Product Quality Control Strategy of Dual Distribution Channel Structure in Three-Echelon Supply Chain

Lilong Zhu (zhulilong2008@126.com)
Shandong Normal University https://orcid.org/0000-0002-9697-3012
Bingjie Lu
Shandong Normal University

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Title Page

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Lilong Zhu[1,2*], Bingjie Lu[1,2]

[1] School of Business, Shandong Normal University, Ji'nan, 250014, China

[1] Quality Research Center, Shandong Normal University, Ji'nan, 250014, China

* Corresponding author.

E-mail: zhulilong2008@126.com. Tel: +86-531-13853193366

Lilong Zhu, Ph.D. and Professor

Postdoctoral research in Shandong University, Ph.D. degree was granted in management science and engineering in Tongji University, Research scholar in College of Business, University of Illinois at Urbana-Champaign, USA, Visiting scholar in Tsinghua University, China. His research interests are product quality management in supply chain.

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Abstract

Based on the three-stage Stackelberg dynamic game model, this paper considers how to make product quality control strategy in the three-echelon supply chain consisting of the manufacturer, retailer and customer in the case of retailer dual channel structure (traditional retail channel, internet channel) and manufacturer dual channel structure (traditional retail channel, a third-party platform internet channel). When there are two types of decision model (decentralized decision, centralized decision), we analyze the demand price elasticity, market share ratio, revenue sharing ratio and quality cost coefficient how to influence the product demand, product quality level, retail price and direct price in different channels, expected revenue functions of manufacturer and retailer, consumer surplus and product quality control strategy. We find that: First of all, the retail price and direct price are positively related to product quality level, and the product quality level is negatively related with the demand price elasticity in traditional retail channel and the demand price elasticity in internet channel. What's more, the retailers' retail price in traditional retail channel will be higher than direct price in internet channel. Thirdly, in the case of centralized decision, the manufacturers' product quality level, retail price, joint expected revenue and consumer surplus will all rise, but the direct price will fall. Fourthly, when the manufacturer establishes the dual channel structure, i.e., entrusting the third-party platform to build the internet channel, the manufacturer's product quality level, retail price, direct price, expected revenue, and consumer surplus will all decline. Finally, we conduct the numerical example by Matlab 2018, which verifies the validity and credibility of our conclusions, and points out the direction for the specific application of the model in practice.

Key words: dual channel structure; three-echelon supply chain; Stackelberg dynamic game; product quality control strategy; simulation analysis

1 Introduction

In recent years, with the rise of internet economy and e-commerce, more and more customers or consumers choose to buy products in internet channel. In 2018, e-commerce transactions in 28 major countries and regions reached 24.72 trillion USD, with online retail transactions totaling 2.97 trillion USD (*Global E-commerce Data Report 2019*). In the fourth quarter of 2019, U.S. e-commerce retail sales grew 16.4 percent to 187 billion USD, and reached 602 billion USD for the full year (U.S. Department of Commerce on February 19, 2020). In 2019, the amount of Chinese online retail sales has exceeded 1.62 trillion USD, up 16.5 percent from 2018 (the Chinese Ministry of Commerce on June 30, 2020). On November 11, 2020, Tmall's "Double Eleven" sales reached 76.2 billion USD, a year-on-year increase of 26%; JD Mall's "Double Eleven" sales also reached 41.53 billion USD, a year-on-year increase of 32.8% (Chinanews.com on November 12, 2020). So, we can see that in addition to traditional retail channel, internet channel has gradually become an important way for product sales in the supply chain.

With the changing of customers or consumers' buying behavior, more and more enterprises begin to redesign or construct their distribution channel structures. For example, HP, Nike, Lenovo, Suning and Gome have opened internet channel in addition to traditional retail channel. Dell and Xiaomi, which used to focus on internet channel, are now beginning to sell products in traditional retail channel. While Apple and Haier have sold products in both traditional retail channel and internet channel from the beginning.

However, there are still some unresolved problems in the exploration of theory and practice. Firstly, how to construct different distribution channels and their influence on product quality decision in the three-echelon supply chain; What's more, influence on making product quality control strategy when the retailer establishes the dual channel structure or the manufacturer establishes the dual channel structure; Thirdly, when the manufacturer entrusts the third-party platform to build the internet channel or the retailer establishes the dual channel structure, how to influence the product quality, retail price and direct price; Finally, the influence of price demand elasticity in different distribution channels on product quality decision, price decision, expected revenue functions, and

consumer surplus of the customer.

In this paper, we construct the three-stage Stackelberg dynamic game model and consider how to make product quality control strategy in the three-echelon supply chain when the retailer establishes the dual channel structure or the manufacturer establishes the dual channel structure. When there are decentralized decision and centralized decision, we analyze the demand price elasticity, market share ratio, revenue sharing ratio and quality cost coefficient how to influence the product demand, product quality level, retail price and direct price in different channels, expected revenue functions of manufacturer and retailer, consumer surplus and product quality control strategy.

The rest of our paper is organized as follows. In section 2, we review relevant literatures and we describe our model and make hypotheses in section 3. In section 4, we analyze the case that the retailer establishes the dual channel structure under decentralized decision and centralized decision. In section 5, we analyze the case that the manufacturer establishes the dual channel structure. We use Matlab 2018 to conduct numerical analysis in section 6. Finally, section 7 gives conclusions and future research direction.

2 Literature Review

At present, scholars around the world have conducted a great deal of researches on how to establish different distribution channel structures in the three-echelon supply chain, and how to formulate product quality control strategy under different distribution channel structures and two decision models (decentralized decision and centralized decision), mainly in the following three aspects.

The first aspect is mainly about the influence of distribution channels in the supply chain on product quality, selling price, corporate profits and consumer surplus. Chen J.X., et al. (2017) employ two themes in terms of channel-adding Pareto zone to characterize the impacts of channel structures on supply-chain performance, including the whole system's profit, each player's profit, and consumer surplus. Modak N.M., et al. (2019) examine a dual-channel supply chain under price and delivery-time dependent stochastic customer demand and find that uncertainty frequently arises in both retail and online channels which has an effect on the optimal order quantity and price. Tian L. and Jiang B.J. (2018) study

how consumer-to-consumer product sharing in the supply chain affects the strategic choice of distribution channels, as well as the impact on manufacturers' profits and consumer surplus. Matsui K. (2017) apply an observable delay game framework developed in noncooperative game theory, investigate the timing problem concerning when a manufacturer managing dual-channel supply chains, consisting of a retail channel and a direct channel, should post its wholesale price and direct price. Wong H., et al. (2019) find that manufacturers adopt generic strategic choices in decentralized channel can reduce channel efficiency losses, and analyze its impact on channel profits and consumer surplus. Zhang J.Q., et al. (2019) consider the case that manufacturers establish a direct platform channel to reach customers directly and study the interrelationship between a platform's contract choice and a manufacturer's product quality decision.

The second aspect is about the strategic choices and decisions of different distribution channels, as well as the impact on channel coordination. Many scholars studied the distribution channel structure (Wang L.S., et al., 2017), mainly including direct channel structure (Wang C.X., et al., 2018), indirect channel structure (Luo Z., et al., 2018 and Dey L., et al., 2019) and mixed channel structure (Yan N.N., et al., 2020). Guo S.S. and Heese H.S. (2017) investigate how the manufacturer's optimal product variety decision differs when selling directly to customers (centralized decision) as compared to selling through a retailer (decentralized decision). Yang Z.B., et al. (2018) study the optimal distribution strategy of a supplier with limited capacity and find the supplier may adopt the supplier-only role, be the solo seller in the market, or use the dual-channel strategy and compete with its downstream buyer. Chen X., et al. (2017) examine how a direct channel added by a manufacturer can influence the decisions of the retailer and the manufacturer and further propose a retailer's margin contract that can coordinate the dual-channel supply chain and ensure that both the retailer and the manufacturer will be more profitable. Feng L.P., et al. (2017) investigate two problems that are comprised of designing and coordinating a reverse supply chain with a traditional and an online recycling channel and in the coordination problem, a contract with transfer and online recycling prices can coordinate the dual-recycling channel reverse supply chain but harms the dealer. Lan Y.Q., et al. (2018) show that the dual-channel system benefits the manufacturer and the retailer if

the level of demand uncertainty exceeds a threshold and that the competition between the two distributors leads to the coordination of the downstream supply chain (the two distributors and the retailer). Rahmani K., et al. (2019) investigate the demand disruption management in a dual-channel supply chain producing and selling green products for the first time and results reveal that when the disruption increases the market scale, or when the greening cost decreases, the optimal prices will be increased in both decision-making structures. Song B.Q. et al. (2020) study dynamic channel control and pricing of a single perishable product distributed through multiple channels and the results show that, the magnitude of the opportunity cost of capacity uniquely determines the optimal channel control.

