Research on Omni-Channel Supply Chain Pricing Decisions under Platform Fee Structure

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Abstract: With the rise of e-commerce platforms, the omni-channel supply chain has become a significant trend in business development. This paper aims to explore the impact of platform fees on pricing decisions within the omni-channel supply chain and how these decisions affect the profits of supply chain members. By constructing a Stackelberg game model, this paper analyzes the relationships among manufacturers, retailers, and e-commerce platforms, and thereby determines the optimal wholesale prices, retail prices, and platform fees. The study's findings reveal that an increase in the manufacturer's online channel supply ratio reduces wholesale and retail prices while increasing the profits of manufacturers and e-commerce platforms, but adversely affects the profits of retailers. Moreover, an increase in e-commerce platform fees has complex effects on the profits of supply chain members and poses challenges to the sustainable development of the supply chain. Therefore, setting platform fees reasonably is crucial for maintaining the healthy development of the omni-channel supply chain and balancing profits among members.

Keywords: Omni-Channel Supply Chain; E-Commerce Platform Fees; Product Pricing; Stackelberg Game Modeling

1. Introduction

In recent years, China's e-commerce development has been strong and resilient. According to the data released by the Ministry of Commerce, China's online retail sales in 2022 amounted to RMB 13.79 trillion, a year-on-year increase of 4.0%, and in 2023, the figure climbed to RMB 15.42 trillion, a year-on-year increase of 11.82%, which has made China the leader in the global online retail market for 11 consecutive years. Moreover, the cross-border e-commerce sector also performed well in 2023, with import and export volume reaching 2.38 trillion yuan, a year-on-year increase of 15.6%, which has become another bright spot in China's e-commerce development. In order to meet consumers' diversified shopping needs and adapt to market changes, many well-known companies, such as Uniqlo, KFC, Starbucks, Wuling, Sephora, etc., use omni-channel strategies to provide consumers with seamless and consistent shopping prices and experiences by integrating online and offline channels. Among them, Uniqlo adopts a “direct-to-consumer” model, providing an omni-channel digital shopping experience based on consumer needs and characteristics.

However, the rapid development of e-commerce has also put tremendous pressure on e-commerce platforms. In this competitive market environment, e-commerce platforms often adjust their platform fees or increase sales commissions in order to cope with their own operating costs, or to increase revenues and profitability. As of March 2023, almost all major cross-border e-commerce platforms have seen their fees rise, with cross-border e-commerce platforms such as Amazon, eBay, Zalando, Lazada, Shopee and Ozon adjusting their seller fees, including increasing sales commissions and introducing new base fees. In October 2023, Amazon announced the commencement of its new charging policy, which will lead to a further rise in costs for platform sellers. In the case of one furniture store, for example, it is estimated that the furniture store will lose $1 million per year as a result. Numerous other merchants on the platform have been forced to raise the prices of their goods in order to deflect the pressure of commission increases. However, boosting fees in a way that could lead to a loss of customers could end up backfiring on the platform instead.

So, what is the right fee for an e-commerce platform? Especially in the omni-channel context, how will e-commerce platform fees affect itself and other participating entities? Are platform fees favorable to omni-channel development? Are platform fees sustainable? In order to answer these questions, this paper will study the pricing decision problem of omni-channel supply chain under platform charging in the context of supply chain.

2. Literature Review

2.1 Research on Omni-Channel Pricing Strategies

Literature has explored omni-channel pricing strategies based on consumer behavior. Du et al. [1] described the impact of consumer's anticipated disappointment aversion on the optimal pricing decisions of retailers within an omni-channel context. Chen Sijia and Guan Zhenzhong [2] conducted an in-depth analysis of market demand, optimal pricing strategies, and expected profits for omni-channel retailers under various return policies. Li et al. [3] investigated the optimal omni-channel pricing for online retailers under consumer reference point effects and loss aversion. Shao [4] noted that while omni-channel strategies are suitable for traditional brick-and-mortar stores, they may not be entirely applicable to online retailers, and such strategies do not always reduce retail costs or enhance consumer welfare. Wu et al. [5] proposed a stochastic pricing strategy for omni-channel retailers, considering the manufacturer's wholesale price, customer perceptions of different channels, and strategic customer waiting behavior. Some literature has also compared different pricing strategies to determine the conditions under which various omni-channel strategies are applicable or to identify optimal pricing strategies. Cachon and Feldman [6] compared three different types of pricing strategies. Hu Qifan and Xu Bing [7] constructed a pricing and service decision model for an omni-channel supply chain, considering both online-offline differentiated pricing strategies and unified pricing strategies, analyzing the impact of these two pricing strategies on profit and service differentiation. Zhang Zijian and Liu Xiaoqiao [8], through a comparison of four pricing strategies, derived the optimal pricing strategy under the "Buy Online, Pick Up In-Store" (BOPS) omni-channel model. Gao Ying et al. [9] studied the conditions under which differentiated and non-differentiated omni-channel pricing strategies are applicable under the reference quality effect, utilizing optimal control theory.

2.2 Research on Pricing Strategies of E-commerce Platform Fees

Literature has approached the study of platform fees through the lens of platform revenue models. Chen and Fan et al. [10] investigated whether eBay's final value fees can effectively coordinate the channel, finding that while eBay's final value fees can enhance channel efficiency, they fail to optimize channel coordination. Chen and Fan et al. [10] compared the revenue models of eBay in the United States and Taobao in China, two online e-commerce platforms. Other studies have examined e-commerce platform pricing strategies under various conditions. Zhang Shen and Meng Qingchun et al. [11] constructed a pricing model for a centralized dual-channel supply chain based on the commission rate of e-commerce platforms and conducted an in-depth discussion on the collaborative pricing issues of dual-channel supply chains. Chen et al. [12] analyzed the relevant commission prices and various commission pricing strategies when selling through e-commerce platforms, revealing the impact of these strategies on e-commerce platforms and suppliers. Gomes et al. [13] studied the contradiction between online e-commerce platforms and other intermediary agencies expanding consumer information and imposing high commissions on sellers. Based on the premise that the fees charged by platforms should reflect the value of the information advantage they provide without imposing excessive costs on sellers, they proposed a utilitarian commission cap as a potential solution. Hasiloglu et al. [14] focused on the challenges and decision dynamics in the relationship between e-commerce platforms and businesses selling products through these platforms. By establishing a game-theoretic model that includes an e-commerce platform and two sellers selling the same product on the same platform, they examined pricing, service level, and commission rate decisions under different scenarios.

