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RESEARCH ARTICLE

Pricing and Subsidy Strategies: The Impacts of Providers' Ability Gap on Competing Knowledge Payment Platforms

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ABSTRACT The growth of the knowledge payment market is driven by the emergence of knowledge payment platforms that match providers looking to achieve cognitive surplus through knowledge sharing with consumers looking to acquire high-quality knowledge quickly. Like many digital platforms, expanding consumer market to generate revenue has been a challenge for knowledge payment platforms as well and subsidy strategy is seen as the most important way for the same. In this paper, we focus on the pricing and subsidy strategies of two knowledge payment platforms with providers of different ability to balance the revenue from consumers and subsidies to providers. Specifically, we introduce a duopoly competition model and characterize the technical service fees and subsidies in this model. Further, we respectively analyze the impacts of providers' ability gap on two competing platforms' pricing and subsidy strategies, market shares, as well as profits. We find that as providers' ability gap increases, the platform with high-ability providers adopts strategies of increasing technical service fees and subsidies, while the platform with low-ability providers has to adopt strategies of decreasing technical service fees and subsidies. In addition, compared with low-quality platform, the platform with high-ability providers can occupy a larger share in consumer market. However, influenced by multiple factors, the provider market is relatively complex and the presence of high-quality platform cannot always ensure a larger share of it. Finally, we also find that as the difference in providers' ability of two competing platforms increases, the profit gap between these platforms also widens.

INDEX TERMS Knowledge payment platforms, pricing strategies, subsidy strategies, providers' ability gap, duopoly competition.

I. INTRODUCTION

Over the past few decades, the rapid development of information technologies and people's eagerness to pursue high-quality knowledge have changed the way of knowledge spreading and acquisition [1]. This has enabled the consumption and sharing of knowledge more convenient and provided a driving force for the development of knowledge payment industry [2]. The development trend of this industry in China is particularly remarkable. According to data released by iiMedie research [3], the scale of knowledge payment market has reached 112.65 billion RMB in 2022 and is expected to reach 280.88 billion RMB by 2025. In such context, knowledge payment platforms, which are usually run by self-interested organizers, have to compete against each other to attract more knowledge consumers and providers to obtain more potential profits [4]. Examples of such platforms are Zhihu, Himalaya FM, Dragonfly FM, Iget, etc.

The core of maintaining the prosperity of knowledge payment platforms is to stimulate its providers spontaneously produce knowledge with high-quality and thus to guarantee high satisfaction of consumers [5]. Therefore, such platforms usually offer subsidies to knowledge providers to encourage high-level professionals to join [6], which contributes to

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enrich the diversity of content and improve the quality of knowledge. For instance, as the largest Q & A knowledge platform in China, Zhihu adopts flexible subsidy strategy. It offers different subsidy rates based on the level of knowledge providers, such as 10% subsidy of their revenue for "Superstar Answerers", 5% subsidy for "Star Answerers", and no subsidy for "Rising Star Answerers" [7]. At this time, the main revenue and expenditure approaches of knowledge payment platforms are (1) charging technical service fees from consumers and (2) offering subsidies to providers. Arguably, the pricing and subsidy strategies are important when considering competition since they can significantly affect the choice of providers and consumers, and thus, the platforms' profit.

Meanwhile, the ability of providers is a key consideration for managers when formulating pricing and subsidy strategies [8], which largely determines the quality of content on these platforms [9]. On the one hand, the improvement of providers' ability effectively increases the positive utility that consumers obtain from the platform, thereby expanding the consumer market and increasing the platform's revenue. On the other hand, the improvement of providers' ability also increases the cost of knowledge production, which efficiently reduces providers' positive utility and further narrows the provider base. However, an important observation is that not all platforms choose to attract high-ability providers. In other words, the quality of knowledge varies across competing platforms. As a result, it is not clear how competing platforms with providers of different ability formulate their pricing and subsidy strategies. The goal of this research is to develop an analytical framework to establish guidelines for competing knowledge payment platforms.

In this paper, we consider a setting in which the providers' ability of two competing platforms is differentiated. We focus on the optimal pricing and subsidy strategies for knowledge payment platforms with the influence of providers' ability gap. Specifically, we seek to answer the following questions:

- Q1: When there are two knowledge payment platforms competing for the market, what will be the optimal pricing and subsidy strategies adopted by these two platforms with providers of different ability?
- Q2: In the context of profit maximization, how providers' ability gap will affect two competing platforms' pricing decisions, subsidy strategies, market shares and profits?

To address these questions, we firstly consider a duopoly competition model that captures social interactions between knowledge consumers and providers, and the platforms' own incentives to maximize profits. Then, we discuss the optimal pricing and subsidy decisions of platforms with providers of different ability. Finally, we analyze the impact of providers' ability gap on two competing platforms' pricing and subsidy strategies, market shares, and profits. The results is also numerically tested with Matlab.

The contributions of our study to the literature on knowledge payment platforms is threefold. Firstly, we propose a coherent and comprehensive model to understand the choice of consumers and providers, and the tradeoff between pricing and subsidy strategies, which further enriches the research on two-sided platforms. Secondly, we study the optimal business decisions for two competing knowledge payment platforms by introducing providers' ability gap into duopoly competition model. To the best of our knowledge, no prior work has been devoted to this research. Thirdly, our paper extends the existing literature by exploring subsidy strategy for knowledge payment platforms, which has attracted some scholars to conduct research on other platforms, but the study on knowledge payment platforms is absent.

Our results reveal that when there are two knowledge payment platforms compete for the market, as providers' ability gap increasing, the platform with high-ability providers adopts strategies of increasing technical service fees and subsidies, while the platform with low-ability providers has to adopt strategies of decreasing technical service fees and subsidies. In addition, we find that compared with low-quality platform, the platform with high-ability providers can occupy a larger share in consumer market with the increase in providers' ability gap between two platforms. However, influenced by multiple factors, the provider market is relatively complex and the presence of high-quality platform cannot always ensure a larger share of it. Finally, we also find that as the difference in providers' ability of two competing platforms increases, the profit gap between these platforms also widens.

The remainder of the paper is organized as follows. In the next section, we position our paper in the context of the recent literature related to knowledge payment platforms, pricing strategies, and subsidy strategies. In Section III, we describe the model when two platforms compete for the market. In Section IV, we analyze the market equilibrium and examine platforms' strategic responses to the change of providers' ability gap. In Section V, we present our conclusions.

II. LITERATURE REVIEW

This paper draws upon three lines of the existing research: knowledge payment platforms, pricing strategies, and subsidy strategies.

A. KNOWLEDGE PAYMENT PLATFOMRS

Knowledge payment is the behavior of purchasing-related knowledge products or services on platforms to enhance cognition, enrich experience, and improve skills [10]. People have the opportunity to engage in direct knowledge exchange with others through platforms, which has evolved into an essential component of knowledge management [11]. In essence, the unique economic model of knowledge payment platforms facilitates the flow and dissemination of knowledge and ultimately optimizes the allocation of social information resources [12]. Certain scholars explore the operation mode of knowledge payment platforms [13], [14].