The third aspect is about how to prevent product quality risks in the strategies of supply chain distribution channels. Liu Y., et al. (2018) study that the uncertainty of market size will reduce the difference of product quality and determine the optimal product quality level in the centralized and decentralized distribution channel structure. Sarkar B., et al. (2016) discuss how to make product quality decision in different distribution channel strategies and how to prevent channel quality risks by building product quality decision model. Zhang J.Q., et al. (2019) analyze the relationship between platform contract selection and manufacturer's product quality decision when online sales channels exist in the supply chain, and further discuss the influence of platform sales and contract design on reducing product quality risks by building a revenue sharing model. Huang H.F., et al. (2019) develop game-theoretic models for a supply chain with a manufacturer and a PI (parallel importer), in which the manufacturer needs to determine distribution structure, product quality, and retail price and find that the advertising effect may motivate the manufacturer to improve product quality. Zhang J.X., et al. (2019) show that manufacturer encroachment leads to a lower quality when the manufacturer's direct selling cost is intermediate and compared to the full and no information cases, asymmetric information may increase quality when direct selling is relatively efficient while decrease quality otherwise. Jabarzare N. and Rasti-Barzoki M. (2020) investigate how the packaging company can influence the quality of products through packaging products in a dual-channel supply chain and find that from quality-seeking customers' perspective, the

cooperation of manufacturer and packaging company under profit-sharing contract is more preferable. Zhu L.L. (2011, 2020) analyzes three types of distribution channels strategy (direct channel, retail channel and mixed channel) in the context of how they influence a manufacturer's product quality decision and quality prevention strategy and focuses on how to control product quality and design quality contract in supply chain when moral hazard exists, which proposing suggestions for quality control strategy and contract design in the supply chain under the conditions of asymmetric information.

Therefore, compared with previous scholars, this paper is mainly different in the following three aspects. Firstly, based on the three-stage Stackelberg dynamic game, this paper constructs the product quality control strategy model in the three-echelon supply chain consisting of the manufacturer, retailer and customer and analyzes the influence of retailer dual channel structure (traditional retail channel, internet channel) and manufacturer dual channel structure (traditional retail channel, a third party-platform internet channel) on product quality decision. Then, when there are decentralized decision and centralized decision, we discuss the demand price elasticity, market share ratio, revenue sharing ratio and quality cost coefficient how to influence the product demand, product quality level, retail price and direct price in different channels, expected revenue functions of manufacturer and retailer, consumer surplus and product quality control strategy. Finally, we use Matlab 2018 for simulation analysis，pointing out the direction for the practical application of this model.

3 Model Description and Hypotheses

In this paper, we construct the three-echelon supply chain consisting of the manufacturer, retailer, third-party platform and customer and make the following hypotheses.

H1. The manufacturer, retailer, third-party platform and customer are risk neutral.

H2. There are two dual channel structures which are the retailer dual channel structure (traditional retail channel, internet channel) and the manufacturer dual channel structure (traditional retail channel, a third party-platform internet channel).

H3. The manufacturer has two decision models to choose which are decentralized

decision and centralized decision.

H4. The manufacturer determines the quality level and wholesale price. The retailer determines the retail price and when it establishes the internet channel, it determines direct price. The customer determines product demand.

H5. In the dual channel structure, the demand price elasticity coefficient is different between traditional retail channel and internet channel.

H6. In the distribution channel strategy of supply chain, both the manufacturer and the retailer pursue the maximization of expected revenue, and the customer pursues the maximization of consumer surplus.

The relevant variables and parameters are described as follows.

q : Manufacturer's product quality level, $q \in [0, +\infty)$.

w : Manufacturer's product wholesale price.

$C(q)$: Manufacturer's product production cost. $C(q) = kq^2 / 2$, so $C^{'}(q) > 0$ $C^{''}(q) > 0$, and k is product quality cost coefficient.

p_r : Product retail price in traditional retail channel.

p_e : Product direct price in internet channel.

The customer's demand function in traditional retail channel is $Q_r = \alpha M - \eta_r p_r / q$.

The customer's demand function in internet channel is $Q_e = (1-\alpha)M - \eta_e p_e / q$.

M is the maximum demand of the customer, α is market share ratio in traditional retail channel, η_r is product price elasticity coefficient in traditional retail channel, η_e is product price elasticity coefficient in internet channel, and the customer is more price sensitive in internet channel, so $\eta_e > \eta_r$.

λ : Revenue sharing ratio between manufacturer and the third-party platform.

The customer's consumer surplus is $vq - p_i . v \sim U(0, M)$ and $f(v)$ is probability density. So, the relationship of dual channel structure constructed in this paper is shown in Figure 1.

(Figure 1 The relationship of dual channel structure)

Case 1 When the retailer establishes the dual channel structure, the sequence of three-stage Stackelberg dynamic game is as follows.

Stage 1, the manufacturer determines the product quality level. *Stage 2*, the manufacturer determines the wholesale price. *Stage 3*, the retailer determines the retail price in traditional retail channel and the direct price in internet channel respectively.

Case 2 When the manufacturer establishes the dual channel structure, the sequence of three-stage Stackelberg dynamic game is as follows.

Stage 1, the manufacturer determines the product quality level. *Stage 2*, the manufacturer determines the wholesale price in traditional retail channel and revenue sharing ratio in internet channel respectively. *Stage 3*, the retailer determines the retail price and the third-party platform determines the direct price.

4 The Retailer Dual Channel Structure

4.1 Decentralized Decision

When the retailer establishes the dual channel structure (traditional retail channel, internet channel), in the case of decentralized decision (manufacturer and retailer make independent decision respectively), first of all, the manufacturer determines the product quality level, then the wholesale price. The retailer determines the retail price in traditional retail channel and the direct price in internet channel respectively. Therefore, we construct the Stackelberg game model of manufacturer and retailer, which is as follows.

$$MaxE\Pi_M(q,w)=(w-kq^2/2)[M-(\eta_r p_r+\eta_e p_e)/q] \quad (1)$$

$$s.t.\{p_r,p_e\}=\arg MaxE\Pi_R(p_r,p_e) \quad (2)$$

$$MaxE\Pi_R(p_r,p_e)=(p_r-w)(\alpha M-\eta_r p_r/q)+(p_e-w)[(1-\alpha)M-\eta_e p_e/q] \quad (3)$$

Equation (1) is the manufacturer's expected revenue function. Equation (3) is the retailer's expected revenue function.

Proposition 1 When the retailer establishes the dual channel structure, in the case of decentralized decision, the retail price in traditional retail channel and the direct price in internet channel are positively related to product quality level (i.e., increasing function).

The product quality level is negatively related to demand price elasticity in traditional retail channel and demand price elasticity in internet channel (i.e., decreasing function). So, the optimal product quality level is $q^{D^*} = 2M/[3k(\eta_r + \eta_e)]$.