2.3 Research Critique

Based on the findings from the aforementioned literature, there is a relative abundance of research on omni-channel pricing decisions, with few studies examining the impact of platform fees on omni-channel pricing decisions. Therefore, building upon existing research on omni-channel pricing decisions, this paper conducts an in-depth exploration of the influence of platform fees on omni-channel pricing decisions.

3. Modeling and Analysis of Omni-Channel Supply Chain Pricing under Platform Fee Structure

3.1 Problem Description

In practice, the majority of manufacturers lack the capability to establish e-commerce platforms or are unable to compete with well-known e-commerce platforms. The omni-channel supply chain studied in this paper comprises an e-commerce platform, a manufacturer, a retailer, and numerous consumers. Within the considered supply chain, the manufacturer sells products directly to consumers through the online channel of the e-commerce platform, which in turn charges the manufacturer a corresponding platform fee; in the offline channel, the manufacturer provides products to the retailer at a wholesale price, and the retailer is responsible for selling the products to consumers in the offline channel. The specific structure is shown in Figure 1.

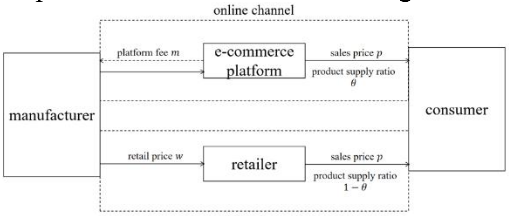

Figure 1. Schematic Diagram of Omni-channel Supply Chain under E-commerce Platform Fee Structure

3.2 Parameter Definitions and Assumptions

This paper assumes that the manufacturer produces only one type of product. To simplify the model, based on the assumptions of Wang et al. [15], and to maintain a general case, the potential market size is standardized to a value of 1. Additionally, the marginal cost per unit product is standardized to 0. Furthermore, in this paper, the cost of the offline channel is not considered and is assumed to be 0 [12]. Consequently, the consumer demand function can be derived as:

$$D = 1 - p \tag{1}$$

The primary symbols related to the omnichannel supply chain model in this paper are illustrated in Table 1.

Table 1. Model Notations and Definitions

Notation	Description of definitions
D	Consumer demand
p	Product selling price, $p \in (0,1)$
w	Product wholesale price, $p - w > 0$, $w > 0$
π	Supply chain member profits
n	Manufacturer
s	Retailer
r	E-commerce platform
θ	Online channel supply ratio, $\theta \in (0,1)$
$1-\theta$	Offline channel supply ratio
m	E-commerce platform unit fee, $m \in (0,1)$

3.3 Model Analysis

Based on the Stackelberg game theory, the e-commerce platform, as the leader, first determines the e-commerce platform unit fee *m*. Subsequently, the manufacturer, as the follower, sets the product wholesale price *w* based on this fee. Finally, the retailer determines the product wholesale price, establishing the final product selling price *p* for the omni-channel supply chain. The profit functions for the three entities are as follows:

$$\pi_r = m \cdot \theta \cdot D \tag{2}$$

$$\pi_s = (p - w) \cdot (1 - \theta) \cdot D \tag{3}$$

$$\pi_n = w \cdot (1 - \theta) \cdot D + (p - m) \cdot \theta \cdot D \tag{4}$$

Proposition 1: Equilibrium retail price, sales price, platform fee, and equilibrium profits earned by members of the omni-channel supply chain are shown in Tables 2 and 3.

This paper selects backward induction as the primary method of proof. Take the first-order partial derivative of equation (3) with respect to *p* and set it to 0 to find the equilibrium selling price *p*; substitute *p* into equation (4), take the first-order partial derivative with respect to *w* and set it to 0 to find the equilibrium wholesale price *w*; substitute the derived p and w into equation (2), take the first-order partial derivative with respect to m and set it to 0 to find the equilibrium platform unit fee m. The equilibrium wholesale price, equilibrium selling price, and equilibrium platform unit charge obtained are as follows:

Table 2. Wholesale Price, Selling Price, and E-Commerce Platform Unit Fee under Equilibrium Conditions

Parameters	Parameter definitions	Equilibrium prices
w	wholesale price	$w^*=\frac{2\theta-3}{2\theta-4}$
p	selling price	$p^*=\frac{4\theta-7}{4\theta-8}$
m	platform unit fee	$m^*=\frac{1}{2\theta}$

Table 3. Equilibrium Profits of Omni-Channel Supply Chain Members

Omni-channel supply chain members	Equilibrium profit
Manufacturer	$\pi_n^*=-\frac{1}{16\theta-32}$
Retailer	$\pi_s^*=\frac{1-\theta}{16(\theta-2)^2}$
E-commerce platform	$\pi_r^*=-\frac{1}{8\theta-16}$

It is important to note that the following conditions need to be met in order to ensure that the equilibrium profit of each member of the omni-channel supply chain can hold:

$$\begin{cases} 0<\frac{2\theta-3}{2\theta-4}<1 \\ 0<\frac{4\theta-7}{4\theta-8}<1 \\ 0<\frac{1}{2\theta}<1 \end{cases} \tag{5}$$

Taking the intersection gives $\theta\in\left(\frac{1}{2},1\right)$. That is, when the manufacturer's online channel supply ratio is within the interval $\left(\frac{1}{2},1\right)$, it results in an appropriate market share distribution, allowing the manufacturer, retailer, and e-commerce platform to each gain a certain market share and achieve profitability.

Proposition 2: The impact of the manufacturer's online channel supply ratio on the wholesale price, selling price, and e-commerce platform unit fee: The wholesale price *w,* selling price p, and e-commerce platform fee m will decrease as the online channel supply ratio θ increases.

