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Dynamic Two-Sided Pricing under Sequential Innovation

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Abstract

Technology innovation engenders products of higher qualities and reduces production costs. This paper focuses on a two-sided platform tied with quality-improving hardware devices that are introduced sequentially. We analyze a monopolist's dynamic pricing strategies facing decreasing future production cost and strategic buyers. Findings in both the traditional (buyer-side only) and two-sided business models show that future cost reductions raise the optimal price of the present product, which shifts the buyer-side demand forward and mitigates intertemporal cannibalization. Furthermore, future cost reductions may also lead to a higher optimal price for the future product, given a substantial quality improvement. Thus, the monopolist may leverage future cost reductions to position its product line to the high-end market. By comparing the traditional and two-sided business models, we find that the impact of future cost reductions is more pronounced for a two-sided platform.

Keywords: Dynamic pricing, two-sided markets, sequential innovation, strategic consumers

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1 Introduction

The growth of platform-based business models is showing an increasingly distinct trend, in which the platform owner directly offers hardware devices to consumers. The hardware device is the medium necessary for consumers to interact and transact with users on the other side of the platform. For example, the video game console is the hardware for playing the games designed by developers for that console. Also, computers are the hardware required to run software created by programmers for the specific operating system on a computer. This type of *two-sided platform* serves consumers on one side and developers on the other side; its revenue model is often linked directly to interactions between these two groups of users. Whereas for some platforms–such as Windows–the hardware market has been dominated by third-party manufacturers, it has become increasingly evident that platform owners are also tapping into the hardware market on their own. Google has introduced its own laptop Chromebook that runs Chrome OS.[1] In turn, Google sells its platform device directly to consumers while managing application developers for Chrome OS software development. In the tablet market, Windows Surface RT is the Microsoft-made tablet with its own Windows 8 OS. Furthermore, some platform owners have historically excluded third-party hardware manufacturers: Apple is a well-known case that keeps hardware production in house offering an array of electronic products running its iOS. The video game consoles have the same characteristics, with Sony PlayStation, Microsoft XBox, and Nintendo Wii all being platform-owned hardware devices.

Similar to other types of IT products, the platform devices advance through waves of technological innovation. These hardware-producing platform owners sequentially release quality-improved products to the market. The iPad, for example, has had a number of upgrades in terms of display, CPU, wireless capability, and other specifications; also, Windows Surface Pro has been widely anticipated since the release of the Surface RT. Such patterns in introducing platform-based products have a number of interesting implications. Inevitably, the innovation trend sparks wide interest and online discussions regarding upcoming products. Consumers' purchasing decisions are rarely made only based on the existing products; more often, purchasing decisions are forward-looking with anticipations for the pricing and quality of future products. In addition, sequential introductions

[1] *http://m.techcrunch.com/2012/11/26/google-reportedly-preparing-to-sell-self-branded-chromebooks/*

of innovative products often involve dynamic pricing considerations by the platform owner. While managing different versions of products, the platform owner tends to adopt pricing strategies that are based on the evolving state of the market by setting price at the launch of new products, rather than committing to a long-term pricing plan.

The platform market is driven by a multitude of forces, including the network-externality across two sides of the platform, consumers' strategic behaviors, and the dynamic nature of sequential innovation; these forces interact with one another and create strategic challenges for the platform owner. The cross-side network externality is a defining characteristic of two-sided platforms, where more users on one side increase the attractiveness of the platform to users on the other side. In the example of iPad, a wider iPad adoption translates to more potential downloads and revenues for app developers in the App Store; and a bigger network of app developers adds value to iPad users as well. Thus, cross-side network externality generates tradeoffs for the platform owner, who uses pricing as an instrument to balance such tradeoffs and optimize revenues from both sides. In particular, by cutting the price charged to one side, the platform might suffer some revenue loss on this side but gain a larger user base, which in turn increases the demand, on the other side. In the context of dynamic pricing, such tradeoffs also have important intertemporal implications. With forward-looking consumers, the platform may need to manage the two-sided tradeoffs differently than if consumers were myopic. In other words, the platform should evaluate whether to leverage consumers' valuation for future consumption and the cross-side network externality to yield higher future revenues at some short-term loss. Furthermore, as the platform owner undertakes dynamic pricing strategies that take into account past consumptions, characteristics of the remaining market, and changes in production costs, the differences in the strengths of the network externality as well as product quality over time may be critical for setting and understanding optimal prices.

Platform owner's pricing strategies are further subject to reductions in future production costs, which is a salient factor in the age of rapid technological advancements. Firms can effectively cut costs for future production in many ways, which have important implications for their current and future prices. Facing uncertain future costs, in many industries, firms engage in upfront negotiations with their suppliers to secure a lower procurement cost for the future. The automobile manufacturers follow different contracts to negotiate prices with suppliers of auto parts. In the IT industry, there is a wide speculation on ways Apple contracts with its factories on the cost of later generations of iPhones and iPads (Opam (2011)). Besides through contractual agreements, future cost reductions are also obtained by learning-by-doing on the manufacturer side and trust establishment in supply chain relationships.