Proof Use *backwards induction method* to solve, and take the first and second partial derivatives of equation (3) with respect to p_r and p_e respectively, and get

$$\partial E\Pi_R / \partial p_r = \alpha M + \eta_r w/q - 2\eta_r p_r/q = 0,\ \partial^2 E\Pi_R / \partial p_r^2 = -2\eta_r/q < 0 \quad (4)$$

$$\partial E\Pi_R / \partial p_e = (1-\alpha)M + \eta_e w/q - 2\eta_e p_e/q = 0,\ \partial^2 E\Pi_R / \partial p_e^2 = -2\eta_e/q < 0 \quad (5)$$

From equations (4) and (5), we get

$$p_r = \alpha Mq/(2\eta_r) + w/2 \quad (6)$$

$$p_e = (1-\alpha)Mq/(2\eta_e) + w/2 \quad (7)$$

Take the first partial derivative of equations (6) and (7) with respect to q respectively, and get

$$\partial p_r / \partial q = \alpha M/(2\eta_r) > 0 \quad \text{(increasing function)} \quad (8)$$

$$\partial p_e / \partial q = (1-\alpha)M/(2\eta_e) > 0 \quad \text{(increasing function)} \quad (9)$$

Substitute equations (6) and (7) into equation (1), and get

$$E\Pi_M(q,w) = (w - kq^2/2)[M/2 - (\eta_r + \eta_e)w/2q] \quad (10)$$

Take the first partial derivative of equation (10) with respect to w, and get

$$w = Mq/2(\eta_r + \eta_e) + kq^2/4 \quad (11)$$

Substitute equation (11) into equation (10), and get

$$E\Pi_M(q) = [Mq/2(\eta_r + \eta_e) - kq^2/4][M/4 - (\eta_r + \eta_e)kq/8] \quad (12)$$

Take the first and second partial derivative of equation (12) with respect to q, and get

$$q_1 = 2M/[k(\eta_r + \eta_e)] \quad \text{or} \quad q_2 = 2M/[3k(\eta_r + \eta_e)] \quad (13)$$

$$\partial^2 E\Pi_M(q)/\partial q^2 = 3k^2(\eta_r + \eta_e)q/16 - Mk/4 < 0 \quad \text{(concave function)}$$

$$q < 4M/[3k(\eta_r + \eta_e)] \quad (14)$$

From equations (13) and (14), we get

$$q^{D^*} = 2M / [3k(\eta_r + \eta_e)] \quad (15)$$

From equation (15), we get

$$\partial q^{D^*} / \partial \eta_r = -2M / 27k^2(\eta_r + \eta_e)^2 < 0 \quad \text{(decreasing function)}$$

$$\partial q^{D^*} / \partial \eta_e = -2M / 27k^2(\eta_e + \eta_r)^2 < 0 \quad \text{(decreasing function)}$$

QED.

Proposition 1 indicates that when the retailer establishes the dual channel structure, in the case of decentralized decision, the retail price in traditional retail channel and the direct price in internet channel increase with the product quality level improving (i.e., increasing function, positive correlation); the product quality level will decrease with demand price elasticity in traditional retail channel and demand price elasticity in internet channel increasing (i.e., decreasing function, negative correlation).

Proposition 2 The retailer's expected revenue function is a joint concave function about the retail price and direct price and the stationary point $\{p_r^{D^*}, p_e^{D^*}\}$ will make $E\Pi_R^{D^*}$ take the maximum. $p_r^{D^*} > p_e^{D^*}$,which indicates that the retail price in traditional retail channel will be higher than the direct price in internet channel.

Proof Solve the Hessian matrix of equation (3) about p_r and p_e, and get

$$H = \begin{bmatrix} \partial^2 E\Pi_R / \partial p_r^2 & \partial^2 E\Pi_R / \partial p_r \partial p_e \\ \partial^2 E\Pi_R / \partial p_e \partial p_r & \partial^2 E\Pi_R / \partial p_e^2 \end{bmatrix} = \begin{bmatrix} -2\eta_r / q & 0 \\ 0 & -2\eta_e / q \end{bmatrix}$$

The first-order principal minor of the matrix H is less than zero and the second-order principal minor is greater than zero, which shows that H is a negative definite matrix.

$E\Pi_R$ is a joint concave function and it has local maximum.

Substitute equation (15) into equation (11), and get

$$w^{D^*} = 4M^2 / 9k(\eta_r + \eta_e)^2 \quad (16)$$

Substitute equations (15) and (16) into equations (6) and (7), and get

$$p_r^{D^*} = \alpha M^2 / 3k\eta_r(\eta_r + \eta_e) + 2M^2 / 9k(\eta_r + \eta_e)^2 \quad (17)$$

311 $$p_e^{D^*} = (1-\alpha)M^2 / 3k\eta_e(\eta_r + \eta_e) + 2M^2 / 9k(\eta_r + \eta_e)^2 \quad (18)$$

312 Compare equation (17) with equation (18), and get

313 $$p_r^{D^*} - p_e^{D^*} > 0, \quad p_r^{D^*} > p_e^{D^*}$$

314 QED.

315 Proposition 2 indicates that the retailer's expected revenue function is a joint concave
316 function about the retail price and direct price. So, there are optimal retail price and
317 optimal direct price to make the retailer's expected revenue maximum and the retail price
318 in traditional retail channel will be higher than the direct price in internet channel, which is
319 consistent with the actual situation.

320 **Corollary 2.1** The expected revenue functions of manufacturer and retailer are
321 negatively related to the demand price elasticity in traditional retail channel and the
322 demand price elasticity in internet channel respectively (i.e., decreasing function).

323 ***Proof*** Substitute equations (15), (16), (17) and (18) into equations (1) and (3), and get

324 $$E\Pi_M^{D^*} = M^3 / 27k(\eta_r + \eta_e)^2 \quad (19)$$

325 $$E\Pi_R^{D^*} = [\eta_e\alpha^2 + \eta_r(1-\alpha)^2]M^3 / [6k\eta_r\eta_e(\eta_r + \eta_e)] - 4M^3 / 27k(\eta_r + \eta_e)^2 \quad (20)$$

326 Take the first partial derivative of equations (19) and (20) with respect to η_r and η_e
327 respectively, and get

328 $\partial E\Pi_M^{D^*} / \partial\eta_r < 0$、$\partial E\Pi_M^{D^*} / \partial\eta_e < 0$ (negative correlation, decreasing function)

329 $\partial E\Pi_R^{D^*} / \partial\eta_r < 0$、$\partial E\Pi_R^{D^*} / \partial\eta_e < 0$ (negative correlation, decreasing function)

330 QED.

331 Corollary 2.1 indicates that the expected revenue functions of manufacturer and
332 retailer will decrease with the demand price elasticity in traditional retail channel and the
333 demand price elasticity in internet channel increasing.

334 So, the customer's consumer surplus is

335 $$CS^{D^*} = \int_0^{\alpha M} (vq^{D^*} - p_r^{D^*}) f(v)dv + \int_{\alpha M}^{M} (vq^{D^*} - p_e^{D^*}) f(v)dv$$

336 $$= [\eta_r\eta_e - \eta_e\alpha^2 - \eta_r(1-\alpha)^2]M^2 / [3k\eta_r\eta_e(\eta_r + \eta_e)] - 2M^2 / 9k(\eta_r + \eta_e)^2 \quad (21)$$

CS^{D^*} is the customer's consumer surplus when retailer establishes the dual channel structure in the case of decentralized decision.

4.2 Centralized Decision

The manufacturer and the retailer make centralized decision, which is the manufacturer and the retailer make joint decision, and the supply chain system composed of the manufacturer and the retailer is vertically integrated. So, we construct the supply chain system decision model composed of the manufacturer and the retailer, the model is as follows.

$$MaxE\Pi_{MR}(q, p_r, p_e) = (p_r - kq^2/2)(\alpha M - \eta_r p_r / q) + (p_e - kq^2/2)[(1-\alpha)M - \eta_e p_e / q] \quad (22)$$

Equation (22) is supply chain joint expected revenue function.

Proposition 3 In the case of centralized decision, the manufacturer and the retailer make joint decision. The manufacturer's product quality level will be higher than that in the case of decentralized decision, i.e. $q^{C^*} > q^{D^*}$.