Marta-Lazo et al. [15] propose that the success of knowledge payment is dependent on its exclusivity, specialization, accessibility, and differentiation. Oh et al. [16] examine how the implementation of paywall by a firm influences the pattern and effectiveness of online word-of-mouth in social media, and indicate that a paywall has implications for product and promotion strategies.

The knowledge providers and consumers, as the two sides of knowledge payment platforms, directly influence the platforms' operation and decision. Most of existing literature focuses on the consumer side, such as their payment demands [17], [18], willingness to pay [19], [20], and payment behavior [21], [22]. The other most important stimuli that attract consumers are the characteristics of knowledge providers. Brownell and Goldsmith [23] consider the professionalism and personal charisma of providers as two aspects reflect providers' common competency and distinctive competency, respectively. He and Wei [24] combine structural equation modeling and neural network analysis to study providers' characteristics, and reveal that providers' professionalism and ability positively influence consumers' knowledge payment intention. Zhao et al. [25] propose that ability is an important indicator for measuring the knowledge quality of providers and become a reference for consumers to judge whether to join the platform.

Therefore, the providers play an important role in the development of knowledge payment platforms. Unlike tangible products, the knowledge quality is hard to guarantee without traditional gate-keeping on the side of knowledge production [26] and cannot be easily evaluated before consuming [27], as it is largely determined by providers' ability. On this basis, our research introduces the providers' ability as an important parameter into the model and analyzes the business decisions of knowledge payment platforms under the influence of providers' ability gap.

B. PRICING STRATEGIES

Digital platforms have become the most popular business model, which has greatly promoted economic growth for a number of sectors, such as Uber and Didi Chuxing in transportation, Airbnb and Xiaozhu in accommodation [28]. With the development of this business model and the upgrading of consumption pattern, several digital platforms have emerged for intangible assets industry, such as Quora and Zhihu in knowledge sharing [29]. Nevertheless, the pricing on digital platforms is a complex topic, and its application requires core knowledge relating to multiple dimensions, including product attributes, market demand, competitors' price and consumers [30]. In addition, digital platforms in different industries also face different problems in pricing under the influence of their own characteristics.

The pricing strategies of digital platforms in the transportation industry is crucial in organically coordinating various factors to maximize the benefits of drivers and customers [31]. One of the most important features of the kind of platforms is its price differentiation. The Uber platform adjusts its prices using a real-time dynamic algorithm known as "Surge" pricing, which automatically raises the price of a trip when demand outstrips supply within a fixed geographic area [32], [33]. Moreover, the locations and waiting time of customers and vacant drivers also have important impact on platform's pricing [34], [35]. For digital accommodation platforms, the development of pricing strategies needs to consider the seasonality of demand [36], the inflexibility of the product supply [37], the possibility for time-based price discrimination and dynamic pricing (e.g. offering early-bird or last-minute discounts) [38].

One of the challenges of any digital platform is to formulate pricing strategies to compete for the market and gain more profit. However, studies on the pricing strategies of digital platforms in a competitive environment are scarce. Hou et al. [39] analytically investigate the impact of competition on the value of PAYW (pay as you want) by comparing it to the traditional fixed pricing strategy and find that both users choose PAYW when the fairness ideal is sufficiently high in equilibrium. Li et al. [40] study the optimal pricing strategies for competing platforms that integrate SNS into their service and address the impact of social effect and service quality on business decisions.

Different from the above researches, our paper considers a duopoly competition model that incorporates social interactions between knowledge consumers and providers, as well as the platforms' inherent incentives to maximize their profits. Furthermore, our research separately examines the optimal pricing strategies of knowledge payment platforms with high-ability providers and low-ability providers. This contributes to the existing literature on duopoly competition model, shedding light on the intricacies of pricing strategies in this context.

C. SUBSIDY STRATEGIES

With the increasingly fierce competition in the market, it is particularly important for enterprises to take measures and have a long-term perspective in order to stand out and achieve sustainable development [41]. Subsidy is the common price strategy of various industries, although the revenue of enterprises is not significant in a short period of time, but it has an important effect on the long-term development and profitability of enterprises [42]. At the same time, subsidy strategy is the natural, and appropriate, instruments for the pursuit of a wide variety of policy goals [43], which attracts many scholars to study under different government policies. Fan and Dong [44] explore an evolutionary game model including enterprises and consumers and discuss how to select subsidy strategy for government in low-carbon diffusion.

In the ear of network economy, the digital platforms has greatly reduced the cost in the traditional trading process [45]. The strategic interactions between digital platforms depend not only on their pricing decisions, but also on whether platforms are equally subsidizing one side of the market [46], [47]. In order to seize the market in the increasingly fierce competition, platforms choose to use subsidy strategy to attract users form both sides to join and trade [48]. As an important supplement to the pricing strategy, subsidies directly affect the interests of participants in the transaction process, aiming to create the correct incentives for each value chain participant [49]. Caillaud and Jullien [50] believe that the subsidy strategy is a useful transition strategy in the early development stage of digital platforms. Kung and Zhong [51] analyze the equilibrium results of platforms under cross-subsidies, membership fees and transaction fees and conclude that these three strategies are equivalent when time discounting is absent and consumers' order frequency is price-insensitive. Fang et al. [52] design subsidy strategy on sharing platforms with the goal of maximizing revenue, and propose that subsidy mechanism has a huge impact on service supple.

Knowledge payment platforms, providing a convenient channel for knowledge sharing and acquisition, is expanding rapidly. However, there is no literature directly studying the subsidy strategies of knowledge payment platforms. In our paper, we creatively propose the subsidy strategies for competing knowledge payment platforms and systematically research how provider's ability gap affect it. Our aim is to provide theoretical support and decision suggestions for knowledge payment industry to expand consumer market and achieve higher profit.