Proof: Compute the first-order partial derivatives of w^*, p^*, and m^* with respect to θ, and obtain:

$$\frac{\partial w^*}{\partial\theta}=-\frac{1}{2(\theta-2)^2} \tag{6}$$

$$\frac{\partial p^*}{\partial\theta}=-\frac{1}{4(\theta-2)^2} \tag{7}$$

$$\frac{\partial m^*}{\partial\theta}=-\frac{1}{2\theta^2} \tag{8}$$

When $\theta\in\left(\frac{1}{2},1\right)$, $\frac{\partial w^*}{\partial\theta}<0$ $\frac{\partial p^*}{\partial\theta}<0$ $\frac{\partial m^*}{\partial\theta}<0$, it is known that w^*, p^*, and m^* are monotonically decreasing in the interval $\left(\frac{1}{2},1\right)$. Second, substituting $\theta=\frac{1}{2}$ and $\theta=1$ into w^*, p^*, and m^* yields the range of values of each parameter as $w^*\in\left(\frac{1}{2},\frac{2}{3}\right),p^*\in\left(\frac{3}{4},\frac{5}{6}\right),m^*\in\left(\frac{1}{2},1\right)$ respectively. Under equilibrium conditions, the wholesale price, the selling price, and the amount charged per unit on the e-commerce platform decrease as the proportion of supply from the online channel increases over the range of values for each parameter.

Proposition 2 indicates that: ① The e-commerce platform unit fee decreases as the online channel supply ratio increases. On one hand, the expansion of online supply implies an increase in transaction volume on the e-commerce platform, leading to higher traffic and, under the effects of economies of scale, allowing the platform to use existing resources more efficiently, thereby reducing per-unit operational costs. On the other hand, the expansion of online supply also signifies intensified competition between online and offline channels. To attract more merchants and consumers, the e-commerce platform may opt to lower the unit fee, thereby increasing transaction volume and market share, and enhancing its competitiveness in a fierce market. ② The wholesale price decreases with an increase in the manufacturer's online channel supply ratio. As the manufacturer's online channel supply ratio rises, the e-commerce platform may reduce its fees due to intensified competition. To maintain cooperation with retailers, the manufacturer may lower the wholesale price to promote offline channel sales. This strategy helps the manufacturer achieve balanced development across multiple channels. ③ The selling price decreases as the online channel supply ratio increases. With an increase in the manufacturer's online channel supply ratio, platform fees and wholesale prices are reduced, which may prompt offline retailers to adjust their selling prices. Adopting a low-price strategy to attract consumers and compete with online channels.

Proposition 3: The impact of the manufacturer's online channel supply ratio on the profits of all members in the omni-channel supply chain: As the manufacturer's online channel supply ratio, denoted by θ, increases, the profits of the manufacturer and the e-commerce platform also increase, while the profits of the offline retailer decrease.

Proof: Compute the first-order partial derivatives of $\pi_n{}^*$; $\pi_s{}^*$; $\pi_r{}^*$ with respect to θ and obtain:

$$\frac{\partial \pi_n{}^*}{\partial \theta} = \frac{1}{16(\theta-2)^2} \tag{9}$$

$$\frac{\partial \pi_s{}^*}{\partial \theta} = \frac{\theta}{16(\theta-2)^3} \tag{10}$$

$$\frac{\partial \pi_r{}^*}{\partial \theta} = \frac{1}{8(\theta-2)^2} \tag{11}$$

Because $\theta \in \left(\frac{1}{2},1\right)$, it follows that $\frac{\partial \pi_n{}^*}{\partial \theta} > 0, \frac{\partial \pi_r{}^*}{\partial \theta} > 0, \frac{\partial \pi_s{}^*}{\partial \theta} < 0$. Therefore, π_r^* and π_n^* are monotonically increasing within the interval $\left(\frac{1}{2},1\right)$, while π_s^* is monotonically decreasing within the same interval.

Proposition 3 indicates that the change in the manufacturer's online supply ratio has an uneven impact on the profits of different participants. The e-commerce platform and the manufacturer can both benefit from an increase in the online supply ratio, but the offline retailer may face intensified competition and lower sales, leading to a decrease in profits.

Corollary 1: Comparison of profits among e-commerce platforms, manufacturers, and retailers: The profit of the e-commerce platform is always higher than that of manufacturers and retailers, and the profit of the manufacturer is always higher than that of the retailer.

Proof: Make the profit function of each member subtracted to obtain:

$$\pi_n{}^* - \pi_s{}^* = \frac{1}{16(\theta-2)^2} \tag{12}$$

$$\pi_n{}^* - \pi_r{}^* = \frac{1}{16\theta-32} \tag{13}$$

$$\pi_s{}^* - \pi_r{}^* = \frac{-3+\theta}{16(\theta-2)^2} \tag{14}$$

Given that $\theta \in \left(\frac{1}{2},1\right)$,it follows that $\pi_n{}^* - \pi_s{}^* > 0, \pi_n{}^* - \pi_r{}^* < 0, \pi_s{}^* - \pi_r{}^* < 0$, thus $\pi_r{}^* > \pi_n{}^* > \pi_s{}^*$.

Corollary 1 indicates that e-commerce platforms, as the key hub connecting manufacturers and consumers, possess unique advantages. On one hand, e-commerce platforms have a vast user traffic and extensive market coverage, enabling them to attract a large number of consumers and manufacturers to join. They achieve economies of scale by charging various platform fees (such as transaction fees and advertising promotion fees), and their operational costs are relatively fixed. As business volume increases, profits also continue to rise. On the other hand, e-commerce platforms have strong market control and can set rules and strategies that are beneficial to themselves, thereby ensuring a higher level of profit. Manufacturers, although selling products to retailers through wholesale in the offline market, can reduce intermediary links through direct sales online and obtain more profit margins. At the same time, manufacturers can use economies of scale to reduce production costs and have stronger professionalism and say in product research and development, which allows their profits to remain at a relatively high level. However, compared to e-commerce platforms, they have certain limitations in market influence and profit sources. Retailers are in a relatively weak position in the game with manufacturers and e-commerce platforms, often being more passive in price negotiations, and the offline market is highly competitive with customer flow easily affected by various factors, leading to relatively lower profits. Moreover, the development of online channels has also impacted offline channels, further compressing the profit space of retailers. However, retailers still have their reasons for existence. Since e-commerce platforms may be in a monopolistic position and manufacturers rely on e-commerce platforms, retailers serve as a means to counterbalance e-commerce platforms. Without retailers, manufacturers might fall into a passive situation.

