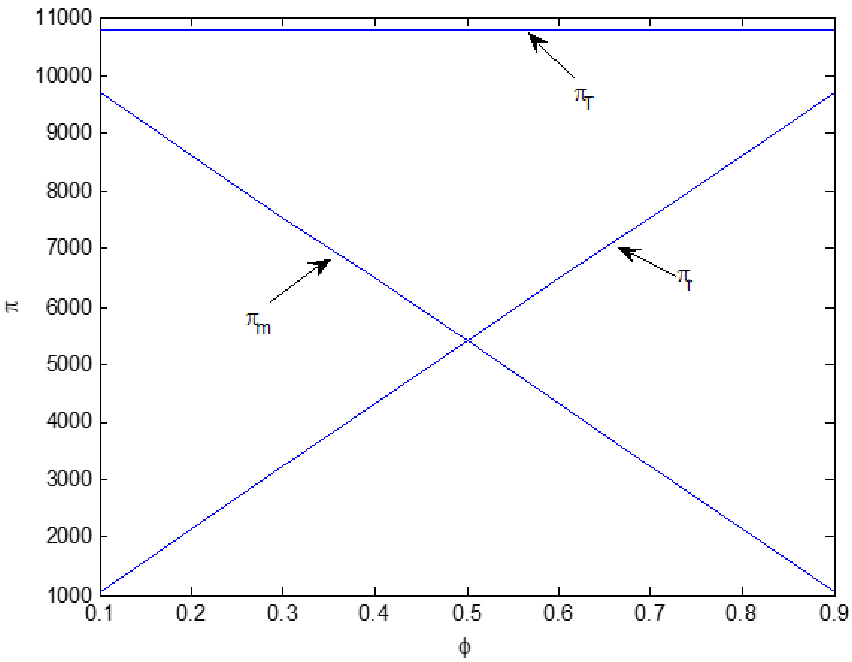
From Table 2, we can see that the profit of the retailer decreases as the revenue sharing coefficient increases, but the profit of the manufacturer increases as the revenue sharing coefficient increases and the total profit of supply chain is constant. When $\phi = \beta$, there is a Pareto-improvement scenario. In the scenario, we obtain that the revenue and cost-sharing contract can coordinate the supply chain perfectly, because not only can the supply chain improve its performance, but also the supply chain members can achieve the equilibrium.

In order to describe the effects of the coefficient of revenue sharing on the profit of supply chain intuitively, their relationships are shown in Figure 2. Figure 2 shows that the curve of the retailer's

Table 2. The results under coordination

φ	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
w	5.4	4.8	4.2	3.6	3	2.4	1.8	1.2	0.6
π_r^2	9702.99	8624.88	7546.77	6468.66	5390.55	4312.44	3234.33	2156.22	1078.11
π_m^2	1078.11	2156.22	3234.33	4312.44	5390.55	6468.66	7546.77	8624.88	9702.99
π_T	10781.1	10781.1	10781.1	10781.1	10781.1	10781.1	10781.1	10781.1	10781.1

Figure 2. Effects of ϕ on supply chain profit



profit intersects the curve of the manufacturer's profit at one point when $\phi = 0.5$ and the curve of the retailer's profit is above the curve of the manufacturer's profit when $\phi < 0.5$ and it is opposite when $\phi > 0.5$, but the curve of the total supply chain's profit is a straight line which indicates that the total supply chain's profit isn't affected by ϕ when other parameters are fixed.

6.2. Effects of *K* and *L* With Uncertainty on the Expected Sales Quantity

First, we assume that the probability of a sale under customer balking *L* is uncertain when $p = 48.7, q = 295, K = 20$ and other parameters are fixed, then we analyze the effects of *L* on the expected sales quantity.

From Equation (2), the relationship between the probability of a sale under customer balking and the expected sales quantity is shown in Table 3 and Figure 3.