Proof Use *backwards induction method* to solve, and take the first partial derivative of equation (22) with respect to p_r and p_e respectively, and get

$$p_r = \alpha Mq/(2\eta_r) + kq^2/4 \quad (23)$$

$$p_e = (1-\alpha)Mq/(2\eta_e) + kq^2/4 \quad (24)$$

Solve the Hessian matrix of equation (22) about p_r, p_e and q, and get

$$H = \begin{bmatrix} \partial^2 E\Pi_{MR}/\partial p_r^2 & \partial^2 E\Pi_{MR}/\partial p_r \partial p_e & \partial^2 E\Pi_{MR}/\partial p_r \partial q \\ \partial^2 E\Pi_{MR}/\partial p_e \partial p_r & \partial^2 E\Pi_{MR}/\partial p_e^2 & \partial^2 E\Pi_{MR}/\partial p_e \partial q \\ \partial^2 E\Pi_{MR}/\partial q \partial p_r & \partial^2 E\Pi_{MR}/\partial q \partial p_e & \partial^2 E\Pi_{MR}/\partial q^2 \end{bmatrix} = \begin{bmatrix} -2\eta_r/q & 0 & k\eta_r/2 + 2\eta_r p_r/q^2 \\ 0 & -2\eta_e/q & k\eta_e/2 + 2\eta_e p_e/q^2 \\ k\eta_r/2 + 2\eta_r p_r/q^2 & k\eta_e/2 + 2\eta_e p_e/q^2 & -kM - 2(\eta_r p_r^2 + \eta_e p_e^2)/q^3 \end{bmatrix}$$

The first-order principal minor of the matrix H is less than zero, the second-order principal minor is greater than zero and the third-order principal minor is less than zero, which shows that H is a negative definite matrix.

$E\Pi_{MR}$ is a joint concave function.

Substitute equations (23) and (24) into equation (22), and get

$$E\Pi_{MR}(q) = (\alpha Mq/2\eta_r - kq^2/4)(\alpha M/2 - \eta_r kq/4) + ((1-\alpha)Mq/2\eta_e - kq^2/4)[(1-\alpha)M/2 - \eta_e kq/4] \quad (25)$$

Take the first and second partial derivative of equation (25) with respect to q, and get

$$q_1 = 2M(2-\sqrt{\varepsilon})/[3k(\eta_r+\eta_e)] \quad \text{or} \quad q_2 = 2M(2+\sqrt{\varepsilon})/[3k(\eta_r+\eta_e)] \tag{26}$$

$$\partial^2 E\Pi_{MR}(q)/\partial q^2 = 3k^2(\eta_r+\eta_e)q/8 - Mk/2 < 0 \text{（concave function）} \tag{27}$$

$$q < 4M/[3k(\eta_r+\eta_e)] \tag{28}$$

From equations (26) and (28), we get

$$q^{C^*} = 2M(2-\sqrt{\varepsilon})/[3k(\eta_r+\eta_e)] \tag{29}$$

$$\varepsilon = [4\eta_r\eta_e - 3(\eta_r+\eta_e)(\eta_e\alpha^2+\eta_r(1-\alpha)^2]/\eta_r\eta_e$$

$$0<\alpha<1,\quad 0<(1-\alpha)<1,\quad \eta_r<\eta_e$$

$$\varepsilon<1$$

Compare equation (29) with (15), and get

$$q^{C^*} = 2M(2-\sqrt{\varepsilon})/[3k(\eta_r+\eta_e)] > 2M/[3k(\eta_r+\eta_e)] = q^{D^*} \tag{30}$$

QED.

Proposition 3 indicates that when the retailer establishes the dual channel structure, in the case of centralized decision, the manufacturer's product quality level will be higher than that in the case of decentralized decision.

From proposition 3, we can get the following corollaries.

Corollary 3.1 The price in traditional retail channel will rise, i.e. $p_r^{C^*} > p_r^{D^*}$. The price in internet channel will fall, i.e. $p_e^{C^*} < p_e^{D^*}$.

Proof Substitute equation (29) into equations (23) and (24) respectively, and get

$$p_r^{C^*} = \alpha M^2(2-\sqrt{\varepsilon})/[3k\eta_r(\eta_r+\eta_e)] + M^2(2-\sqrt{\varepsilon})^2/[9k(\eta_r+\eta_e)^2] \tag{31}$$

$$p_e^{C^*} = (1-\alpha)M^2(2-\sqrt{\varepsilon})/[3k\eta_e(\eta_r+\eta_e)] + M^2(2-\sqrt{\varepsilon})^2/[9k(\eta_r+\eta_e)^2] \tag{32}$$

Compare equations (31) and (32) with equations (17) and (18) respectively, and get

$$p_r^{C^*} - p_r^{D^*} > 0,\quad p_e^{C^*} - p_e^{D^*} < 0$$

$$p_r^{C^*} > p_r^{D^*},\quad p_e^{C^*} < p_e^{D^*}$$

QED.

Corollary 3.1 indicates that when the retailer establishes the dual channel structure, compared with decentralized decision, centralized decision make the price in traditional retail channel increase, but make the price in internet channel decrease.

Corollary 3.2 In the case of centralized decision, the supply chain system joint expected revenue will higher than the sum of the expected revenues of the manufacturer and the retailer in the case of decentralized decision, i.e., $E\Pi_{MR}^{C*} > E\Pi_{M}^{D*} + E\Pi_{R}^{D*}$.

Proof Substitute equations (29), (31) and (32) into equation (22), and get

$$E\Pi_{MR}^{C*} = M^3(2-\sqrt{\varepsilon})[\eta_e\alpha^2 + \eta_r(1-\alpha)^2]/[6k\eta_r\eta_e(\eta_r+\eta_e)] - M^3(2-\sqrt{\varepsilon})^2(4+\sqrt{\varepsilon})/[54k(\eta_r+\eta_e)^2] \quad (33)$$

From equations (19) and (20), we get

$$E\Pi_{M}^{D*} + E\Pi_{R}^{D*} = M^3[\eta_e\alpha^2 + \eta_r(1-\alpha)^2]/[6k\eta_r\eta_e(\eta_r+\eta_e)] - 6M^3/[54k(\eta_r+\eta_e)^2]$$

$$E\Pi_{MR}^{C*} - (E\Pi_{M}^{D*} + E\Pi_{R}^{D*}) =$$

$$M^3(1-\sqrt{\varepsilon})[\eta_e\alpha^2 + \eta_r(1-\alpha)^2]/[6k\eta_r\eta_e(\eta_r+\eta_e)] + M^3[6-(2-\sqrt{\varepsilon})^2(4+\sqrt{\varepsilon})]/[54k(\eta_r+\eta_e)^2] > 0$$

$$E\Pi_{MR}^{C*} > (E\Pi_{M}^{D*} + E\Pi_{R}^{D*})$$

QED.

Corollary 3.2 indicates that in the case of centralized decision, the supply chain system joint expected revenue will increase, because the centralized decision enables the manufacturer and retailer to make joint decision, forms the vertical integration of the supply chain system and improves the operation efficiency.

Corollary 3.3 In the case of centralized decision, the consumer surplus of the customer will be higher than that in the case of decentralized decision, i.e., $CS^{C*} > CS^{D*}$.

Proof From equations (29), (31) and (32), we get

$$CS^{C*} = M^2(2-\sqrt{\varepsilon})[\eta_r\eta_e - \eta_e\alpha^2 - \eta_r(1-\alpha)^2]/[3k\eta_r\eta_e(\eta_r+\eta_e)] - M^2(2-\sqrt{\varepsilon})/[9k(\eta_r+\eta_e)^2] \quad (34)$$

Compare equation (34) with (21), and get

$$CS^{C*} - CS^{D*} = M^2(1-\sqrt{\varepsilon})[\eta_r\eta_e - \eta_e\alpha^2 - \eta_r(1-\alpha)^2]/[3k\eta_r\eta_e(\eta_r+\eta_e)] + M^2\sqrt{\varepsilon}/[9k(\eta_r+\eta_e)^2] > 0$$

$$CS^{C*} > CS^{D*}$$

QED.