The main objective of this paper is to examine how reductions in future production cost of platform-owned hardware impact the platform owner's dynamic two-sided pricing decisions. Our research questions highlight the important elements associated with the hardware market: What is the effect of hardware *quality improvements* on the platform's two-sided pricing strategies? How does the platform owner intertemporally segment the hardware market to account for changes in hardware *production cost* and network externality? What is the difference in a platform owner's strategies compared to a traditional hardware producer (without the seller-side market) in pricing *sequentially-improving* devices?

Our work differentiates with existing studies on two-sided platforms by considering innovative hardware products. Research work on two-sided pricing mechanisms and platform strategies has been tremendously fruitful and continues to expand rapidly. However, to the best of our knowledge, most insights thus far do not account for the platform's role in introducing hardware devices, which are inseparable from platform operations.[2] As dominant players in the platform industry focus more on innovating hardware devices, considerations for marketing platform-owned hardware become increasingly relevant. Our study turns to this facet of platforms' decision problems and contributes novel ideas to the related literature.

We study both a traditional ("one-sided"), durable-good monopolist and a two-sided, monopolistic platform owner using economic modeling and numerical analysis. The model captures sequential introduction of quality-improved products and dynamic pricing decisions of the monopolist. We derive the optimal price of the low-quality product in the *present* and that of the high-quality product in the *future*; furthermore, we analyze changes in these optimal strategies when the monopolist anticipates future cost reductions. The one-sided case provides the baseline results for the two-sided case, in which the platform's pricing strategies on both the buyer-side and the seller-side involve dynamic effects of sequential introduction and cross-group network externality. The comparison between the two cases illustrates the role of network externality in the platform's strategies to leverage future cost reductions and to position its products.

[2] The existing research findings are nevertheless applicable to platforms that rely on third-party hardware manufacturers or focus on service provision such as online retailers (e.g., eBay), Hulu, Pandora and others.

In the one-sided case with interactions between the platform and buyers, we find that future cost reductions can lead to higher optimal prices for both the low-quality product and the quality-improved product that are introduced sequentially. The intuition is that future cost reductions increase the profitability of the high-quality product introduced later. Thus, the firm is inclined to encourage some buyers to delay purchase by raising the price of the low-quality product and extracts more surplus from those who purchase early. The forward intertemporal demand shift populates the future market with more high-valuation buyers. As a result, when the quality improvement is sufficiently high, the firm also raises the price of the high-quality product. Overall, the firm is able to leverage future cost reductions to push its product line toward the high-end market.

When we introduce the seller-side, the platform has a two-sided pricing problem in both periods and needs to account for the cross-side network externality from the buyer-side to the seller-side. The results in the one-sided case continue to hold qualitatively. Moreover, as costs decrease in the future, the strategic adjustments of the optimal prices may be more pronounced compared to the one-sided case. Here, the buyer-to-seller network effect raises the value of buyers, who not only generate profits for the platform but also attract sellers to the platform. The intertemporal forward demand shift on the buyer-side in response to future cost reductions is more pronounced in the two-sided model, because, in addition to the incentives in the one-sided case, the platform also derives additional seller-side revenues by expanding the buyer-side demand in the later period. In this sense, the future profitability in response to cost reductions is further enhanced in the two-sided case because the platform can benefit from profits on both sides of the market. The platform is then able to raise the buyer-side price for both the low-quality and high-quality products at a higher rate than in the one-sided case to extract higher surplus from buyers who remain to purchase early as well as those who delay purchase.

Whereas the analytical results are based on an unidirectional network externality from the buyers to the sellers, we add the seller-to-buyer network externality in the numerical study and derive consistent findings. The new network externality does not alter the platform's intertemporal incentives because it amplifies the increases in demands on both sides in the later period. As a result, the platform nonetheless raises the price of the low-quality product to induce buyers to delay purchase, and it does so with a higher intensity compared to the one-sided case.

The remaining of the paper is organized as follows. We discuss the related literature in Section

2. In Section 3, we introduce the baseline model with only the buyer-side and present the main results. In Section 4, we extend the baseline model to the two-sided case, incorporating the cross-side network externality of buyers on the seller-side and two-sided pricing. In Section 5, we also incorporate the network externality exerted by sellers to the buyer-side and use numerical analysis to show that the insights obtained in Section 4 persist. Section 6 concludes the paper.

2 Related Literature

Our work is most closely related to three streams of research, including the literatures on two-sided platforms, sequential innovation, and strategic customers. To the best of our knowledge, our paper is among the first to consider the dynamic pricing problem of a two-sided platform that sequentially introduce innovative hardware devices in the presence of strategic consumers. Moreover, we connect thoughts from these bodies of literature to gain further in-depth understanding on problems across these domains.