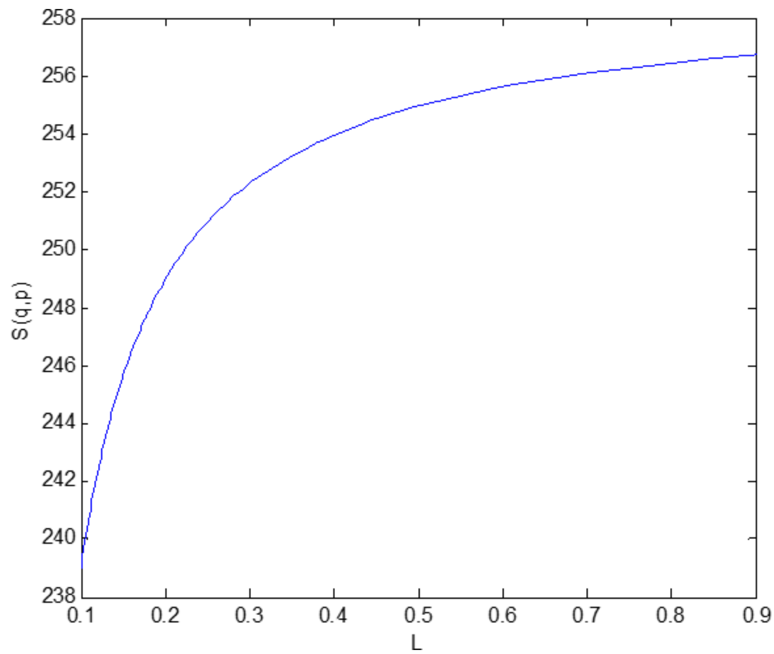
From Table 3 and Figure 3, we can see that the expected sales quantity is increasing in L, which is consistent with Lemma 1 and the relationship between the probability of a sale under customer balking and the expected sales quantity is non-linear and the increasing rate is getting slowly. In order to increase the expected sales, we can increase the probability of a sale under customer balking and the expected sales quantity is maximum when *L* is maximum.

Second, we assume that *K* is uncertain when other parameters are fixed and $p = 48.7, q = 295, L = 0.8$, then we analyze the effects of *K* on the expected sales quantity.

Table 3. The excepted sales quantity under uncertain

L	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$S(q,p)$	238.96	248.96	252.29	253.96	254.96	255.63	256.10	256.46	256.74

Figure 3. Effects of L on S(q,p)



From Equation (2), the relationship between the threshold of inventory udder customer balking and the expected sales quantity is shown in Table 4 and Figure 4.

In Figure 4, we can easily see that the relationship between the threshold of inventory under customer balking and the expected sales quantity is non-linear and the expected sales quantity is maximum when *K* is minimum, which is constant with Lemma 2.

In order to analyze the effect of *K* and *L* on *S(q,p)* simultaneously, we obtain Figure 5 by software of Matlab. From Figure 5, it can be seen that *S(q,p)* is affected by *K* and *L* intuitively: *S(q,p)* is obviously incremental when *K* is increased and *L* is reductive and is increasing if *K* is reductive and *L* is increased. It can be also seen that *S(q,p)* is not always positive.

So the parameters of customer balking are considered together in order to improve the excepted sales for managers.

6.3. Effects of *K* and *L* on the Expected Reduced Sales Quantity

First, we assume that the probability of a sale under customer balking is uncertain when $p = 48.7, q = 295, K = 20$ and other parameters are fixed, then we analyze the effects of *L* on the expected reduced sales quantity.

From Equation (3), the relationships between the probability of a sale under customer balking and the expected reduced sales quantity is shown in Table 5 and Figure 6.

Table 4. The excepted sales quantity with uncertain K

K	20	50	80	100	120	150	180	200	220
$S(q,p)$	256.5	253.9	249	244.5	239	228.9	216.5	207	196.5

Figure 4. Effects of K on S(q,p)