III. MODEL

In this section, we consider a market with two competing knowledge payment platforms A and B that provide transaction services, as well as consumers and knowledge providers that we normalize to 1, respectively. We follow the common assumption of both consumers and providers can only join one platform, namely, single-homing [53], [54], [55]. These two platforms located at the two end points of a Hotelling line with platform A located at 0, and platform B at 1 [56], [57], [58]. On the one hand, the knowledge platforms A and B provide technical support and charge consumers a certain technical service fees P_A and P_B, respectively. On the other hand, in order to compete for high-quality provider market to produce original content, the platforms provide subsidies S_A and S_B to providers, respectively. At this time, the profits of both platform A and platform B are determined by two parts: the technical service fees paid by consumers and subsidy fees provided for providers. In addition, we suppose that n_1^A and n_2^A represent the number of consumers and providers who join platform A, while n_1^B and n_2^B represent the number of consumers and providers who join platform B. Therefore, the profits of knowledge payment platforms A and B are:

$$\eta_A = P_A n_1^A - S_A n_2^A \tag{1}$$

$$\eta_B = P_B n_1^B - S_B n_2^B \tag{2}$$

We use the parameter x to designate the type of consumers, that is, the location in the linear city, and assume that x is uniformly distributed in [0, 1]. Transport cost is linear in distance traveled. We use t_1 to represent the unit transport cost of consumers, so that the distance costs of consumers on platforms A and B are $t_1 x$ and $t_1(1-x)$, respectively. Let β be a consumer's utility from an additional provider. The utility that the consumer get from the provider base of platforms A and B are βn_2^A and βn_2^B, respectively. In addition, we use parameters q_A, q_B and θ to describe the providers' ability of platform A, the providers' ability of platform B and consumers' sensitivity to providers' ability, and assume that $\theta \in (0, 1)$. Therefore, the utility of consumers on platforms A and B can be shown as:

$$U_1^A = \beta n_2^A + \theta q_A - P_A - t_1 x \tag{3}$$

$$U_1^B = \beta n_2^B + \theta q_B - P_B - t_1(1-x) \tag{4}$$

where θq_A and θq_B mean positive utilities that consumers get from providers' ability of platforms A and B, respectively.

Similarly, we use the parameter y to represent the type of providers, which satisfies the uniform distribution with support [0, 1]. t_2 is the unit transport cost of providers, so that the distance costs of providers on platforms A and B are $t_2 y$ and $t_2(1-y)$, respectively. Furthermore, as platforms' consumer base increases, the benefit of the provider will increase. We use parameter α to describe this network externality, so that the utility that providers get from the consumer base of platforms A and B are αn_1^A and αn_1^B, respectively. Let δ be the unit cost of providers' ability and assume that $\delta \in (0, 1)$. δq_A and δq_B are the utility brought by the cost of providers' ability improvement on platforms A and B, respectively. In addition, we respectively use V_A and V_B to denote the basic service valuation that providers can get by joining platforms A and B, and assume that V_A and V_B are exogenous constant. Therefore, the utility of providers on platforms A and B can be shown as:

$$U_2^A = V_A + \alpha n_1^A - \delta q_A + S_A - t_2 y \tag{5}$$

$$U_2^B = V_B + \alpha n_1^B - \delta q_B + S_B - t_2(1-y) \tag{6}$$

Moreover, we suppose that the consumers' sensitivity to providers' ability is greater than the unit cost of providers' ability ($\theta > \delta$), which motivates providers to improve their own capability. Meanwhile, to simplify the analysis, we assume that the network externality from providers to consumers is greater than the network externality from consumers to providers, namely, $\beta > \alpha$.

Table 1 summarizes all parameters used in this paper.

IV. ANALYSIS

A. EQUILIBRIUM ANALYSIS

When there are two knowledge payment platforms in the market, consumers and knowledge providers will choose to join the platform that can maximize their utility. Considering that consumers are uniformly distributed in the linear city, we use x' to denote the marginal consumers who is indifferent between joining either platform, namely, $U_1^A = U_1^B$. Let $t_1 = 1$. The marginal consumers x' can be derived as:

$$x' = \frac{1}{2} + \frac{\beta\left(n_2^A - n_2^B\right) + \theta\left(q_A - q_B\right) - \left(P_A - P_B\right)}{2} \tag{7}$$

Therefore, consumers located on the left side of x' will sign to platform A, while those located on the right side of x' will

TABLE 1. Summary of notations.

Parameters	Description
α	The network externality from consumers to providers
β	The network externality from providers to consumers
x	The location of consumers in the linear city
y	The location of providers in the linear city
n_1^A	The number of consumers on platform A
n_2^A	The number of providers on platform A
n_1^B	The number of consumers on platform B
n_2^B	The number of providers on platform B
t_1	The unit transport cost of consumers
t_2	The unit transport cost of providers
q_A	The providers' ability of platform A
q_B	The providers' ability of platform B
Δq	The difference in providers' ability of platforms A and B
θ	The consumers' sensitivity to providers' ability
δ	The unit cost of providers' ability
η_A	The profit of platform A
η_B	The profit of platform B
$\Delta\eta$	The difference in profit of platforms A and B
V_A	The basic service valuation of providers provided by platform A
V_B	The basic service valuation of providers provided by platform B
P_A	The technical service fees charged by platform A
P_B	The technical service fees charged by platform B
S_A	The subsidies provided by platform A
S_B	The subsidies provided by platform B
U_1^A	The utility of consumers on platform A
U_1^B	The utility of consumers on platform B
U_2^A	The utility of providers on platform A
U_2^B	The utility of providers on platform B

sign to platform B. The number of consumers joining either platform is given by the following equation:

$$n_1^A = x', \quad n_1^B = 1 - x' \tag{8}$$

Similarly, we suppose that there exists y' where knowledge providers have equal utility in joining platform A or B, namely, $U_2^A = U_2^B$. Let $t_2 = 1$, The marginal providers y' can be expressed as:

$$y' = \frac{(V_A - V_B) + \alpha\left(n_1^A - n_1^B\right) - \delta\left(q_A - q_B\right) + (S_A - S_B)}{2} + \frac{1}{2} \tag{9}$$

At this point, providers on the left side of y' will join platform A, while those on the right side of y' will join platform B. The number of providers on platform A and B should satisfy the following equation:

$$n_2^A = y', \quad n_2^B = 1 - y' \tag{10}$$

Bring x' and y' into equations (8) and (10), the equilibriums of users can be expressed as:

$$n_1^A(P_A, S_A) = \frac{1}{2} + \frac{\beta\left(V_A - V_B\right) + \left(\theta - \beta\delta\right)\left(q_A - q_B\right) + \beta\left(S_A - S_B\right)}{2(1 - \alpha\beta)} - \frac{(P_A - P_B)}{2(1 - \alpha\beta)} \tag{11}$$

$$n_1^B\left(P_B, S_B\right) = \frac{1}{2} - \frac{\beta\left(V_A - V_B\right) + \left(\theta - \beta\delta\right)\left(q_A - q_B\right) + \beta\left(S_A - S_B\right)}{2(1 - \alpha\beta)} + \frac{(P_A - P_B)}{2(1 - \alpha\beta)} \tag{12}$$

$$n_2^A\left(P_A, S_A\right) = \frac{1}{2} + \frac{(V_A - V_B) + \left(\alpha\theta - \delta\right)\left(q_A - q_B\right) - \alpha\left(S_A - S_B\right)}{2(1 - \alpha\beta)} + \frac{(S_A - S_B)}{2(1 - \alpha\beta)} \tag{13}$$

$$n_2^B\left(P_B, S_B\right) = \frac{1}{2} - \frac{(V_A - V_B) + \left(\alpha\theta - \delta\right)\left(q_A - q_B\right) - \alpha\left(S_A - S_B\right)}{2(1 - \alpha\beta)} - \frac{(S_A - S_B)}{2(1 - \alpha\beta)} \tag{14}$$