Proposition 4: The relationship between the manufacturer's online and offline channel profits and the online channel supply ratio, as well as a comparison of profits: ①As the online channel supply ratio increases, the manufacturer's profit from the online channel will increase, while the profit from the offline channel will decrease;②When $\theta\in\left(\frac{1}{2},\ \frac{19-\sqrt{41}}{16}\right]$, the manufacturer's profit from the offline channel is greater than or equal to that from the online channel. When $\theta\in\left(\frac{19-\sqrt{41}}{16},1\right)$,the manufacturer's profit from the offline channel will be less than that from the online channel.

Proof: According to equation (4), the manufacturer's offline channel profit function can be set as $\pi_{n1}=w\cdot(1-\theta)\cdot D$, and the online channel profit function as $\pi_{n2}=(p-m)\cdot\theta\cdot D$,where $D=1-p$. Substituting $p^*=\frac{4\theta-7}{4\theta-8}$ and $w^*=\frac{2\theta-3}{2\theta-4}$ into the equations, the following is obtained:

$$\pi_{n1}=\frac{2\theta^2-5\theta+3}{8(\theta-2)^2} \tag{15}$$

$$\pi_{n2}=\frac{-4\theta^2+9\theta-4}{16(\theta-2)^2} \tag{16}$$

Take the first-order partial derivatives of equations (15) and (16) with respect to θ to obtain:

$$\frac{\partial\pi_{n1}}{\partial\theta}=\frac{-3\theta+4}{8(\theta-2)^3} \tag{17}$$

$$\frac{\partial\pi_{n2}}{\partial\theta}=\frac{7\theta-10}{16(\theta-2)^3} \tag{18}$$

Given that $\theta\in\left(\frac{1}{2},1\right)$,it follows that $\frac{\partial\pi_{n1}}{\partial\theta}<0$, $\frac{\partial\pi_{n2}}{\partial\theta}>0$. The manufacturer's offline channel profit function is monotonically decreasing within the interval $\left(\frac{1}{2},1\right)$, while the online channel profit function is monotonically increasing within the same interval.

Let $\pi_{n1}-\pi_{n2}$ be obtained:

$$\pi_{n1}-\pi_{n2}=\frac{8\theta^2-19\theta+10}{16(\theta-2)^2} \tag{19}$$

Set the numerator of equation (19) to $8\theta^2-19\theta+10=0$ to find the roots $\theta_1=\frac{19-\sqrt{41}}{16}$ and $\theta_2=\frac{19+\sqrt{41}}{16}$. Therefore, when $\theta\in\left(\frac{19-\sqrt{41}}{16},\frac{19+\sqrt{41}}{16}\right)$, $\pi_{n1}-\pi_{n2}<0$; when $\theta\in\left(-\infty,\frac{19-\sqrt{41}}{16}\right)\cup\left(\frac{19+\sqrt{41}}{16},+\infty\right)$, $\pi_{n1}-\pi_{n2}>0$ .Given that under equilibrium conditions $\theta\in\left(\frac{1}{2},1\right)$, it follows that $\frac{1}{2}<\frac{19-\sqrt{41}}{16}<1<\frac{19+\sqrt{41}}{16}$. Consequently, when $\frac{1}{2}<\theta\le\frac{19-\sqrt{41}}{16}$, the manufacturer's offline channel profit is greater than or equal to the online channel profit. When $1>\theta>\frac{19-\sqrt{41}}{16}$, the manufacturer's offline channel profit is less than the online channel profit.

Proposition 4 illustrates that: ①As the supply ratio of the online channel increases, the product supply through this channel becomes more abundant, while the supply through the offline channel relatively decreases. This may lead some consumers to shift their purchases online, thereby reducing the manufacturer's offline channel sales and profits. ②When the online channel supply ratio is within the interval $\left(\frac{1}{2},\frac{19-\sqrt{41}}{16}\right]$, the offline market has a comparatively significant demand base and consumer inertia. Under these circumstances, some consumers exhibit a high dependency on offline experiences and immediate availability, making the advantages of the offline channel more attractive to consumers than those of the online channel. However, when the online channel supply ratio is within the interval $\left(\frac{19-\sqrt{41}}{16},1\right)$, the manufacturer's online channel profit exceeds that of the offline channel. This could be due to a significant increase in consumer acceptance and reliance on online shopping within this interval, and the online channel's stronger market expansion capabilities at this stage, which can overcome geographical restrictions to reach a broader customer base, leading to a reduction in offline customer flow and affecting profits. Additionally, as the online supply ratio increases, channel competition intensifies, and retailers may choose to lower prices to maintain competitiveness, which could also result in offline profits being lower than online profits.

Corollary 2: Comparison of the impact of the online channel supply ratio on the manufacturer's online and offline channel profit functions: The influence of the online channel supply ratio on the manufacturer's offline channel profit is less than its influence on the manufacturer's online channel profit.

Proof: let $\frac{\partial \pi_{n1}}{\partial \theta}-\frac{\partial \pi_{n2}}{\partial \theta}$ be obtained:

$$\frac{\partial \pi_{n1}}{\partial \theta}-\frac{\partial \pi_{n2}}{\partial \theta}=\frac{-13\theta+18}{16(\theta-2)^3} \quad (20)$$

Given that $\theta\in\left(\frac{1}{2},1\right)$,it follows that $\frac{\partial \pi_{n1}}{\partial \theta}-\frac{\partial \pi_{n2}}{\partial \theta}<0$.

Corollary 2 indicates that the profit of the manufacturer's online channel is more closely and directly related to the supply ratio. The online channel supply ratio can directly impact sales, market presence, and consumer attention in the online channel, rapidly and directly affecting online channel profits. Moreover, due to the broad market of the manufacturer's online channel, diverse marketing methods, and rapid changes in technology and consumer preferences, there are numerous profit growth points and variables, making the cascading effects of supply ratio changes more pronounced. In contrast, while the offline channel profit is indirectly affected by the online supply ratio, such as the shift of some consumers and changes in competitive landscape, the offline retailers possess a stable customer base and geographical advantages, as well as reliance on long-term cooperation and wholesale business with retailers. This provides a certain degree of cushioning against the impact of changes in the online supply ratio, thus the influence of the online supply ratio on offline profits is relatively delayed, indirect, and of lesser magnitude.