Corollary 3.3 indicates that in the case of centralized decision, the consumer surplus of the customer will be higher than that in the case of decentralized decision, which shows that centralized decision is also beneficial to the customer.

5 The Manufacturer Dual Channel Structure

When the manufacturer establishes the dual channel structure, the manufacturer builds its own traditional retail channel and entrusts the third-party platform to build the internet channel. The manufacturer and the third-party platform determine the revenue sharing ratio λ (revenue sharing contract). The manufacturer determines the product quality level and wholesale price. The retailer determines the retail price and the third-party platform determines internet direct price. Therefore, we construct the Stackelberg game model between the manufacturer, retailer and third-party platform, which is as follows.

$$MaxE\Pi_M(q,w)=(w-kq^2/2)(\alpha M-\eta_r p_r/q)+(\lambda p_e-kq^2/2)[(1-\alpha)M-\eta_e p_e/q] \quad (35)$$

$$s.t.\quad p_r=\arg MaxE\Pi_R$$

$$p_e=\arg MaxE\Pi_T$$

$$MaxE\Pi_R(p_r)=(p_r-w)(\alpha M-\eta_r p_r/q) \quad (36)$$

$$MaxE\Pi_T(p_e)=(1-\lambda)p_e[(1-\alpha)M-\eta_e p_e/q] \quad (37)$$

Equation (35) is the manufacturer's expected revenue function, equation (36) is the retailer's expected revenue function and equation (37) is the third-party platform's expected revenue function.

Proposition 4 When the manufacturer establishes the dual channel structure, i.e., entrusting the third-party to build the internet channel, the manufacturer's product quality level is positively related to the revenue sharing ratio (i.e., increasing function). And its product quality level is lower than that when the retailer establishes the dual channel structure under decentralized decision and centralized decision, i.e. $q^{T*}<q^{D*}<q^{C*}$.

Proof Use *backwards induction method* to solve, and take the first partial derivative of equations (36) and (37) with respect to p_r and p_e respectively, and get

$$p_r=\alpha Mq/(2\eta_r)+w/2 \quad (38)$$

$$p_e = (1-\alpha)Mq/(2\eta_e) \quad (39)$$

Substitute equations (38) and (39) into equation (35), and get

$$E\Pi_M(q,w) = (w-kq^2/2)(\alpha M/2-\eta_r w/2q)+(1-\alpha)M/2(\lambda(1-\alpha)Mq/2\eta_e - kq^2/2) \quad (40)$$

Take the first partial derivative of equation (40) with respect to w, and get

$$w = \alpha Mq/2\eta_r + kq^2/4 \quad (41)$$

Substitute equation (41) into equation (40), and get

$$E\Pi_M(q) = (\alpha Mq/2\eta_r - kq^2/4)(\alpha M/4 - k\eta_r q/8)+(1-\alpha)M/2(\lambda(1-\alpha)Mq/2\eta_e - kq^2/2) \quad (42)$$

Take the first and second partial derivative of equation (42) with respect to q, and get

$$q_1 = [4(2-\alpha)M - 2M\sqrt{\eta}]/3k\eta_r \quad \text{or} \quad q_2 = [4(2-\alpha)M + 2M\sqrt{\eta}]/3k\eta_r \quad (43)$$

$$\eta = 4(2-\alpha)^2 - 3\alpha^2 - 6\eta_r\eta_e^{-1}\lambda(1-\alpha)^2$$

$$\partial^2 E\Pi_M(q)/\partial q^2 = 3k^2\eta_r q/16 - (2-\alpha)Mk/4 < 0 \quad \text{（concave function）}$$

$$q < 4(2-\alpha)M/3k\eta_r \quad (44)$$

From equations (43) and (44), we get

$$q^{T^*} = [4(2-\alpha)M - 2M\sqrt{\eta}]/3k\eta_r \quad (45)$$

From equation (45), we get

$$\partial q^{T^*}/\partial\lambda = 2M(1-\alpha)^2/k\eta_e\sqrt{\eta} > 0 \text{（increasing function, positive correlation）} \quad (46)$$

$\lambda \in [0,1]$, $q^{T^*}(\lambda)$ is the increasing function.

$$q^{T^*}(\lambda=1)/q^{D^*} = (\eta_r+\eta_e)(4-2\alpha-\sqrt{\eta})/\eta_r < 1 \quad (47)$$

$q^{T^*}(\lambda=1) < q^{D^*}$.

So, when $\lambda \in [0,1]$, $q^{T^*} < q^{D^*}$

$q^{D^*} < q^{C^*}$ （Proposition 3 has proved）

$$q^{T^*} < q^{D^*} < q^{C^*} \quad (48)$$

QED.

Proposition 4 indicates that when the manufacturer establishes the dual channel

structure entrusting the third-part platform to build the internet channel, the manufacturer's product quality level is positively related to the revenue sharing ratio. And its product quality level is lower than that when the retailer establishes the dual channel structure under decentralized decision and centralized decision.

Substitute equation (45) into equation (41), and get

$$w^{T*} = [(16+\eta-2\alpha^2-4\alpha)-(8-\alpha)\sqrt{\eta}]M^2/9k\eta_r^2 \quad (49)$$

Substitute equations (45) and (49) into equations (38) and (39) respectively, and get

$$p_r^{T*} = [(16+\eta-14\alpha^2+20\alpha)-(8+5\alpha)\sqrt{\eta}]M^2/18k\eta_r^2 \quad (50)$$

$$p_e^{T*} = [2(1-\alpha)(2-\alpha)-(1-\alpha)\sqrt{\eta}]M^2/3k\eta_r\eta_e \quad (51)$$

Substitute equations (45), (49), (50) and (51) into equations (35), (36) and (37) respectively, and get

$$E\Pi_R^{T*} = [(-10\alpha^2+28\alpha-\eta-16)-(7\alpha-8)\sqrt{\eta}]^2M^3/18k\eta_r^2[24(2-\alpha)-12\sqrt{\eta}] \quad (52)$$

$$E\Pi_T^{T*} = [2(1-\alpha)(2-\alpha)-(1-\alpha)\sqrt{\eta}]^2(1-\lambda)M^3/3k\eta_r\eta_e[4(2-\alpha)-2\sqrt{\eta}] \quad (53)$$

$$E\Pi_M^{T*} = \frac{[(6(\alpha^2-3\alpha+2)\lambda\eta_r-2(4\alpha^2-16\alpha+\eta+16)\eta_e)-(3(1-\alpha)\lambda\eta_r-8(2-\alpha)\eta_e)\sqrt{\eta}][2(\alpha^2-3\alpha+2)-(1-\alpha)\sqrt{\eta}]M^3}{9k\eta_r^2\eta_e[4(2-\alpha)-2\sqrt{\eta}]}$$

$$+\frac{[(-10\alpha^2+28\alpha-\eta-16)-(7\alpha-8)\sqrt{\eta}]^2M^3}{9k\eta_r^2[24(2-\alpha)-12\sqrt{\eta}]} \quad (54)$$

So, the customer's consumer surplus is

$$CS^{T*} = \int_0^{\alpha M}(vq^{T*}-p_r^{T*})f(v)dv+\int_{\alpha M}^{M}(vq^{T*}-p_e^{T*})f(v)dv$$

$$=[12(2-\alpha)\eta_r-\alpha(16+\eta-14\alpha^2+20\alpha)-(6\eta_r-8\alpha-5\alpha^2)\sqrt{\eta}]M^2/18k\eta_r^2$$

$$+[2(1-\alpha)^2(2-\alpha)-(1-\alpha)^2\sqrt{\eta}]M^2/3k\eta_r\eta_e \quad (55)$$

CS^{T*} is the customer's consumer surplus when the manufacturer establishes the dual channel structure.