From the above derivation, the decision problems of platforms A and B can be expressed as:

$$\max\eta_A\left(P_A, S_A\right) = P_A n_1^A\left(P_A, S_A\right) - S_A n_2^A\left(P_A, S_A\right) \tag{15}$$

$$\max\eta_B\left(P_B, S_B\right) = P_B n_1^B\left(P_B, S_B\right) - S_B n_2^B\left(P_B, S_B\right) \tag{16}$$

The Hessian matrix of $\eta_A\left(P_A, S_A\right)$ is negative, that is η_A has an optimal solution. As a result, the optimal technical service fees and subsidies of platform A can be deduced as:

$$P_A^* = \frac{\delta\left(\beta - \alpha\right)\left(q_A - q_B\right) + \theta\left(2\alpha\beta + \alpha^2 - 3\right)\left(q_A - q_B\right)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} + \frac{(\alpha - \beta)(V_A - V_B)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} + 1 - \alpha \tag{17}$$

$$S_A^* = \frac{\delta\left(2\alpha\beta + \beta^2 - 3\right)\left(q_A - q_B\right) + \theta\left(\alpha - \beta\right)\left(q_A - q_B\right)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} + \frac{\left(3 - 2\alpha\beta - \beta^2\right)\left(V_A - V_B\right)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} + \beta - 1 \tag{18}$$

Similarly, the Hessian matrix of $\eta_B\left(P_B, S_B\right)$ is negative, that is η_B has an optimal solution. Therefore, the optimal technical service fees and subsidies of platform B can be derived as:

$$P_B^* = -\frac{\delta\left(\beta - \alpha\right)\left(q_A - q_B\right) + \theta\left(2\alpha\beta + \alpha^2 - 3\right)\left(q_A - q_B\right)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} - \frac{(\alpha - \beta)(V_A - V_B)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} + 1 - \alpha \tag{19}$$

$$S_B^* = -\frac{\delta\left(2\alpha\beta + \beta^2 - 3\right)\left(q_A - q_B\right) + \theta\left(\alpha - \beta\right)\left(q_A - q_B\right)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} - \frac{\left(3 - 2\alpha\beta - \beta^2\right)\left(V_A - V_B\right)}{\left(2\alpha + \beta\right)\left(2\beta + \alpha\right) - 9} + \beta - 1 \tag{20}$$

Bring the optimal technical service fees P_A^*, P_B^* and the optimal subsidies S_A^*, S_B^* into equations (11)-(16), we conclude the equilibriums in lemma 1.

Lemma 1: When there are two knowledge payment platforms in the market, the equilibriums of the model are as follows:

$$P_A^* = \frac{\delta(\beta-\alpha)(q_A-q_B)+\theta\left(2\alpha\beta+\alpha^2-3\right)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{(\alpha-\beta)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+1-\alpha$$

$$P_B^* = -\frac{\delta(\beta-\alpha)(q_A-q_B)+\theta\left(2\alpha\beta+\alpha^2-3\right)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} - \frac{(\alpha-\beta)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+1-\alpha$$

$$S_A^* = \frac{\delta\left(2\alpha\beta+\beta^2-3\right)(q_A-q_B)+\theta(\alpha-\beta)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{\left(3-2\alpha\beta-\beta^2\right)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+\beta-1$$

$$S_B^* = -\frac{\delta\left(2\alpha\beta+\beta^2-3\right)(q_A-q_B)+\theta(\alpha-\beta)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} - \frac{\left(3-2\alpha\beta-\beta^2\right)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+\beta-1$$

$$n_1^A\left(P_A^*, S_A^*\right) = \frac{1}{2}+\frac{\delta(2\alpha+\beta)(q_A-q_B)-3\theta(q_A-q_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]} - \frac{(2\alpha+\beta)(V_A-V_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]}$$

$$n_1^B\left(P_B^*, S_B^*\right) = \frac{1}{2}-\frac{\delta(2\alpha+\beta)(q_A-q_B)-3\theta(q_A-q_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]} + \frac{(2\alpha+\beta)(V_A-V_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]}$$

$$n_2^A\left(P_A^*, S_A^*\right) = \frac{1}{2}+\frac{3\delta(q_A-q_B)-\theta(\alpha+2\beta)(q_A-q_B)-3(V_A-V_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]}$$

$$n_2^B\left(P_B^*, S_B^*\right) = \frac{1}{2}-\frac{3\delta(q_A-q_B)-\theta(\alpha+2\beta)(q_A-q_B)-3(V_A-V_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]}$$

$$\eta_A\left(P_A^*, S_A^*\right) = 1-\frac{\alpha+\beta}{2}+\left(\frac{1}{2}+Y\right)X+(1-\alpha)Y - \left(\frac{1}{2}+Z\right)K+(1-\beta)Z$$

$$\eta_B\left(P_B^*, S_B^*\right) = 1-\frac{\alpha+\beta}{2}+\left(Y-\frac{1}{2}\right)X-(1-\alpha)Y + \left(\frac{1}{2}-Z\right)K-(1-\beta)Z$$

$$\Delta\eta = X+2(1-\alpha)Y-K+2(1-\beta)Z$$

$$X = \frac{\delta(\beta-\alpha)(q_A-q_B)+\theta\left(2\alpha\beta+\alpha^2-3\right)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{(\alpha-\beta)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}$$

$$Y = \frac{\delta(2\alpha+\beta)(q_A-q_B)-3\theta(q_A-q_B)-(2\alpha+\beta)(V_A-V_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]}$$

$$K = \frac{\delta\left(2\alpha\beta+\beta^2-3\right)(q_A-q_B)+\theta(\alpha-\beta)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{\left(3-2\alpha\beta-\beta^2\right)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}$$

$$Z = \frac{3\delta(q_A-q_B)-\theta(\alpha+2\beta)(q_A-q_B)-3(V_A-V_B)}{2\left[(2\alpha+\beta)(2\beta+\alpha)-9\right]}$$

B. SENSITIVITY ANALYSIS

In this part, we characterize the properties of equilibrium outcomes derived in Lemma 1. Without loss of generality, we assume that the ability of knowledge providers on platform A is greater than that on platform B, namely, $q_A > q_B$. Therefore, the difference in providers' ability of platforms A and B is $\Delta q = q_A - q_B$. All proofs are provided in Appendix.

Proposition 1: When the difference in providers' ability of platforms A and B (i.e., Δq*) increases, we find:*

(i) The platform with high-ability providers increases technical service fees charged from consumers, and increases subsidies to providers. Mathematically, $\partial P_A^*/\partial\Delta q > 0$ and $\partial S_A^*/\partial\Delta q > 0$.