The literature on two-sided platforms explores the platform's pricing problem taking into consideration network effects, user multi-homing, platform governance, and innovation. Earlier works by Rochet and Tirole (2002), Rochet and Tirole (2003), Caillaud and Jullien (2003), Parker and Alstyne (2005), and Armstrong (2006) examine different applications of two-sided markets and generate insights for the optimal fees levied on the two sides of the platform. Innovation is receiving increasing research attention in the realm of platforms. Lin et al. (2011) study the innovation race among sellers of a two-sided market. By analyzing innovation incentives and price competition among sellers, they find the platform's optimal two-sided pricing strategy. They show that the seller-side fee may have a positive impact on sellers' innovation incentives, while the buyer-side fee slows down the innovation race. Boudreau (2012) conducts an empirical study on the effect of the number of applications on software variety. He finds that an increase in the number of application producers leads to an overall reduction in innovation incentives, which creates a tension with the positive network effects assumed by many studies of two-sided markets. Hagiu (2009) accounts for the effect of consumers' preference for variety. He examines the effect of such variety on the platform's pricing strategies and discuss how the seller-side pricing structure influences sellers' innovation incentives. These studies focus on innovation that drives the products offered by the seller-side in transaction with the buyer-side, whereas our work recognizes that the platform-owned hardware device is another highly innovative market. We devote our attention to the the platform's strategies in managing this hardware market accounting for the two-sided elements.

Although studies on two-sided pricing models have been commonly based on static settings to derive crisp insights and maintain analytical tractability, recently a growing body of research work has begun to explore dynamic strategies in the platform context (Lin et al. (2011), Zhu and Iansiti (2012), and Hagiu (2006)). Hagiu (2006) investigates price commitment by a platform, where one side of the platform arrives before the other side. He finds that the platform can attract the early-arrival side without committing to a low price for the late-arrival side. Our paper also focuses on a dynamic pricing problem with particular attention to the quality-improving hardware device offered by the platform. Lin et al. (2011) study sellers' dynamic innovation race to create products for the platform market and find implications on the platform's pricing decisions. Rather than focusing on sellers' dynamics, our work considers the platform's sequential decisions. Zhu and Iansiti (2012) consider forward-looking consumers and focus on a platform's entry problem in competition with an incumbent, with constant quality. Through both analytical modeling and empirical validation, they find that, when both the network externality and consumers' valuation for future applications are sufficient low, a platform entrant may capture its market with quality advantage. Our results coincide with theirs by also indicating these two factors to play a role in the platform's dynamic pricing strategies facing future cost reductions. One of the main features that differentiate our paper is our consideration for quality improvements over time.

Network effects and other key elements of two-sided platforms have been considered in a variety of contexts. Sun et al. (2004) finds that the strength of network effects is an important factor in deciding which product strategy a firm should adopt among single-product monopoly, technology licensing, product-line extension, and a combination of licensing and product-line extension strategies. Our model aims to address a two-sided problem and accounts for bi-directional network effects from/to both sides. Chen and Xie (2007) model the competition between two firms with asymmetric levels of consumer loyalty for a primary product. They study the network effect exerted by the primary product onto the market of the secondary product. Interestingly, they identify the range of consumer loyalty for the firm with higher consumer loyalty to be at a disadvantage as a result of the network effect. Gilbert and Jonnalagedda (2011) anchors on the concept of "contingent product," which is the product that is required to consume a durable good (e.g., ink is the contingent product of printer). They evaluate the lock-in strategy with consideration for strategic consumers and find that the firm's ability to commit to shutting down the production of the durable good plays an important role. Cheng et al. (2011) evaluate net neutrality policies by studying the the broadband service provider as a platform, which charges a fee to consumers and possibly also a price to the content provider side. By modeling two-sided pricing, they find that abolishing net neutrality benefits the broadband service provider while taxing the content providers; the change to consumer surplus further depends on relative capabilities of the content providers in generating revenues. Tucker and Zhang (2010) conduct a field experiment and find that seller-side participation decisions may be dependent on the amount of information advertised about the network size. In fact, their results show that advertising buyer-side network size may deter seller-side participation.