6 Numerical Analysis

The manufacturer M provides a certain type of electronic products to the market. In addition to selling electronic products through retailer R, M can also entrust the third-party

platform (such as Amazon, eBay, Tmall, JD, etc.) to sell electronic products. The production cost coefficient of M is 2 USD per piece, and the basic demand of customers (consumers) is 30 pieces per day. The demand price elasticity coefficient in internet channel is greater than that in traditional retail channel (i.e. $\eta_e = 2\eta_r$). The revenue sharing ratio of the manufacturer is 0.5. We will analyze changes in product quality level, wholesale price, retail price, direct price, market demand, expected revenue and customer's consumer surplus in traditional retail channel and internet channel.

Equations(15)-(21) are the description of the retailer dual channel structure (decentralized decision), equations(29)-(34) are the description of the retailer dual channel structure (centralized decision), and equations(45) and (49)-(55) are the description of the manufacturer dual channel structure (entrusting the third-party platform to build internet channel), we conduct the numerical analysis by Matlab 2018, and the results are shown in Table 1-Table 3 and Figure 2-Figure 4.

Table1 The retailer dual channel structure (decentralized decision)

η_r	η_e	q^{D*}	w^{D*}	p_r^{D*}	p_e^{D*}	$E\Pi_R^{D*}$	$E\Pi_M^{D*}$	$E\Pi_{MR}^{D*}$	CS^{D*}
1.000	2.000	3.333	22.222	36.111	23.611	59.028	55.556	114.583	20.139
1.100	2.200	3.030	18.365	29.844	19.513	48.783	45.914	94.697	20.776
1.200	2.400	2.778	15.432	25.077	16.397	40.992	38.580	79.572	20.930
1.300	2.600	2.564	13.149	21.368	13.971	34.928	32.873	67.801	20.792
1.400	2.800	2.381	11.338	18.424	12.046	30.116	28.345	58.461	20.479
1.500	3.000	2.222	9.877	16.049	10.494	26.235	24.691	50.926	20.062
1.600	3.200	2.083	8.681	14.106	9.223	23.058	21.701	44.759	19.586
1.700	3.400	1.961	7.689	12.495	8.170	20.425	19.223	39.648	19.079
1.800	3.600	1.852	6.859	11.145	7.287	18.218	17.147	35.365	18.561
1.900	3.800	1.754	6.156	10.003	6.540	16.351	15.389	31.741	18.044
2.000	4.000	1.667	5.556	9.028	5.903	14.757	13.889	28.646	17.535

From Table 1, we can see that when the retailer establishes the dual channel structure (decentralized decision), with the demand price elasticity in traditional retail channel and the demand price elasticity in internet channel increase, product quality level, wholesale

price, retail price, direct price, expected revenue and consumer surplus will all decrease.

Table2 The retailer dual channel structure (centralized decision)

η_r	η_e	q^{C*}	p_r^{C*}	p_e^{C*}	$E\Pi_{MR}^{C*}$	CS^{C*}
1.000	2.000	4.033	38.383	23.258	145.519	31.090
1.100	2.200	3.667	31.722	19.222	120.264	30.694
1.200	2.400	3.361	26.655	16.152	101.055	29.993
1.300	2.600	3.103	22.712	13.762	86.106	29.136
1.400	2.800	2.881	19.583	11.866	74.244	28.209
1.500	3.000	2.689	17.059	10.337	64.675	27.262
1.600	3.200	2.521	14.993	9.085	56.843	26.324
1.700	3.400	2.373	13.281	8.048	50.353	25.412
1.800	3.600	2.241	11.847	7.178	44.913	24.534
1.900	3.800	2.123	10.633	6.443	40.310	23.695
2.000	4.000	2.017	9.596	5.815	36.380	22.898

From Table 2, we can see that when the retailer establishes the dual channel structure (centralized decision), compared with decentralized decision, product quality level, retail price, joint expected revenue and consumer surplus will increase. But direct price will decrease.

Table 3 The manufacturer dual channel structure

η_r	η_e	q^{T*}	w^{T*}	p_r^{T*}	p_e^{T*}	$E\Pi_R^{T*}$	$E\Pi_T^{T*}$	$E\Pi_M^{T*}$	$E\Pi_{MR}^{T*}$	CS^{T*}
1.000	2.000	1.940	16.500	22.800	7.275	20.459	27.280	38.949	59.408	14.063
1.100	2.200	1.764	13.636	18.843	6.012	16.908	22.545	32.189	49.098	14.027
1.200	2.400	1.617	11.458	15.833	5.052	14.208	18.944	27.048	41.256	13.807
1.300	2.600	1.492	9.763	13.491	4.305	12.106	16.142	23.047	35.153	13.487
1.400	2.800	1.386	8.418	11.633	3.712	10.438	13.918	19.872	30.310	13.114
1.500	3.000	1.293	7.333	10.133	3.233	9.093	12.124	17.311	26.404	12.717
1.600	3.200	1.213	6.445	8.906	2.842	7.992	10.656	15.214	23.206	12.313
1.700	3.400	1.141	5.709	7.889	2.517	7.079	9.439	13.477	20.556	11.914
1.800	3.600	1.078	5.093	7.037	2.245	6.315	8.420	12.021	18.336	11.525

1.900	3.800	1.021	4.571	6.316	2.015	5.667	7.557	10.789	16.457	11.150
2.000	4.000	0.970	4.125	5.700	1.819	5.115	6.820	9.737	14.852	10.791

From Table 3, we can see that when the manufacturer establishes the dual channel structure (entrusting the third-party platform to build internet channel), compared with the retailer dual channel structure (decentralized decision and centralized decision), the product quality level, wholesale price, retail price, direct price, retailer's expected revenue, manufacturer's expected revenue, joint expected revenue, and consumer surplus will all decrease; with the demand price elasticity in internet channel increasing, the third-party platform's expected revenue will decrease.

(Figure 2 Comparison of product quality level under three situations)

We can find that the product quality level under centralized decision will be higher than that under decentralized decision, and will also be higher than when the manufacturer entrusts the third-party platform to build internet channel.

(Figure 3 The expected revenue functions under three situations)

We can find that the manufacturer's expected revenue and retailer's expected revenue under decentralized decision will be higher than that when the manufacturer entrusts the third-party platform. The joint expected revenue under centralized decision will be higher than that under decentralized decision, and also higher than that when the manufacturer entrusts the third-party platform.

(Figure 4 Consumer surplus under three situations)

From Figure 4, we can see that the customer's consumer surplus in the case pf centralized decision will be higher than that in the case of decentralized decision, and also higher than that when the manufacturer entrusts the third-party platform.

7 Conclusions and Future Research

Based on the three-stage Stackelberg dynamic game, this paper considers how to make product quality control strategy in the three-echelon supply chain composed of the manufacturer, retailer and customer when the retailer establishes the dual channel structure and the manufacturer establishes the dual channel structure. We analyze when there are decentralized decision and centralized decision, the demand price elasticity, market share

ratio, revenue sharing ratio and quality cost coefficient how to influence the product demand, product quality level, retail price and direct price in different channels, expected revenue functions of the manufacturer and retailer, consumer surplus and product quality control strategy.

When the retailer establishes the dual channel structure (decentralized decision), with the demand price elasticity in traditional retail channel and the demand price elasticity in internet channel increase, product quality level, wholesale price, retail price, direct price, expected revenue and consumer surplus will all decrease. When the retailer establishes the dual channel structure (centralized decision), compared with decentralized decision, product quality level, retail price, joint expected revenue and consumer surplus will increase, but direct price will decrease. When the manufacturer establishes the dual channel structure (entrusting the third-party platform to build internet channel), compared with the retailer dual channel structure (decentralized decision and centralized decision), the product quality level, wholesale price, retail price, direct price, retailer's expected revenue, manufacturer's expected revenue, joint expected revenue, and consumer surplus will all decrease; with the demand price elasticity in internet channel increasing, the third-party platform's expected revenue will decrease.