(ii) The platform with low-ability providers decreases technical service fees charged from consumers, and decreases subsidies to providers. Mathematically, $\partial P_B^*/\partial\Delta q < 0$ and $\partial S_B^*/\partial\Delta q < 0$.

The results show that when there are two knowledge platforms in the market, the greater the difference in providers' ability, the higher the technical service fees and subsidies of the platform with high-ability providers, and the lower the technical service fees and subsidies of the platform with low-ability providers. The quality of knowledge content, which is largely determined by providers' ability [9], has a positive impact on consumer decision to choose and pay for the knowledge [5]. It is easy to understand that when there is a big difference in providers' ability, consumers are more likely to join the platform with high-ability providers. At this time, the high-quality platform naturally choose to increase technical service fees to increase its revenue. Moreover, as platform's revenue increasing, it is capable of providing more subsidies to providers, which further stimulates high-ability providers to join the platform, enriches the diversity of content, and ultimately forms a positive cycle. However, with the continuous expansion of ability gap between two platforms, the competitiveness and consumer base of platform with low-ability providers are gradually decreasing. Therefore, the platform can only choose to lower technical service fees to offset loss and attract consumers. At the same time, the narrowed consumer base leads to a decrease in platform's revenue, which actually forces the platform to reduce subsidies to providers.

Fig. 1 graphically illustrates the impact of the difference in providers' ability of platforms A and B on the technical service fees and subsidies with the conditions of $\alpha = 0.5, \beta = 0.9, \theta = 0.9, \delta = 0.8, V_A = V_B = 2$. The basic service valuation of providers is not the focus of this research. To simplify the analysis, we assume that the basic service valuation of providers is the same for the two platforms in the following of the paper, namely, $V_A = V_B$.

It can be observed from Fig. 1 that both technical service fees and subsidies of the platform with high-ability providers show upward trend with the increase of the providers' ability gap between two platforms, while both technical service fees and subsidies of the platform with low-ability providers show downward trend with the increase of the providers' ability gap between two platforms. Interestingly, we also find that when two platforms with varying content quality compete for knowledge payment market, the narrowed consumer base and reduced technical service fees of the low-ability platform leads to a rapid decrease in platform's revenue. At this time, the platform will not adopt the strategy of subsidizing providers, but in turn will charge a certain fees to those who join the platform.

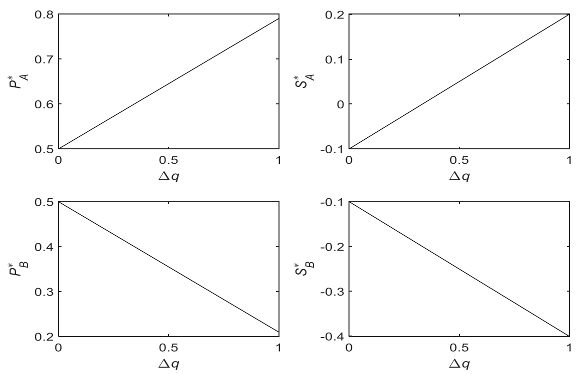

FIGURE 1. The impact of the difference in providers' ability of platforms A and B on the technical service fees and subsidies.

Proposition 2: When the difference in providers' ability of platforms A and B (i.e., Δq) increases, we find:

(i) The number of consumers on the platform with high-ability providers increases, while decreases on the platform with low-ability providers. Mathematically, $\partial n_1^{A*}/\partial \Delta q > 0$ and $\partial n_1^{B*}/\partial \Delta q < 0$.

(ii) If $\delta/\theta > (\alpha + 2\beta)/3$, the number of providers on the platform with high-ability providers decreases, while increases on the platform with low-ability providers. Mathematically, $\partial n_2^{A*}/\partial \Delta q < 0$ and $\partial n_2^{B*}/\partial \Delta q > 0$. Otherwise, if $\delta/\theta < (\alpha + 2\beta)/3$, the number of providers on the platform with high-ability providers increases, while decreases on the platform with low-ability providers. Mathematically, $\partial n_2^{A*}/\partial \Delta q > 0$ and $\partial n_2^{B*}/\partial \Delta q < 0$.

Part (i) of Proposition 2 explains that as the providers' ability gap between the two platforms widens, the difference in knowledge quality on platforms is more significant, which efficiently attracts consumers to join the platform with high-quality knowledge. Therefore, compared with low-ability platform, the high-ability platform naturally occupies a larger share in consumer market with the increase in providers' ability gap between two platforms.

Fig. 2 reflects the impact of the providers' ability gap between platforms A and B on the number of consumers where $\alpha = 0.5, \beta = 0.6, \theta = 0.8, \delta = 0.4, V_A = V_B = 2$. It can be observed that the number of consumers on the platform with high-ability providers shows an upward trend with the increase of providers' ability gap.

Part (ii) of Proposition 2 indicates that the impact of providers' ability gap on the number of providers depends on multiple factors: network externalities between consumers and providers, consumers' sensitivity to providers' ability, and the unit cost of provider's ability. Specifically, under the condition of $\delta/\theta > (\alpha + 2\beta)/3$, the number of providers on low-ability platform continues to increase with an increase in providers' ability gap, while the number of providers on high-ability platform decreases gradually. On the contrary, the scale of provider on the platform with high-ability providers expands as the difference in providers' ability rising, while reduces on the low-ability platform with the condition of $\delta/\theta < (\alpha + 2\beta)/3$. It is understandable that the utility of providers is influenced by several parameters. On the one hand, the number of consumers and subsidies of platforms have positive effect on providers' utility. On the other hand, providers have to bear more cost to produce knowledge of higher quality, which definitely leads to a reduction in the utility they derive from platforms. Combined with Proposition 1, it can be seen that with the increase in providers' ability gap, the negative utility of increasing in production cost is greater than positive utility of increasing in the number of consumers and subsidies for platform with high-ability providers if $\delta/\theta > (\alpha + 2\beta)/3$. However, for platform with low-ability providers, the decrease in production cost can offset the loss of consumer base and subsidies, thereby expanding provider base. In contrast, for platform with high-ability providers, the positive utility generated by the increased consumer base and subsidies outweighs the negative utility caused by the increased cost as the difference in providers' ability rising if $\delta/\theta < (\alpha + 2\beta)/3$. At this time, the decrease in production cost of low-ability platform cannot make up for the massive loss caused by the narrowed consumer base and reduced subsidies.

The impact of the difference in providers' ability of platforms A and B on the number of providers can be seen from Fig. 3-4 where $\alpha = 0.5, \beta = 0.6, \theta = 0.9, \delta = 0.8, V_A = V_B = 2$ and $\alpha = 0.5, \beta = 0.6, \theta = 0.9, \delta = 0.2, V_A = V_B = 2$, respectively. The results show that the number of providers on the platform with high-ability providers shows a downward trend as providers' ability gap increasing when $\delta/\theta > (\alpha + 2\beta)/3$; on the contrary, the number of providers on the platform with low-ability providers shows an upward trend. Nevertheless, when $\delta/\theta < (\alpha + 2\beta)/3$, the number of providers on the platform with high-ability providers shows an upward trend as providers' ability gap increasing, while the number of providers on the platform with low-ability providers shows a downward trend.