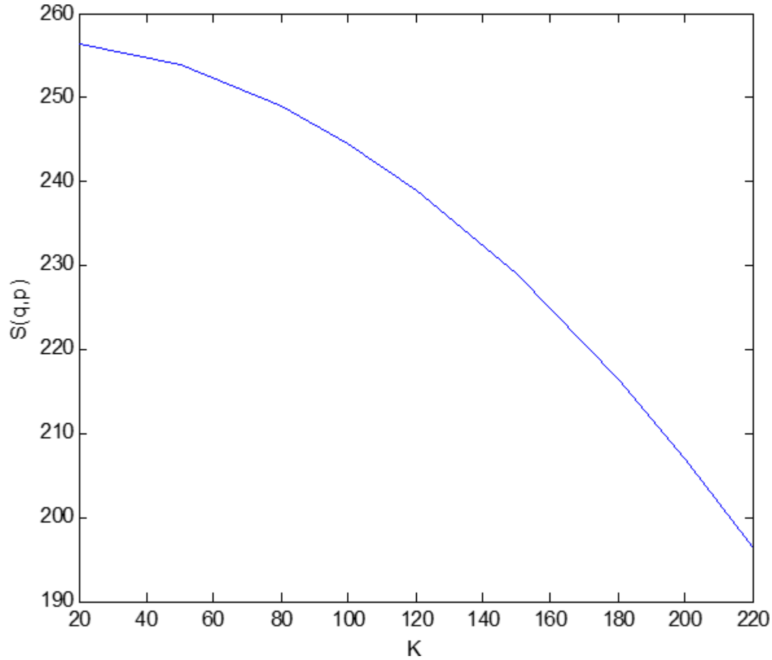


Figure 5. Effects of K and L on S(q,p)

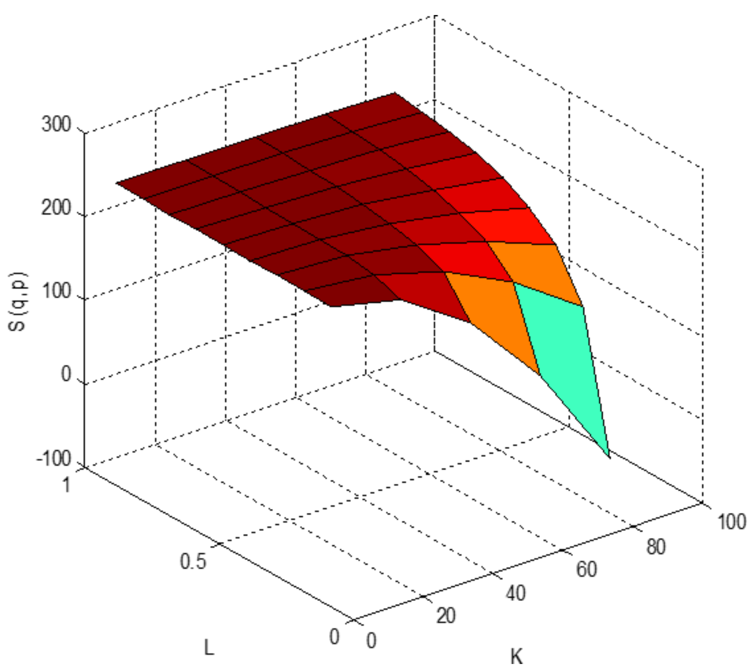
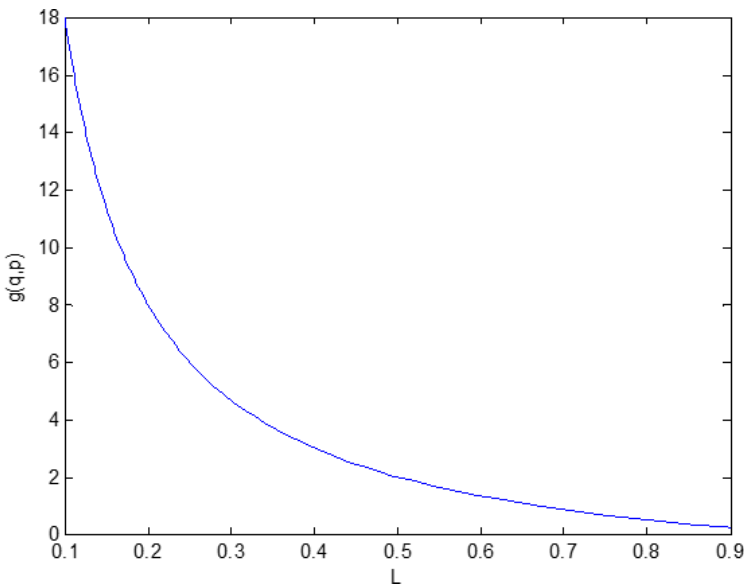


Table 5. The excepted reduced sales with uncertain L

L	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$g(q,p)$	18	8	4.7	3	2	1.3	0.9	0.5	0.2

Figure 6. Effects of L on g(q,p)



From Table 5 and Figure 6, we can see intuitively that the expected reduced sales quantity decreases as L increases, so we should increase the probability of a sale under customer balking in order to decrease the expected reduced sales when other parameters are fixed.