Proposition 5: The impact of the manufacturer's online channel supply ratio on the overall profit of the omni-channel supply chain: As the manufacturer's online channel supply ratio θ increases, the overall profit of the omni-channel supply chain also increases.

Proof: The total profit function of the omni-channel supply chain is:

$$\pi=\pi_n^*+\pi_s^*+\pi_r^*=\frac{-4\theta+7}{16(\theta-2)^2} \quad (21)$$

Taking the first-order partial derivative of equation (21) with respect to θ yields $\frac{\partial \pi}{\partial \theta}=\frac{2\theta-3}{8(\theta-2)^3}$. Since $\theta\in\left(\frac{1}{2},1\right)$,it follows that $\frac{\partial \pi}{\partial \theta}>0$. Therefore, π is monotonically increasing within the interval $\left(\frac{1}{2},1\right)$.

Combining Proposition 3 and Proposition 5, it can be observed that as the manufacturer's online channel supply ratio increases, although the profits of offline retailers decline, this negative impact is offset by the significant growth in profits of the manufacturer and the e-commerce platform. Specifically, the increase in profits of the manufacturer and the e-commerce platform not only compensates for the reduced profits of offline retailers but also leads to an overall increase in profits. This indicates that despite profit fluctuations at the local level, the positive impact of increasing the online channel supply ratio on the omni-channel supply chain is dominant. The logic behind this may stem from the complementarity between online and offline channels. By increasing the supply through online channels, the manufacturer successfully expands the consumer base, thereby meeting a more diverse range of shopping needs. At the same time, the online channel also provides an effective supplement to the offline channel, offering consumers more choices and shopping convenience. This complementarity not only enhances the overall efficiency of the supply chain but also significantly strengthens its profitability, ultimately driving an upward trend in the overall profits of the omni-channel supply chain.

Proposition 6: The impact of the e-commerce platform unit fee on wholesale and retail prices: As the unit fee *m* of the e-commerce platform increases, the wholesale price *w* and the retail price *p* will also increase.

According to the Stackelberg game theory and backward induction, first take the first-order partial derivative of equation (3) with respect to *p* and set it to 0 to find the equilibrium selling price $p^* = \frac{w+1}{2}$; then, substitute the equilibrium selling price into equation (4), take the first-order partial derivative with respect to *w* and set it to 0 to find the equilibrium wholesale price $w^* = -\frac{\theta m - \theta + 1}{\theta - 2}$. Substituting $w^* = -\frac{\theta m - \theta + 1}{\theta - 2}$ into $p^* = \frac{w+1}{2}$ yields $p^* = \frac{-\theta m + 2\theta - 3}{2\theta - 4}$. Taking the first-order partial derivatives of w^* and p^* with respect to *m* gives: $\frac{\partial w}{\partial m} = -\frac{\theta}{\theta - 2}; \frac{\partial p}{\partial m} = -\frac{\theta}{2\theta - 4}$. When $\theta \in \left(\frac{1}{2}, 1\right)$, $\frac{\partial w}{\partial m} > 0, \frac{\partial p}{\partial m} > 0$ .Therefore, when $\theta \in \left(\frac{1}{2}, 1\right)$, the wholesale and retail prices are monotonically increasing.

Proposition 6 indicates that: ①The wholesale price is positively correlated with the platform unit fee. An increase in the e-commerce platform's fee may lead to higher costs for selling products on the platform. To maintain profit levels or profit margins, manufacturers may pass on these costs to the wholesale price of the products, causing the wholesale price to rise with the platform fee. ②An increase in the e-commerce platform unit fee also leads to an increase in the selling price. As the platform's fees increase, so does the wholesale price, and the increased costs are passed down to the downstream retailers. This typically results in retailers raising their selling prices to maintain their own profits.

Corollary 3: The impact of wholesale price on platform fees and the comparison of the extent of influence: Platform fees increase with the increase of wholesale prices. The extent of the influence of wholesale price on platform fees is greater than the extent of the influence of platform fees on wholesale prices.

Proof: The wholesale price $w^* = -\frac{\theta m - \theta + 1}{\theta - 2}$, hence $m = \frac{w(2-\theta) + \theta - 1}{\theta}$. Taking the first-order derivative of *m* with respect to *w* yields: $\frac{\partial m}{\partial w} = \frac{2-\theta}{\theta}$. Since $\theta \in \left(\frac{1}{2}, 1\right)$,it follows that $\frac{\partial m}{\partial w}>0$. Comparing $\frac{\partial w}{\partial m}$ and $\frac{\partial m}{\partial w}$, their difference is obtained by subtracting the two:

$$\frac{\partial w}{\partial m} - \frac{\partial m}{\partial w} = \frac{-4\theta + 4}{(\theta - 2)\theta} \quad (22)$$

Given that $\theta \in \left(\frac{1}{2}, 1\right)$, it follows that $\frac{\partial w}{\partial m} - \frac{\partial m}{\partial w}<0$.

Corollary 3 elucidates several points. The increase in wholesale prices leads to higher platform fees for two main reasons: firstly, e-commerce platforms adjust fees based on product value and market demand; secondly, platforms may raise fees due to increased manufacturer costs or enhanced market position to share in the additional profits of the manufacturers. Additionally, changes in wholesale prices have a significant impact on platform fees because a rise in wholesale prices directly affects manufacturers' profits and market strategies, which are then transmitted to e-commerce platforms. The dominant position of e-commerce platforms in the supply chain makes them sensitive to changes in wholesale prices, further prompting them to adjust fees to accommodate market shifts. In contrast, changes in platform fees have a lesser effect on wholesale prices, as manufacturers consider a multitude of factors when setting prices and are unlikely to make substantial adjustments in response to minor changes in platform fees.

Proposition 7: The impact of wholesale price on the profits of all members in the omni-channel supply chain: As the wholesale price increases, the profits of retailers and e-commerce platforms will decline. When $w \in \left(\frac{1}{2}, \frac{2\theta-3}{2\theta-4}\right)$, the manufacturer's profit will increase with the rise in wholesale price; when $w \in \left(\frac{2\theta-3}{2\theta-4}, 1\right)$, the manufacturer's profit will decrease with the rise in wholesale price.