Proposition 3: As the difference in providers' ability of platforms A and B (i.e., Δq) increases, the profit gap between

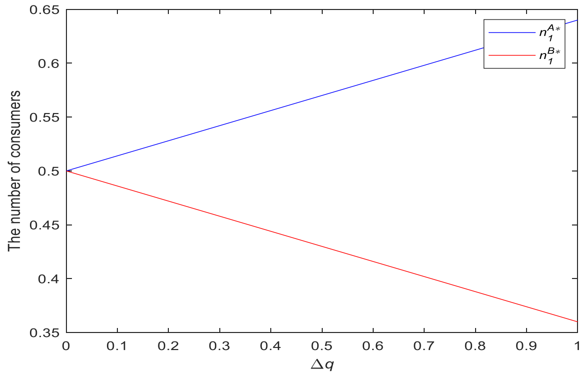

FIGURE 2. **The impact of the difference in providers' ability of platforms A and B on the number of consumers.**

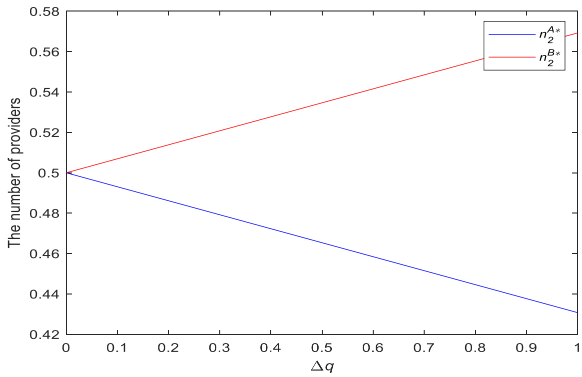

FIGURE 3. **The impact of the difference in providers' ability of platforms A and B on the number of providers ($\delta/\theta > (\alpha + 2\beta)/3$).**

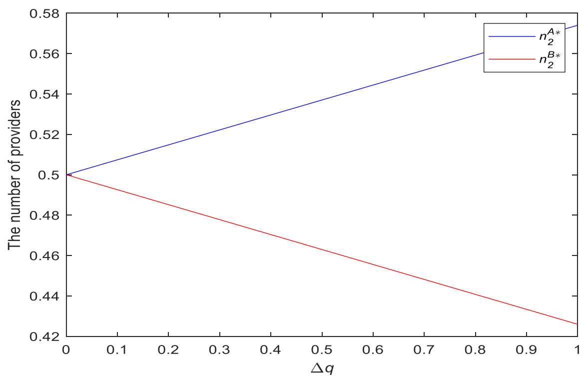

FIGURE 4. **The impact of the difference in providers' ability of platforms A and B on the number of providers ($\delta/\theta < (\alpha + 2\beta)/3$).**

platforms A and B (i.e., $\Delta\eta$) increases. Mathematically, $\partial\Delta\eta/\partial\Delta q > 0$.

Combined with Proposition 1 and Proposition 2, we find that the increase in the number of consumers on the platform with high-ability providers leads to an increase in technical service fees and subsidies as the difference in providers' ability rising. However, the consumer base on the low-ability platform continues to shrink, which has negative effect on technical service fees and subsidies. Meanwhile, although it is uncertain how the number of providers on platforms A and B change under the influence of multiple factors, compared with low-ability platform, the positive utility of increasing revenue obtained by the platform with high-ability providers is greater than the negative utility of increasing cost, and thereby increasing its profit. Hence we can conclude that the profit gap between platforms A and B widens with the increasing of the difference in those two providers' ability.

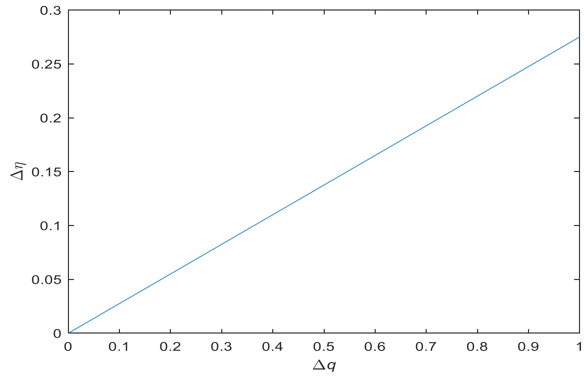

FIGURE 5. **The impact of the difference in providers' ability of platforms A and B on the profit gap.**

Fig. 5 explores how the providers' ability gap between platforms A and B affect profit gap under the conditions of $\alpha = 0.5$, $\beta = 0.6$, $\theta = 0.8$, $\delta = 0.4$, $V_A = V_B = 2$. Obviously, the profit gap between two platforms shows an upward trend as providers' ability gap increasing.

V. CONCLUSION

In this paper we study the pricing and subsidy strategies within two competing knowledge payment platforms. We extend traditional duopoly models of two-sided markets to consider the influence of providers' ability gap. The platforms with providers of different ability need to choose the optimal business decisions to maximize the tradeoff between revenue and subsidies as well as maintain its profit.

This study has the following implications. Firstly, previous studies on pricing decisions of digital knowledge platforms mainly explore factors influencing consumer decision from the viewpoint of platform characteristics and consumer behavior [59], [60], [61], [62]. However, we believe that in digital knowledge platforms where consumers cannot get any commodity information in advance other than the price, the ability of providers is much more critical in consumer payment decision. Therefore, to fill this research gap, based on the classic Hotelling model in industrial organization, we introduce provider's ability gap into the duopoly competition model and examine that providers' ability gap have significant impact on pricing and subsidy strategies, market share, and profit of knowledge payment platforms. The results show that with an increase in providers' ability gap between two competing platforms, the platform with high-ability providers adopts strategies of increasing technical service fees, while in turn the platform with low-ability providers adopts strategies of decreasing technical service fees.

Secondly, our paper is the first attempt to study the subsidy strategy of knowledge payment platforms. Subsidy strategy plays an important role in winning market competition, which has attracted many scholars to conduct in-depth research on different platforms [63], [64], [65], but the research on knowledge payment platforms is inadequate. Thus, our paper fills the gap of research on subsidy strategy of knowledge payment platforms and provides a more precise insight for researchers into knowledge payment. Our research reveals that as the difference in providers' ability of two competing platforms rising, high subsidies is a better choice for high-quality platform, while low-quality platform has to decrease subsidies.

Meanwhile, we find that compared with low-quality platform, the platform with high-ability providers can occupy a larger share in consumer market with the increase in providers' ability gap between two platforms. However, influenced by multiple factors, the provider market is relatively complex and the presence of high-quality platform cannot always ensure a larger share of it. In addition, we develop the profit maximization model to test pricing and subsidy strategies of competing knowledge payment platforms, and investigate the impact of provider's ability gap on profits as well. The result shows that the profit gap between two competing platforms widens as the difference in providers' ability of those platforms increasing.