Next, we assume that the threshold of inventory under customer balking is uncertain when $p = 48.7, q = 295$, $L = 0.8$ and other parameters are fixed, then we analyze the effects of K on the expected reduced sales quantity.

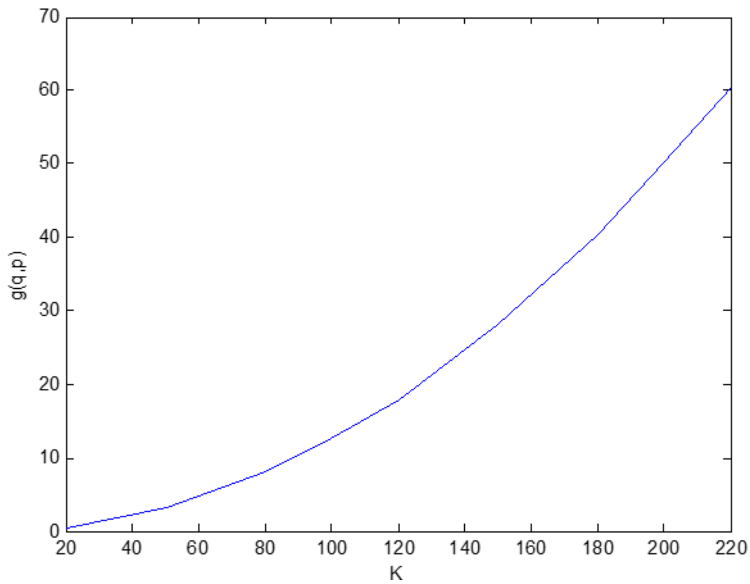
From Equation (3), the relationship between the threshold of inventory under customer balking and the expected reduced sales quantity is shown in Table 6 and Figure 7.

From Table 6 and Figure 7, it can be seen that the increasing rate of the expected reduced sales becomes faster as the threshold of inventory under customer balking increases and the minimum of the expected reduced sales quantity is zero when $K=0$, hence, in order to decrease the loss caused by customer balking, we should reduce the threshold of inventory under customer balking.

Table 6. The excepted reduced sales quantity with uncertain K

K	20	50	80	100	120	150	180	200	220
$g(q,p)$	0.5	3.125	8	12.5	18	28.125	40.5	50	60.5

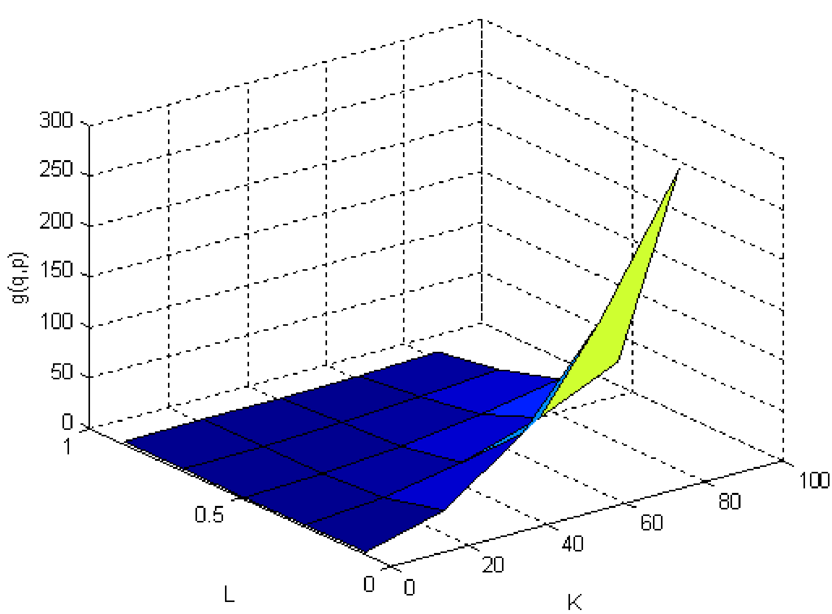
Figure 7. Effects of K on g(q,p)



From the effects of customer balking parameters with uncertainty on the expected reduced sales, we can find that the effects of L and K on the expected reduced sales are opposite and the above outcomes are constant with Lemma 3 and 4.