Proof: substituting $p^* = \frac{w+1}{2}, m^* = \frac{1}{2\theta}$ into equations (2)(3)(4) yields the profit function containing w for each member:

$$\pi_r = \frac{1}{4} - \frac{w}{4} \tag{23}$$

$$\pi_s = \left(\frac{1}{2} - \frac{w}{2}\right)^2 (1-\theta) \tag{24}$$

$$\pi_n = \frac{(-1+w)\left((\theta-2)w-\theta+1\right)}{4} \tag{25}$$

Take the first-order partial derivatives of equations (23) to (25) with respect to w to obtain:

$$\frac{\partial \pi_r}{\partial w} = -\frac{1}{4} \tag{26}$$

$$\frac{\partial \pi_n}{\partial w} = \frac{(2w-2)\theta - 4w + 4}{4} \tag{27}$$

$$\frac{\partial \pi_s}{\partial w} = -\frac{(-1+w)(-1+\theta)}{2} \tag{28}$$

Given that $\theta \in \left(\frac{1}{2}, 1\right)$ and $w \in \left(\frac{1}{2}, \frac{2}{3}\right)$, it follows that $\frac{\partial \pi_s}{\partial w} < 0$. Setting the numerator of $\frac{\partial \pi_n}{\partial w}$ to 0, $(2w-2)\theta - 4w + 4 = 0$, yields $w = \frac{2\theta-3}{2\theta-4}$, which is the equilibrium wholesale price. When $w \in \left(\frac{1}{2}, \frac{2\theta-3}{2\theta-4}\right)$, $\frac{\partial \pi_n}{\partial w} > 0$;when $w \in \left(\frac{2\theta-3}{2\theta-4}, 1\right)$, $\frac{\partial \pi_n}{\partial w} < 0$.

Proposition 7 indicates that: ①An increase in the wholesale price implies higher purchase costs for retailers, who may raise selling prices to maintain profits. However, this could also lead to a decrease in consumers' willingness to buy offline, resulting in reduced sales volumes and ultimately lower profits. ②In conjunction with Corollary 3, it is evident that platform fees will rise with the increase in wholesale prices. Manufacturers who sell products directly through e-commerce platforms may adjust their strategies due to the increase in both wholesale prices and platform fees, such as reducing their investment or supply in the online channel, affecting the scale of platform transactions. The profits derived from this situation may not compare to the profits generated by a higher transaction volume under lower platform fees. For manufacturers, when the wholesale price w is in the interval $\left(\frac{1}{2}, \frac{2\theta-3}{2\theta-4}\right)$, the increase in wholesale prices leads to a gain in revenue that exceeds the losses from other factors that may reduce profits, hence manufacturers' profits rise with the increase in wholesale prices. When the wholesale price w is in the interval $\left(\frac{2\theta-3}{2\theta-4}, 1\right)$, further increases in wholesale prices may lead to heightened market sensitivity to product prices and a decline in sales volumes. The losses from these adverse factors exceed the gains from the increase in wholesale prices, causing manufacturers' profits to decline as wholesale prices rise.

Proposition 8: When the wholesale price increases, the overall profit of the supply chain will decrease.

Summing equations (23) to (25) yields the total supply chain profit function:

$$\pi = \pi_n{}^* + \pi_s{}^* + \pi_r{}^* = -\frac{w^2}{4} + \frac{1}{4} \tag{29}$$

Taking the first-order partial derivative of equation (29) with respect to w yields: $\frac{\partial \pi}{\partial w} = -\frac{w}{2}$. Since $w \in \left(\frac{1}{2}, \frac{2}{3}\right)$, it follows that $\frac{\partial \pi}{\partial w} < 0$.

Proposition 8 reveals a negative correlation between the wholesale price and the overall profit of the omni-channel supply chain. In conjunction with Proposition 7, it can be inferred that the manufacturer's profit will exhibit an increasing trend followed by a decline due to the different intervals in which the wholesale price falls. However, the profits of both retailers and e-commerce platforms will decrease as a result of an increase in the wholesale price. The comprehensive profit of the omni-channel supply chain is constituted by the profits of manufacturers, retailers, and e-commerce platforms. From a holistic perspective, even if the manufacturer's profit rises within the interval $\left(\frac{1}{2},\frac{2\theta-3}{2\theta-4}\right)$, the more significant decline in profits for retailers and e-commerce platforms, or the inability of the manufacturer's profit increase to offset the decline in profits for retailers and e-commerce platforms, ultimately leads to a downward trend in the overall profit of the omni-channel supply chain.

Proposition 9: As the platform's unit fee m gradually increases, the profits of manufacturers and retailers gradually decrease. When $m\in\left(\frac{1}{2},\frac{1}{2\theta}\right)$, the e-commerce platform's profit will rise with the increase in the platform's unit fee; when $m\in\left(\frac{1}{2\theta},1\right)$, the e-commerce platform's profit will decline with the increase in the platform's unit fee.

Proof: Substitute $w^*=-\frac{\theta m-\theta+1}{\theta-2}$ and $p^*=\frac{-\theta m+2\theta-3}{2\theta-4}$ into equations (2), (3), and (4) to obtain the profit functions for the e-commerce platform, manufacturer, and retailer, respectively:

$$\pi_r=\frac{m\theta(\theta m-1)}{2\theta-4} \tag{30}$$

$$\pi_n=-\frac{(\theta m-1)^2}{4\theta-8} \tag{31}$$

$$\pi_s=-\frac{(\theta m-1)^2(-1+\theta)}{4(\theta-2)^2} \tag{32}$$

Taking the first-order partial derivatives of equations (30) to (32) with respect to m yields:

$$\frac{\partial\pi_n}{\partial m}=-\frac{2(\theta m-1)\theta}{4\theta-8} \tag{33}$$

$$\frac{\partial\pi_r}{\partial m}=\frac{\theta(2\theta m-1)}{2\theta-4} \tag{34}$$

$$\frac{\partial\pi_s}{\partial m}=-\frac{(\theta m-1)(-1+\theta)\theta}{2(\theta-2)^2} \tag{35}$$

Since m and θ are in the interval $\left(\frac{1}{2},1\right)$ it follows that $\frac{\partial\pi_n}{\partial m}<0,\frac{\partial\pi_s}{\partial m}<0$ .Setting the numerator of $\frac{\partial\pi_r}{\partial m}$, $\theta(2\theta m-1)$, to 0 gives $m=\frac{1}{2\theta}$, which is the platform fee under equilibrium conditions. Since $\theta\in\left(\frac{1}{2},1\right)$, it follows that $\frac{1}{2\theta}\in\left(\frac{1}{2},1\right)$. When $m\in\left(\frac{1}{2},\frac{1}{2\theta}\right)$, $\frac{\partial\pi_r}{\partial m}>0$, and the e-commerce platform's profit function is monotonically increasing, while when $m\in\left(\frac{1}{2\theta},1\right)$, $\frac{\partial\pi_r}{\partial m}<0$, and the e-commerce platform's profit function is monotonically decreasing.