The product quality level under centralized decision will be higher than that under decentralized decision, and higher than that when the manufacturer entrusts the third-party platform to build the internet channel; The manufacturer and retailer's expected revenues under decentralized decision will be higher than that when the manufacturer entrusts the third-party platform; The joint expected revenue under centralized decision will be higher than that under decentralized decision, and also higher than that when the manufacturer entrusts the third-party platform; The customer's consumer surplus under centralized decision will be higher than that under decentralized decision, and also higher than that when the manufacturer entrusts the third-party platform.

In our paper, the model only considers the situation of one manufacturer and one retailer or only entrusting one third-party platform, and it is a Stackelberg dynamic game under the condition of complete information. In future research, we will consider how to formulate product quality control strategy in different distribution channels under the

condition of asymmetric information, and try to establish a multi-stage, dynamic and repeated game between the manufacturer and retailer or third-party platform to analyze the impact on product quality decision, expected revenue function, customer's consumer surplus and social welfare.

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Statistical data

All the data is available and within the manuscript, no supplement materials data.

Competing interests

The authors declare that no competing interests exist.

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Figure legends

Figure 1. The relationship of dual channel structure

Figure 2. Comparison of product quality level under three situations

Figure 3. The expected revenue functions under three situations

Figure 4. Consumer surplus under three situations

Figures

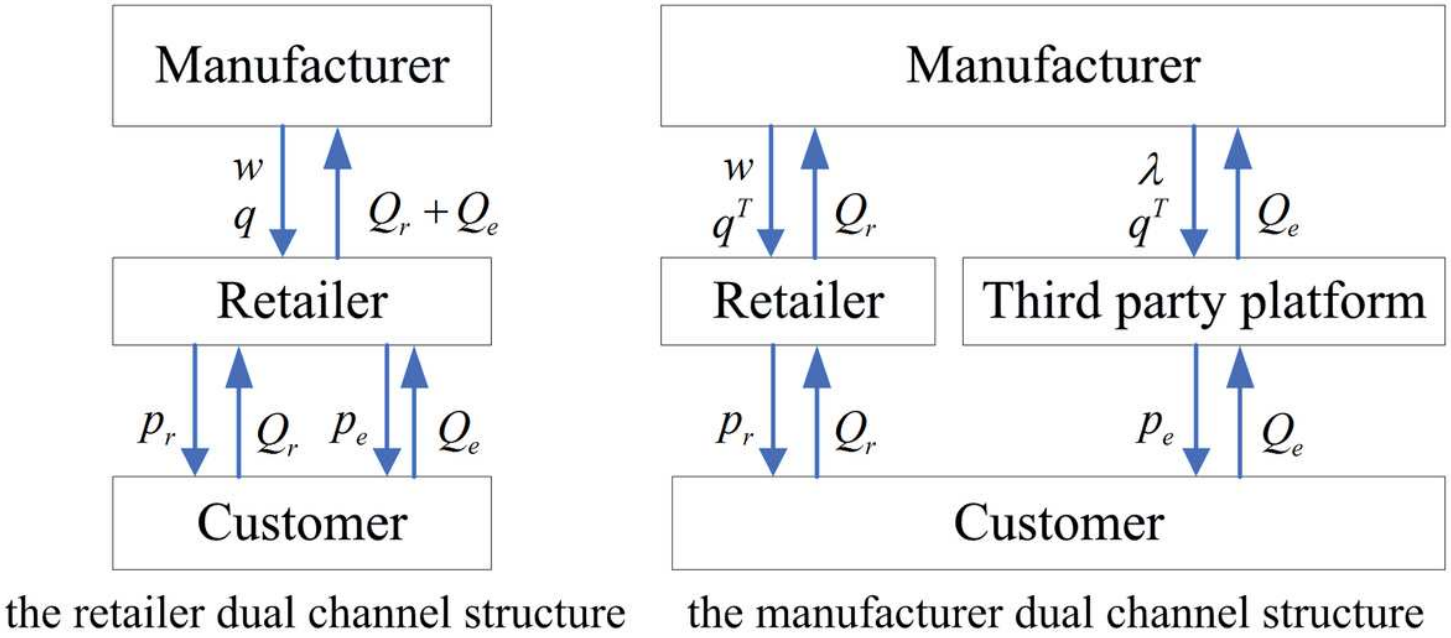

Figure 1

The relationship of dual channel structure

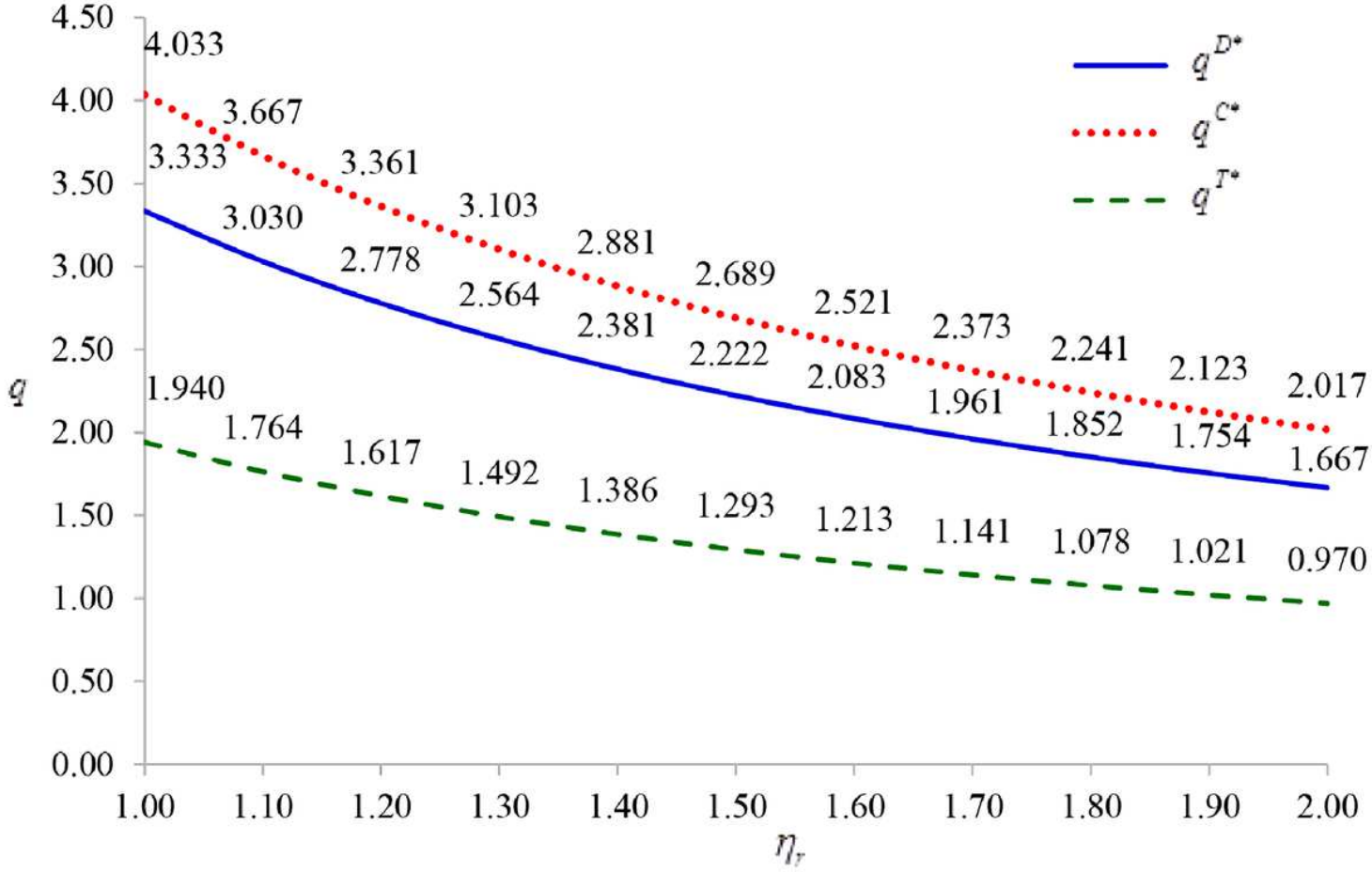

Figure 2

Comparison of product quality level under three situations

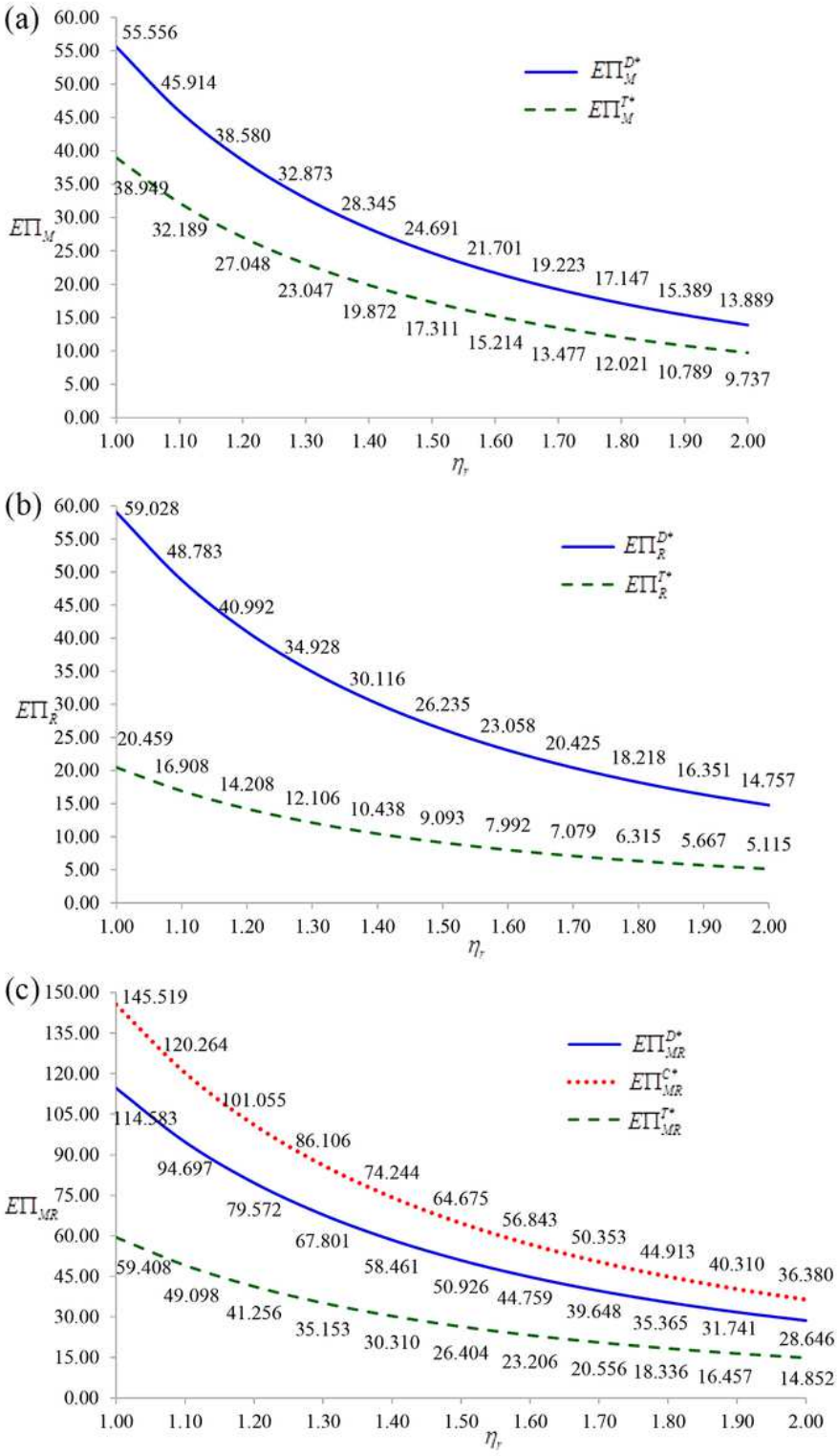

Figure 3

The expected revenue functions under three situations

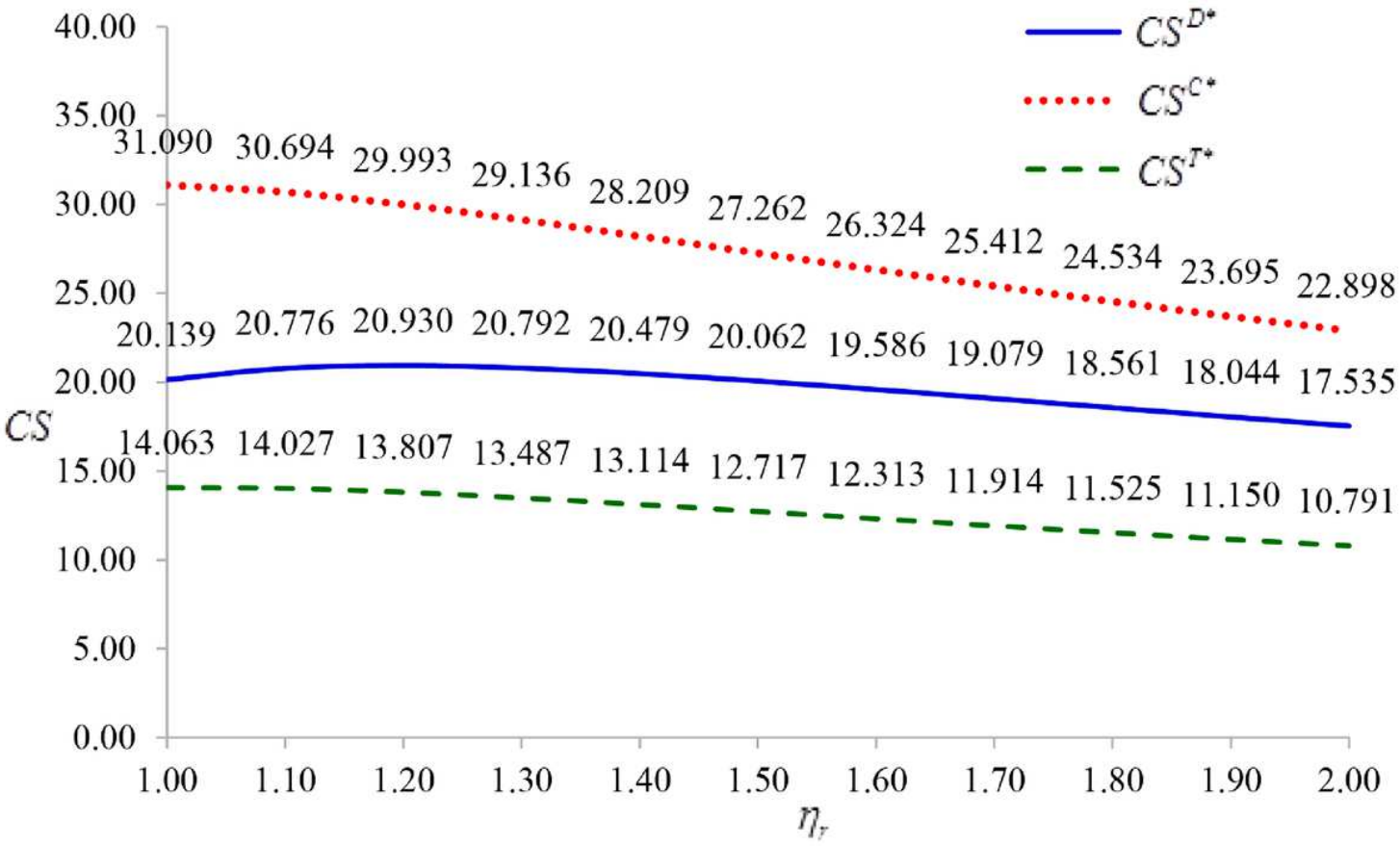

Figure 4

Consumer surplus under three situations