But the effects of K and L on the expected reduced sales quantity are more complex than that in the case of single parameter and it is practical that two parameters are analyzed together to obtain the mixed effects which are shown in Figure 8. From Figure 8, it can be known that the expected

Figure 8. Effects of K and L on g(q,p)



reduced sales quantity is always positive when $0 < L < 1, 0 < K < q$ and increasing when L is decreasing and K is increasing.

7. CONCLUSION

The paper makes use of the extended newsvendor model to investigate the coordination problems with centralized and decentralized supply chain under customer balking and price-dependent demand. It shows that the revenue and cost-sharing contract can coordinate supply chain better than the revenue sharing-only contract and revenue sharing contract with SRP, because the total profit of supply chain under the coordination condition is higher than that in the decentralized supply chain with no coordination and there is an equilibrium solution between the manufacturer and the retailer, so it is a Pareto-improvement scenario. Next, the effects of the uncertain parameters of customer balking on the expected sales quantity and expected reduced sales quantity are analyzed and it is found that the effects of the probability of a sale and threshold of inventory under customer balking on the expected sales quantity and expected reduced sales quantity are opposite. In the section of numerical analysis, it is also seen that the expected sales quantity is maximum when the probability of a sale under customer balking is maximum and the threshold of inventory under customer balking is minimum, but the expected reduced sales quantity is minimum when the probability of a sale under customer balking is maximum and the threshold of inventory under customer balking is minimum.

The paper suggests that the manufacturer and the retailer can be coordinated by special contracts under price-dependent demand and customer balking. It is also shown that the extensive newsvendor model under stochastic demand and customer balking can be applied in coordinating supply chain, which is innovative and the model of excepted reduced sales quantity is applied in supply chain, which is original. In addition, the managers can do better in work by optimizing the inventory when customer balking occurs.

Although the paper coordinates a two-echelon supply chain in the case of considering customer balking and also analyzes the effects of the parameters of customer balking on the supply chain, the model is more complex and difficult in the case of uncertain parameters of customer balking, so it doesn't consider all effects of customer balking in the paper and will have more work to do in the future. For example, can be the multi-echelon supply chain coordinated? Can other contracts coordinate the supply chain under customer balking? Are other parameters of the contract in the paper affected by the parameters of customer balking? It may have more anecdotal observations in the future and hopes that the findings of this paper are helpful for future work.

ACKNOWLEDGMENT

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APPENDIX: PROOF OF PROPOSITIONS

Proof of Proposition 1

For a given q, we take the first partial derivatives of Equation (4) with respect to p yields:

$$\frac{\partial \pi_c\left(q,p\right)}{\partial p} = S\left(q,p\right) + p\frac{\partial S\left(q,p\right)}{\partial p} - \alpha\frac{\partial g\left(q,p\right)}{\partial p} = 0 \tag{18}$$

Then, we take:

$$\frac{\partial \pi_c}{\partial p} = 0$$

$$S\left(p,q\right) + p\frac{\partial S\left(q,p\right)}{\partial p} - \alpha\frac{\partial g\left(q,p\right)}{\partial p} = 0$$

Proposition 1 is proved.

Proof of Proposition 2

For a given p, we take the first partial derivatives of Equation (4) with respect to q as zero and obtain:

$$\frac{\partial \pi_c\left(q,p\right)}{\partial q} = p\frac{\partial S\left(q,p\right)}{\partial q} - c - \alpha\frac{\partial g\left(q,p\right)}{\partial q} = 0 \tag{19}$$

while:

$$\begin{aligned}\frac{\partial S\left(q,p\right)}{\partial q} &= 1\text{-}F\left(\left(q-K\right)\middle|\,p\right)\text{-}LF\left(\left(q-K+K\,/\,L\right)\middle|\,p\right)+LF\left(\left(q-K\right)\middle|\,p\right)\\ &= 1\text{-}LF\left(\left(q-K+K\,/\,L\right)\middle|\,p\right)+\left(L\text{-}1\right)F\left(\left(q-K\right)\middle|\,p\right)\end{aligned} \tag{20}$$