Table 4. Comparison of the Impact of Platform Fees on the Profits of Manufacturers, Retailers, and E-Commerce Platforms

The range of values for θ	The range of values for m	Degree of impact
$\left(\frac{1}{2},1\right)$	$\left(\frac{1}{2},1\right)$	$\frac{\partial\pi_n}{\partial m}<\frac{\partial\pi_s}{\partial m}$
$\left(\frac{2}{3},1\right)$	$\left(\frac{1}{2},\frac{2}{3\theta}\right)$	$\frac{\partial\pi_n}{\partial m}<\frac{\partial\pi_r}{\partial m}$
$\left(\frac{2}{3},1\right)$	$\left(\frac{2}{3\theta},1\right)$	$\frac{\partial\pi_n}{\partial m}>\frac{\partial\pi_r}{\partial m}$
$\left(\frac{7-\sqrt{13}}{6},1\right)$	$\left(\frac{1}{2},\frac{-3+2\theta}{\theta(3\theta-5)}\right)$	$\frac{\partial\pi_r}{\partial m}>\frac{\partial\pi_s}{\partial m}$
$\left(\frac{7-\sqrt{13}}{6},1\right)$	$\left(\frac{-3+2\theta}{\theta(3\theta-5)},1\right)$	$\frac{\partial\pi_r}{\partial m}<\frac{\partial\pi_s}{\partial m}$

Proposition 9 indicates that increasing fees by e-commerce platforms affect the profits of manufacturers and retailers. When the fees are within the acceptable range for manufacturers ($m\in\left(\frac{1}{2},\frac{1}{2\theta}\right)$), platform profits increase. However, if the fees are excessively high ($m\in\left(\frac{1}{2\theta},1\right)$), platform profits decrease, which may lead to manufacturers reducing their investment or exiting, affecting transaction volumes and supply chain stability. Therefore, e-commerce platforms should set reasonable fees to maintain cooperative relationships with manufacturers and retailers, ensuring long-term development.

Corollary 4: The impact of platform fees on the profits of all members in the omni-channel supply chain is compared as shown in Table 4.

Proof: Subtract each pair of $\frac{\partial\pi_n}{\partial m},\frac{\partial\pi_r}{\partial m},\frac{\partial\pi_s}{\partial m}$ to obtain:

$$\frac{\partial\pi_n}{\partial m}-\frac{\partial\pi_r}{\partial m}=\frac{-3\theta^2m+2\theta}{2\theta-4} \quad (36)$$

$$\frac{\partial\pi_n}{\partial m}-\frac{\partial\pi_s}{\partial m}=\frac{(\theta m-1)\theta}{2(\theta-2)^2} \quad (37)$$

$$\frac{\partial\pi_r}{\partial m}-\frac{\partial\pi_s}{\partial m}=\frac{3m\theta^3+(-5m-2)\theta^2+3\theta}{2(\theta-2)^2} \quad (38)$$

Given that m and θ belong to the interval $\left(\frac{1}{2},1\right)$, it can be determined that $\frac{\partial\pi_n}{\partial m}<\frac{\partial\pi_s}{\partial m}$ .Setting the numerator of equation (36), $-3\theta^2m+2\theta$, to 0 yields $m=\frac{2}{3\theta}$. Since $m\in\left(\frac{1}{2},1\right)$, setting $\frac{1}{2}<\frac{2}{3\theta}<1$ leads to $\theta\in\left(\frac{2}{3},\frac{4}{3}\right)$, and since $\theta<1$,therefore when $\theta\in\left(\frac{2}{3},1\right),m\in\left(\frac{2}{3\theta},1\right)$, $\frac{\partial\pi_n}{\partial m}>\frac{\partial\pi_r}{\partial m}$; when $\theta\in\left(\frac{2}{3},1\right)$, $m\in\left(\frac{1}{2},\frac{2}{3\theta}\right)$, $\frac{\partial\pi_n}{\partial m}<\frac{\partial\pi_r}{\partial m}$.

Setting the numerator of equation (38), $3m\theta^2+(-5m-2)\theta+3$, to 0 yields $m=\frac{-3+2\theta}{\theta(3\theta-5)}$. Since $m\in\left(\frac{1}{2},1\right)$, setting $\frac{1}{2}<\frac{-3+2\theta}{\theta(3\theta-5)}<1$ leads to $\theta\in\left(\frac{7-\sqrt{13}}{6},1\right)$, therefore when $\theta\in\left(\frac{7-\sqrt{13}}{6},1\right)$, $m\in\left(\frac{1}{2},\frac{-3+2\theta}{\theta(3\theta-5)}\right)$, $\frac{\partial\pi_r}{\partial m}>\frac{\partial\pi_s}{\partial m}$; when $\theta\in\left(\frac{7-\sqrt{13}}{6},1\right), m\in\left(\frac{-3+2\theta}{\theta(3\theta-5)},\ 1\right), \frac{\partial\pi_r}{\partial m}<\frac{\partial\pi_s}{\partial m}$.

Corollary 4 indicates the following: ①The manufacturer's profit is affected by the e-commerce platform's fees, but can be mitigated by having both direct online sales and wholesale channels. Retailers, who rely on offline sales and are significantly impacted by the manufacturer's wholesale price adjustments, are more noticeably affected by platform fees.

②When $\theta\in\left(\frac{2}{3},1\right)$, $m\in\left(\frac{1}{2},\frac{2}{3\theta}\right)$, similar to the aforementioned reasons, manufacturers can balance profits through two channels, while e-commerce platforms mainly rely on fees for profit, so fee changes affect platforms more directly and have a smaller impact on manufacturers' profits.