The current study can be extended in several directions. Firstly, the payment behavior of consumers is largely determined by providers' ability in our study. However, there are many other important factors that can affect consumer's choice, such as reputation, expertise, ranking and the number of followers of knowledge providers. Future studies can focus on those factors to further provide platforms with practical decisions. In addition, platform investment is another popular strategy for knowledge payment platforms to expand market and increase profit. Therefore, studying the impact of investment strategy will also be an interesting direction.

APPENDIX A
PROOF FOR LEMMA 1.

Bring $n_1^A(P_A, S_A)$ and $n_2^A(P_A, S_A)$ into equation (1), the profit of platform A can be expressed as:

$$\begin{aligned}\eta_A(P_A, S_A) &= P_A\left[\frac{\beta(V_A-V_B)+(\theta-\beta\delta)(q_A-q_B)+\beta(S_A-S_B)}{2(1-\alpha\beta)}\right] \\ &\quad - S_A\left[\frac{(V_A-V_B)+(\alpha\theta-\delta)(q_A-q_B)-\alpha(S_A-S_B)}{2(1-\alpha\beta)}\right] \\ &\quad - P_A\left[\frac{P_A-P_B}{2(1-\alpha\beta)}\right]+S_A\left[\frac{S_A-S_B}{2(1-\alpha\beta)}\right]+\frac{1}{2}(P_A-S_A)\end{aligned} \tag{21}$$

From the above equation, we take the first derivatives of $\eta_A(P_A, S_A)$ with respect to P_A and S_A, respectively. $\partial\eta_A/\partial P_A$ and $\partial\eta_A/\partial S_A$ can be expressed as:

$$\frac{\partial\eta_A}{\partial P_A} = \frac{\beta(V_A-V_B)+(\theta-\beta\delta)(q_A-q_B)+\beta(S_A-S_B)}{2(1-\alpha\beta)} + \frac{P_B+\alpha S_A}{2(1-\alpha\beta)} - \frac{P_A}{1-\alpha\beta} + \frac{1}{2} \tag{22}$$

$$\frac{\partial\eta_A}{\partial S_A} = \frac{(V_A-V_B)+(\alpha\theta-\delta)(q_A-q_B)-\alpha(P_A-P_B)}{2(1-\alpha\beta)} + \frac{\beta P_A-S_B}{2(1-\alpha\beta)} - \frac{S_A}{1-\alpha\beta} - \frac{1}{2} \tag{23}$$

Meanwhile, we take the second derivatives of $\eta_A(P_A, S_A)$ and get the results of $\partial^2\eta_A/\partial P_A^2$, $\partial^2\eta_A/(\partial P_A\partial S_A)$, and $\partial^2\eta_A/\partial S_A^2$.

$$\frac{\partial^2\eta_A}{\partial P_A^2} = -\frac{1}{1-\alpha\beta} \tag{24}$$

$$\frac{\partial^2\eta_A}{\partial P_A\partial S_A} = \frac{\alpha+\beta}{2(1-\alpha\beta)} \tag{25}$$

$$\frac{\partial^2\eta_A}{\partial S_A^2} = -\frac{1}{1-\alpha\beta} \tag{26}$$

Therefore, the Hessian matrix of platform A can be expressed as:

$$H_A = \begin{bmatrix} -\dfrac{1}{1-\alpha\beta} & \dfrac{\alpha+\beta}{2(1-\alpha\beta)} \\ \dfrac{\alpha+\beta}{2(1-\alpha\beta)} & -\dfrac{1}{1-\alpha\beta} \end{bmatrix} \tag{27}$$

It can be seen from Table 1 that α and β are network externalities, which means that $0 < \alpha < 1$ and $0 < \beta < 1$. Therefore, we can deduce that $|H_{A1}| = -1/(1-\alpha\beta) < 0$, $|H_{A2}| = \left[4-(\alpha+\beta)^2\right]/[4(1-\alpha\beta)^2] > 0$. As a result, the Hessian matrix of $\eta_A(P_A, S_A)$ is negative. In order to derive the optimal technical service fees and subsidies of platform A, we let $\partial\eta_A/\partial P_A = 0$ and $\partial\eta_A/\partial S_A = 0$. The optimal technical service fees P_A^* and the optimal subsidies S_A^* can be expressed as:

$$P_A^* = \frac{\delta(\beta-\alpha)(q_A-q_B)+\theta\left(2\alpha\beta+\alpha^2-3\right)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{(\alpha-\beta)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+1-\alpha \tag{28}$$

$$S_A^* = \frac{\delta\left(2\alpha\beta+\beta^2-3\right)(q_A-q_B)+\theta(\alpha-\beta)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{\left(3-2\alpha\beta-\beta^2\right)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+\beta-1 \tag{29}$$

Similarly, we can obtain the optimal technical service fees P_B^* and the optimal subsidies S_B^* of platform B.

$$P_B^* = -\frac{\delta(\beta-\alpha)(q_A-q_B)+\theta\left(2\alpha\beta+\alpha^2-3\right)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} - \frac{(\alpha-\beta)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+1-\alpha \tag{30}$$

$$S_B^* = -\frac{\delta\left(2\alpha\beta+\beta^2-3\right)(q_A-q_B)+\theta(\alpha-\beta)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} - \frac{\left(3-2\alpha\beta-\beta^2\right)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9}+\beta-1 \tag{31}$$

Bring P_A^*, P_B^*, S_A^*, and S_B^* into equations (11)-(14) and the number of consumers and providers on platforms A and B can be expressed as:

$$n_1^A\left(P_A^*, S_A^*\right) = \frac{1}{2} + \frac{\delta(2\alpha+\beta)(q_A-q_B)-3\theta(q_A-q_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} - \frac{(2\alpha+\beta)(V_A-V_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{32}$$

$$n_1^B\left(P_B^*, S_B^*\right) = \frac{1}{2} - \frac{\delta(2\alpha+\beta)(q_A-q_B)-3\theta(q_A-q_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} + \frac{(2\alpha+\beta)(V_A-V_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{33}$$

$$n_2^A\left(P_A^*, S_A^*\right) = \frac{1}{2} + \frac{3\delta(q_A-q_B)-\theta(\alpha+2\beta)(q_A-q_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} - \frac{3(V_A-V_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{34}$$

$$n_2^B\left(P_B^*, S_B^*\right) = \frac{1}{2} - \frac{3\delta(q_A-q_B)-\theta(\alpha+2\beta)(q_A-q_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} + \frac{3(V_A-V_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{35}$$