$$\begin{aligned}\frac{\partial g\left(q,p\right)}{\partial q} &= L\left[F\left(\left(q-K+K\,/\,L\right)\middle|\,p\right)-F\left(\left(q-K\right)\middle|\,p\right)\right]-F\left(q\middle|\,p\right)\\ &= LF\left(\left(q-K+K\,/\,L\right)\middle|\,p\right)+\left(1+L\right)F\left(\left(q-K\right)\middle|\,p\right)-F\left(q\middle|\,p\right)\end{aligned} \tag{21}$$

Then, substituting (20) and (21) into (19), we have:

$$\left(1-L\right)\left(p+\alpha\right)F\left(\left(q-k\right)\middle|p\right)+L\left(p+\alpha\right)F\left(\left(q-K+K/L\right)\middle|p\right)-\alpha F\left(q\middle|p\right)=p-c$$

Proof of Proposition 3

For any given ordering quantity q, we take the first partial derivatives of Equation (11) with respect to p as zero, we can derive (22) as follows:

$$\frac{\partial \pi_r\left(q, p^*\right)}{\partial p} = S\left(q, p^*\right) + p\frac{\partial S\left(q, p^*\right)}{\partial p} - \alpha\frac{\partial g\left(q, p^*\right)}{\partial p} = 0 \quad (22)$$

From (22), we can see that:

$$\frac{\partial \pi_r\left(q, p^*\right)}{\partial p} = \frac{\partial \pi_c\left(q, p^*\right)}{\partial p}$$

hence, $p_d^* = p_c^*$, which satisfies the first condition of supply chain coordination.

Proof of Proposition 4

For any given selling price *p*, we take the first partial derivatives of Equation (12) with respect to *q* as zero, we can derive (23) as follows:

$$\frac{\partial \pi_r\left(q^*, p\right)}{\partial q} = p\frac{\partial S\left(q^*, p\right)}{\partial q} - w - \alpha\frac{\partial\left(q^*, p\right)}{\partial q} = 0 \quad (23)$$

From (23), it can be seen that Proposition 4 is proved.

Proof of Proposition 5

For any given ordering quantity *q*, we take the first partial derivatives of Equation (11) with respect to *p* as zero, it should be satisfied:

$$\frac{\partial \pi_r^1}{\partial p} = \varphi S\left(p^*, q\right) + \varphi p\frac{\partial S\left(p^*, q\right)}{\partial p} - \alpha\frac{\partial g\left(q, p^*\right)}{\partial p} = 0 \quad (24)$$

Because $0 < \phi < 1$, comparing (24) and (5), it can easily be derived that:

$$\frac{\partial \pi_r^1\left(q, p^*\right)}{\partial p} < \frac{\partial \pi_c\left(q, p^*\right)}{\partial p}$$

hence, the revenue sharing-only contract can't coordinate supply chain.

Proof of Proposition 6

Proof: We assume that:

$$\varphi + \beta = 1, w = \varphi c$$

then:

$$\begin{aligned}\pi_r^2\left(q,p\right) &= \varphi pS\left(q,p\right) - wq - \left(1-\beta\right)\alpha g\left(q,p\right) \\ &= \varphi pS\left(q,p\right) - \varphi cq - \varphi\alpha g\left(q,p\right) \\ &= \varphi\left[pS\left(q,p\right) - cq - \alpha g\left(q,p\right)\right] \\ &= \varphi\pi_c\left(q,p\right)\end{aligned} \tag{25}$$

It can be seen that the profit of the retailer is a constant fraction of the centralized supply chain's profit from (25), so the supply chain can be coordinated.