When $\theta\in\left(\frac{2}{3},1\right),m\in\left(\frac{2}{3\theta},1\right)$, high platform fees significantly compress the manufacturer's profit margins, and e-commerce platforms, which already have considerable earnings, are less affected, thus platform fees have a greater impact on manufacturers' profits at this time.

③When $\theta\in\left(\frac{7-\sqrt{13}}{6},1\right)$, $m\in\left(\frac{1}{2},\frac{-3+2\theta}{\theta(3\theta-5)}\right)$, the e-commerce platform's main source of profit largely depends on platform fees, and its profits will be directly and significantly affected by changes in platform fees. Retailers, who mainly rely on offline sales and purchase from manufacturers, will have their profits impacted through the buffering of the manufacturer, which is not as intense as the impact on e-commerce platforms. When $\theta\in\left(\frac{7-\sqrt{13}}{6},1\right)$, $m\in\left(\frac{-3+2\theta}{\theta(3\theta-5)},\ 1\right)$, higher platform fees may lead manufacturers to adjust strategies, which in turn more directly affect retailers' purchase costs and sales, causing a significant impact on retailers' profits. E-commerce platforms, at a higher fee level, may already have a certain stable profit structure and are relatively less affected than retailers.

Proposition 10: The impact of platform fees on the development of the omni-channel supply chain is negative and sustainable.

Proof: The total profit function of the omni-channel supply chain is:

$$\pi = {\pi_n}^* + {\pi_s}^* + {\pi_r}^* = -\frac{(\theta m-1)(\theta m-2\theta+3)}{4(\theta-2)^2} \quad (39)$$

Taking the first-order partial derivative of equation (40) with respect to m yields: $\frac{\partial \pi}{\partial m} = -\frac{(1+(m-1)\theta)\theta}{2(\theta-2)^2}$. Since m and θ are in the interval $\left(\frac{1}{2},1\right)$, it follows that $\frac{\partial \pi}{\partial m} < 0$.

Proposition 10 illustrates that as platform fees increase, the overall profit of the omni-channel supply chain shows a declining trend. In conjunction with Proposition 9, it is evident that when e-commerce platforms raise their fees, it negatively impacts the profits of manufacturers and retailers. Although platforms may increase their own profits in the short term by raising fees, as the negative effects on manufacturers and retailers gradually expand, the operation of the entire supply chain becomes less smooth, which in turn affects the long-term interests of the e-commerce platforms, leading to unsustainable profit growth or even a decline. In summary, the omni-channel supply chain is an interdependent and interconnected whole, and when the profits of manufacturers, retailers, and e-commerce platforms are all negatively affected to varying degrees, the profit of the omni-channel supply chain will tend to decline.

4. Conclusions and Implications

This paper focuses on in-depth research on the pricing decision issues of the omni-channel supply chain under e-commerce platform fees. Centered on platform fees, it explores the equilibrium solutions that can benefit all participating members and draws the following main conclusions:

(1) In the omni-channel supply chain, the change in the manufacturer's online channel supply ratio has a significant impact on wholesale prices, retail prices, and platform fees. An increase in this ratio leads to a decrease in these three factors, while increasing the profits of manufacturers, e-commerce platforms, and the overall omni-channel supply chain, with a corresponding decrease in retailers' profits. Moreover, the profits of the manufacturer's online and offline channels will show different trends due to this change.

(2) As e-commerce platform fees gradually increase, retail and wholesale prices will rise accordingly, but this situation will correspondingly reduce the profits of manufacturers and retailers. Furthermore, when the platform fee is within a certain range, the platform's profit will increase with the increase of the fee, and vice versa. In addition, platform fees have a sustainable negative impact on the development of the omni-channel supply chain.

(3) The profits of retailers, e-commerce platforms, and the overall omni-channel supply chain will decrease with the rise of wholesale prices; within a certain range of wholesale prices, the manufacturer's profit will rise with the increase of wholesale prices, and will decline beyond that range.

(4) From the perspective of profit relationships, e-commerce platform profits are generally higher than those of manufacturers and retailers, and manufacturer profits are also higher than those of retailers. The online channel supply ratio has different impacts on the profits of the manufacturer's different channels, platform fees and wholesale prices interact with each other, and wholesale prices have a greater impact on platform fees. Additionally, the extent of the impact of platform fees on the profits of all members in the omni-channel supply chain needs to be specifically compared and analyzed based on the manufacturer's online channel supply ratio and platform fees.

In summary, the following management implications are derived:

(1) When formulating platform fee pricing strategies, to ensure the sustainable development of the platform, e-commerce platforms can moderately increase fees within a certain range to increase profits, but they should avoid the negative impact of excessive fees on the development of the omni-channel supply chain. They must clarify their advantageous position in profit relationships, use the profit differences with other members to reasonably formulate operational strategies, and not only pursue their own profits but also maintain relationships with supply chain partners. A portion of the fees should be invested in improving the efficiency, quality, and service level of the entire supply chain.

(2) For manufacturers, it is necessary to focus

on the rational allocation of channel supply shares, use the changes to wholesale prices, retail prices, and platform fees to achieve growth in their own and the overall omni-channel supply chain profits. However, the impact on retailers' profits cannot be ignored in this process. Measures should be taken to coordinate and avoid deteriorating relationships with retailers due to their own decisions, ensuring the stability and harmony of the entire supply chain and achieving a win-win development for all parties.

(3) Although retailers are in a relatively weak position in the profit distribution of the omni-channel supply chain, their existence is necessary. E-commerce platforms are in a monopolistic position in the supply chain, and manufacturers depend on them, while retailers are a means to counterbalance e-commerce platforms. Moreover, offline channels represented by retailers have functions that online channels do not have. Therefore, to promote the development of retailers, they need to actively adapt to market changes and explore new competitive advantages in offline channel sales. With the continuous increase in consumer demand for online services, retailers can use digital technology and innovative marketing strategies to enhance the experience and service level of physical stores, thereby winning consumer favor. This positive transformation is beneficial for retailers to stand out in fierce market competition, maintain their competitiveness, and open up new development spaces.

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