Similarly, bring P_A^*, P_B^*, S_A^*, and S_B^* into equations (15) and (16), and the profit of platforms A and B can be deduced as:

$$\eta_A\left(P_A^*, S_A^*\right) = 1-\frac{\alpha+\beta}{2}+\left(\frac{1}{2}+Y\right)X+(1-\alpha)Y - \left(\frac{1}{2}+Z\right)K+(1-\beta)Z \tag{36}$$

$$\eta_B\left(P_B^*, S_B^*\right) = 1-\frac{\alpha+\beta}{2}+\left(Y-\frac{1}{2}\right)X-(1-\alpha)Y + \left(\frac{1}{2}-Z\right)K-(1-\beta)Z \tag{37}$$

$$X = \frac{\delta(\beta-\alpha)(q_A-q_B)+\theta\left(2\alpha\beta+\alpha^2-3\right)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{(\alpha-\beta)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} \tag{38}$$

$$Y = \frac{\delta(2\alpha+\beta)(q_A-q_B)-3\theta(q_A-q_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} - \frac{(2\alpha+\beta)(V_A-V_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{39}$$

$$K = \frac{\delta\left(2\alpha\beta+\beta^2-3\right)(q_A-q_B)+\theta(\alpha-\beta)(q_A-q_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} + \frac{\left(3-2\alpha\beta-\beta^2\right)(V_A-V_B)}{(2\alpha+\beta)(2\beta+\alpha)-9} \tag{40}$$

$$Z = \frac{3\delta(q_A-q_B)-\theta(\alpha+2\beta)(q_A-q_B)-3(V_A-V_B)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{41}$$

Therefore, the profit gap between platforms A and B can be shown as:

$$\Delta\eta = X+2(1-\alpha)Y-K+2(1-\beta)Z \tag{42}$$

APPENDIX B
PROOF FOR PROPOSITION 1.

From equations (17)-(20), we can get results of $\partial P_A^*/\partial\Delta q$, $\partial S_A^*/\partial\Delta q$, $\partial P_B^*/\partial\Delta q$, and $\partial S_B^*/\partial\Delta q$.

$$\frac{\partial P_A^*}{\partial\Delta q} = \frac{\delta(\beta-\alpha)+\theta\left(2\alpha\beta+\alpha^2-3\right)}{(2\alpha+\beta)(2\beta+\alpha)-9} \tag{43}$$

$$\frac{\partial S_A^*}{\partial\Delta q} = \frac{\delta\left(2\alpha\beta+\beta^2-3\right)+\theta(\alpha-\beta)}{(2\alpha+\beta)(2\beta+\alpha)-9} \tag{44}$$

$$\frac{\partial P_B^*}{\partial\Delta q} = -\frac{\delta(\beta-\alpha)+\theta\left(2\alpha\beta+\alpha^2-3\right)}{(2\alpha+\beta)(2\beta+\alpha)-9} \tag{45}$$

$$\frac{\partial S_B^*}{\partial\Delta q} = -\frac{\delta\left(2\alpha\beta+\beta^2-3\right)+\theta(\alpha-\beta)}{(2\alpha+\beta)(2\beta+\alpha)-9} \tag{46}$$

Note that $0 < \alpha < \beta < 1$, and we can get $(2\alpha+\beta)(2\beta+\alpha)-9 < 0$, $3-2\alpha\beta-\alpha^2 > \beta-\alpha$, $\alpha-\beta < 0$, and $2\alpha\beta+\beta^2-3 < 0$. In addition, δ and θ satisfy the condition of $0 < \delta < \theta < 1$, so that $\partial P_A^*/\partial\Delta q > 0$, $\partial S_A^*/\partial\Delta q > 0$, $\partial P_B^*/\partial\Delta q < 0$, and $\partial S_B^*/\partial\Delta q < 0$.

APPENDIX C
PROOF FOR PROPOSITION 2.

From equations (32)-(35), we can get results of $\partial n_1^{A*}/\partial\Delta q$, $\partial n_1^{B*}/\partial\Delta q$, $\partial n_2^{A*}/\partial\Delta q$, and $\partial n_2^{B*}/\partial\Delta q$.

$$\frac{\partial n_1^{A*}}{\partial\Delta q} = \frac{\delta(2\alpha+\beta)-3\theta}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{47}$$

$$\frac{\partial n_1^{B*}}{\partial\Delta q} = -\frac{\delta(2\alpha+\beta)-3\theta}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{48}$$

$$\frac{\partial n_2^{A*}}{\partial\Delta q} = \frac{3\delta-\theta(\alpha+2\beta)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{49}$$

$$\frac{\partial n_2^{B*}}{\partial\Delta q} = -\frac{3\delta-\theta(\alpha+2\beta)}{2[(2\alpha+\beta)(2\beta+\alpha)-9]} \tag{50}$$

Because of $0 < \alpha < \beta < 1$, we can get $(2\alpha+\beta)(2\beta+\alpha)-9 < 0$ and $2\alpha+\beta < 3$. Meanwhile, δ and θ satisfy the condition of $0 < \delta < \theta < 1$, we can see that $\partial n_1^{A*}/\partial\Delta q > 0$ and $\partial n_1^{B*}/\partial\Delta q < 0$.

Let $\partial n_2^{A*}/\partial\Delta q = 0$, and we can get $\delta/\theta = (\alpha+2\beta)/3$. Therefore, we can conclude that $\partial n_2^{A*}/\partial\Delta q < 0$ and $\partial n_2^{B*}/\partial\Delta q > 0$ if $\delta/\theta > (\alpha+2\beta)/3$; otherwise, $\partial n_2^{A*}/\partial\Delta q > 0$ and $\partial n_2^{B*}/\partial\Delta q < 0$

APPENDIX D
PROOF FOR PROPOSITION 3.

From equation (42), we can get the result of $\partial\Delta\eta/\partial\Delta q$ which can be expressed as:

$$\frac{\partial\Delta\eta}{\partial\Delta q} = \frac{\delta\left(\alpha-\beta-3\alpha\beta-\beta^2-2\alpha^2+6\right)}{(2\alpha+\beta)(2\beta+\alpha)-9} - \frac{\theta\left(6-\alpha+\beta-3\alpha\beta-\alpha^2-2\beta^2\right)}{(2\alpha+\beta)(2\beta+\alpha)-9} \tag{51}$$

Because of $0 < \alpha < \beta < 1$, we can see $(2\alpha+\beta)(2\beta+\alpha)-9 < 0$ and $\left(6-\alpha+\beta-3\alpha\beta-\alpha^2-2\beta^2\right) > (\alpha-\beta-3\alpha\beta-\beta^2-2\alpha^2+6)$. Moreover, δ and θ satisfy the condition of $0 < \delta < \theta < 1$, so that $\delta\left(\alpha-\beta-3\alpha\beta-\beta^2-2\alpha^2+6\right)-\theta\left(6-\alpha+\beta-3\alpha\beta-\alpha^2-2\beta^2\right) < 0$. Therefore, $\partial\Delta\eta/\partial\Delta q > 0$.

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