Proof of Proposition 7

We take the first partial derivatives and the second partial derivatives of Equation (4) with respect to *L*, then we have:

$$\begin{aligned}\frac{\partial\pi_c\left(q,p,L\right)}{\partial L} &= p\frac{\partial S\left(q,p,L\right)}{\partial L} - \alpha\frac{\partial g\left(q,p,L\right)}{\partial L} \\ &= -p\left[\int_{q-K}^{q-K+K/L} F\left(x\middle|p\right)dx\text{-} KF\left(\left(q-K+K/L\right)\middle|p\right)\Big/L\right] \\ &\quad -\alpha\left[\int_{q-K}^{q-K+K/L} F\left(x\middle|p\right)dx\text{-} KF\left(\left(q-K+K/L\right)\middle|p\right)\Big/L\right] \\ &= \left(p+\alpha\right)\left(KF\left(\left(q-K+K/L\right)\middle|p\right)\Big/L - \int_{q-K}^{q-K+K/L} F\left(x\middle|p\right)dx\right) \\ &= \left(p+\alpha\right)\int_{q-K}^{q-K+K/L}\left[x-\left(q-K\right)\right]f\left(x\middle|p\right)dx > 0\end{aligned} \tag{26}$$

$$\frac{\partial^2\pi_c\left(q,p,L\right)}{\partial^2 L} = -\frac{K^2\left(p+\alpha\right)}{L^3}f\left(\left(q-K+K/L\right)\middle|p\right) < 0$$

So, Proposition 7 is proved.

Proof of Proposition 8

We take the first partial derivatives and the second partial derivatives of Equation (4) with respect to *K* respectively and we have:

$$\begin{aligned}\frac{\partial\pi_c\left(q,p,K\right)}{\partial K} &= p\frac{\partial S\left(q,p,K\right)}{\partial K} - \alpha\frac{\partial g\left(q,p,K\right)}{\partial K} \\ &= p\left[F\left(\left(q-K\right)\middle|p\right) - \left(1-L\right)F\left(\left(q-K+K/L\right)\middle|p\right) - LF\left(\left(q-K\right)\middle|p\right)\right] \\ &\quad -\alpha\left(1-L\right)\left[F\left(\left(q-K+K/L\right)\middle|p\right)\text{-}F\left(\left(q-K\right)\middle|p\right)\right] \\ &= \text{-}\left(\text{1-L}\right)\left(p+\alpha\right)\left[F\left(\left(q-K+K/L\right)\middle|p\right)\text{-}F\left(\left(q-K\right)\middle|p\right)\right] < 0\end{aligned} \tag{27}$$

Hence, the profit of the centralized supply chain is decreasing in the threshold of inventory under customer balking. Then:

$$\frac{\partial^2 \pi_c\left(q,p,K\right)}{\partial^2 K} = -\left(1-L\right)\left(p+\alpha\right)\left[\frac{1-L}{L} f\left(\left(q-K+K/L\right)\middle| p\right) + f\left(\left(q-K\right)\middle| p\right)\right] \quad (28)$$

So, the profit of the centralized supply chain is strictly concave in the threshold of inventory under customer balking. Combining (27) and (28), Proposition 8 is proved.

Proof of Proposition 9

Taking the first-order derivatives of Equation (17) with respect to *p*, then the function is obtained as follows:

$$\frac{\partial \pi_r^3}{\partial p} = S\left(q,p^*\right) + \left(p+\tau\right)\frac{\partial S\left(q,p^*\right)}{\partial p} - \alpha\frac{\partial g\left(q,p^*\right)}{\partial p} \quad (29)$$

Comparing (18) and (29), it can be seen that the revenue sharing contract with SRP can't coordinate supply chain, because only when $\tau = 0$, Equation (18) is equal to Equation (29), but when $\tau = 0$, the revenue sharing contract with SRP is the same as the revenue sharing contract which can't coordinate supply chain.

Proof of Lemma 1

Taking the first partial derivatives of Equation (2) with respect to *L*, using Leibniz's rule and Fubini's theorem, and having:

$$\begin{aligned}\frac{\partial S\left(q,p,L\right)}{\partial L} &= -\left[\int_{q-K}^{q-K+K/L} F\left(x\middle|p\right)dx\text{-}KF\left(\left(q-K+K/L\right)\middle|p\right)\middle/L\right] \\ &= \text{-}\left(q-K\right)\left[F\left(\left(q-K+K/L\right)\middle|p\right)\text{-}F\left(\left(q-K\right)\middle|P\right)\right] + \int_{q-K}^{q-K+K/L} xf\left(x\middle|p\right)dx \\ &= \int_{q-K}^{q-K+K/L} xf\left(x\middle|p\right)dx\text{-}\int_{q-K}^{q-K+K/L}\left(q-K\right)f\left(x\middle|p\right)dx \\ &= \int_{q-K}^{q-K+K/L}\left[x-\left(q-K\right)\right]f\left(x\middle|p\right)dx > 0 \end{aligned} \quad (30)$$

$$\frac{\partial^2 S\left(q,p,k\right)}{\partial^2 L} = -\frac{K^2}{L^3} f\left(\left(q-K+K/L\right)\middle|P\right) < 0$$

The Lemma 1 is proved.

Proof of Lemma 2

Taking the first partial derivatives of Equation (2) with respect to *L* respectively and having:

$$\begin{aligned}&\frac{\partial S\left(q,p,K\right)}{\partial K} = F\left(\left(q-K\right)\middle|p\right) - \left(1-L\right)F\left(\left(q-K+K/L\right)\middle|p\right) - LF\left(\left(q-K\right)\middle|p\right) \\ &= \left(1\text{-L}\right)\left[F\left(\left(q-K\right)\middle|p\right)\text{-}F\left(\left(q-K+K/L\right)\middle|p\right)\right] < 0\end{aligned} \quad (31)$$

Because:

$$\frac{\partial S\left(q,p,K\right)}{\partial K}<0$$

so the expected sales quantity is decreasing in the threshold of inventory under customer balking.

And we take the second partial derivatives of (31) with respect to *K* and have:

$$\frac{\partial^2 S\left(q,p,k\right)}{\partial^2 K}=-\left(1-L\right)\left[f\left(\left(q-K\right)\middle|P\right)+\frac{1-L}{L}f\left(\left(q-K+K/L\right)\middle|P\right)\right]<0 \tag{32}$$

Lemma 2 is proved.

Proof of Lemma 3

Taking the first partial derivatives and the second partial derivatives of Equation (3) with respect to *L* and having:

$$\begin{aligned}\frac{\partial g\left(q,p,L\right)}{\partial L}&=\int_{q-K}^{q-K+K/L}F\left(x\middle|p\right)dx\text{-}KF\left(\left(q-K+K/L\right)\middle|p\right)\Big/L\\&=\left(q-K+K/L\right)F\left(\left(q-K+K/L\right)\middle|p\right)-\left(q-K\right)F\left(\left(q-K\right)\middle|P\right)-\int_{q-K}^{q-K+K/L}xf\left(x\middle|p\right)dx\\&=-\int_{q-K}^{q-K+K/L}\left[x-\left(q-K\right)\right]f\left(x\middle|p\right)dx<0\end{aligned}$$

$$\frac{\partial^2 g\left(q,p,L\right)}{\partial^2 L}=\frac{K^2}{L^3}f\left(\left(q-K+K/L\right)\middle|p\right)>0 \tag{33}$$

It can be seen that:

$$\frac{\partial g\left(q,p,L\right)}{\partial L}<0$$

and:

$$\frac{\partial g^2\left(q,p,L\right)}{\partial^2 L}<0$$

so Lemma 3 is proved.

Proof of Lemma 4

Taking the first partial derivatives of (3) with respect to K and having:

$$\begin{aligned}\frac{\partial g\left(q,p,K\right)}{\partial K}&=\left[F\left(\left(q-K+K/L\right)\middle|P\right)\left(-1+\frac{1}{L}\right)-F\left(\left(q-K\right)\middle|p\right)\times\left(-1\right)\right]-F\left(\left(q-K\right)\middle|P\right)\\&=\left(1-L\right)\left[F\left(\left(q-K+K/L\right)\middle|P\right)-F\left(\left(q-K\right)\middle|P\right)\right]>0\end{aligned} \tag{34}$$

And we take the second partial derivatives of (34) with respect to K and we derive:

$$\frac{\partial^2 g\left(q,p,L\right)}{\partial^2 L} = \left(1\text{-}L\right)\left[f\left(\left(q-K+K/L\right)\middle| p\right)+f\left(\left(q-K\right)\middle| p\right)\right]>0 \tag{35}$$

It can be seen that Lemma 4 is proved.

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