This paper is also closely related to the literature on rapid sequential innovation. Our model is similar to the setup in Dhebar (1994) and Kornish (2001), who consider the problem of a durable-goods monopolist selling low-quality and high-quality products in the first and second period, respectively. They examine whether there exists an equilibrium pricing strategy when the pace of quality improvement varies. Dhebar (1994) concludes that rapid quality improvement is not desirable even with the option of upgrading the low-quality products, whereas Kornish (2001) shows that any large quality improvement could be optimal under different parameter settings without offering the special upgrading pricing in the second period. Our work considers a firm producing quality-improving hardware devices, for which upgrades are not commonly feasible; thus, we focus on other issues such as the two-sided business model. Moreover, Dhebar (1994) considers a general cost function of the quality and Kornish (2001) assumes zero marginal cost, whereas we adopt a convex cost function of product quality. Our goal is to examine the impact of future cost reductions on a firm's pricing strategy. Bhattacharya et al. (2003) investigate how to optimally introduce high technology products with an option of holding the low quality products until the high quality products launch. They show that introducing low quality products before high quality products may be still preferred. For topics on sequential innovation, Ramachandran and Krishnan (2008) provide a detailed review.

A key component in most dynamic pricing models is strategic consumer behavior, that is, consumers are forward-looking and may delay their purchases to maximize their utilities over time.

Researchers are often interested in how a monopolist optimally prices a single product over time. Stokey (1979) and Bulow (1982) show that a monopolist is forced to price at the marginal cost; Besanko and Winston (1990) prove that the optimal price decreases over time due to consumers' strategic behavior. By taking into account capacity constraints/inventory, the literature in operations management shows that markdown or markup could be optimal (see Su (2007) and Aviv and Pazgal (2008)). Liu and Zhang (2012) extend the model of Besanko and Winston (1990) to a duopoly market with vertically differentiated products and obtain a similar optimal pricing strategy. Our work emphasizes the role of production cost in the firm's and consumers' decisions. We show that, as future production cost decreases, consumers' strategic behaviors make possible for the firm to raise the price of the low-quality product in the first period and to raise or lower the price of the high-quality product in the second period, depending on the extent of quality improvement.

3 Buyer-Side Only (Baseline Case)

Consider a monopoly firm[3] that produces a low-quality product in the first period and offers a product of an improved quality in the second period. We focus on the case of durable goods; thus, buyers purchase either quality of product but not both. Since the product of interest is a hardware product, unlike in the case of software products, buyers cannot simply update the low-quality version to obtain the high-quality version. Moreover, suppose that the second-hand market, if present, only has a negligible impact on the primary market. Let q_i and p_i denote the quality and the selling price of product i respectively, for $i = L, H$. We assume that q_i is exogenously determined and that the firm is unable to commit in advance to future prices. The firm sets the price p_L in period 1 and p_H in period 2 with the objective of maximizing the total profit over the two periods. Following the common assumption (Netessine and Taylor (2007)), let the production cost be a convex function in quality: The costs of the low and high-quality products in period t are $\beta_t q_L^2$ and $\beta_t q_H^2$ respectively, where $0 < \beta_t < 1$ can be interpreted as the costliness of quality. Also, for notational simplicity, denote by α the common per-period discount factor for both the firm and buyers, although our results hold when the firm's discount factor is greater than that of the buyers.

Consider a continuum of buyers of density μ. We assume that buyers are characterized by their

[3]The term "*platform*" is used for the two-sided case in Section 4 to distinguish from the current setting where we use the term "*firm*."

valuation (or willingness-to-pay) for one unit of quality in the product. A buyer with valuation θ receives utility $\theta q_i - p_i$ from buying one unit of product i for $i = L, H$ and does not gain from any additional units. Without loss of generality, let the utility of buying nothing be zero. A buyer purchases the either the low- or high-quality product (in period 1 or 2, respectively) that gives him the higher utility, provided that the utility is positive. Furthermore, the firm cannot identify the θ value for each buyer, but it observes that θ is uniformly distributed over $[0, 1]$. Both the firm and buyers have rational expectations.

Let θ_H be the valuation of the buyer who is indifferent between purchasing the high-quality product in period 2 and nothing; that is, $\theta_H q_H - p_H = 0$. And let θ_2 be the valuation of the buyer who is indifferent between purchasing in period 1 and period 2: $\theta_2 q_L - p_L = \alpha(\theta_2 q_H - p_H)$. Then, given p_L and p_H, θ_H and θ_2 are determined by $\theta_H = \frac{p_H}{q_H}$ and $\theta_2 = \frac{p_L - \alpha p_H}{q_L - \alpha q_H}$ respectively.

We follow the assumption adopted in the literature that innovation is not "too rapid," such that quality only improves in absolute terms and not in present-value terms (i.e., $q_L > \alpha q_H$) (Liu and Zhang (2012)). Violation of this condition rules out the subgame-perfect equilibrium for sequential product introduction (see Dhebar (1994)), implying that the optimal pricing strategy may lead to consumer regret. As a result, buyers with higher valuations are early adopters of the low-quality product in period 1, whereas those with lower valuations may purchase the high-quality product in period 2. If a buyer with valuation θ purchases in period t, buyers with $\hat{\theta} > \theta$ who have not yet purchased will clearly also make the purchase in the same period. Therefore, θ_2 serves as the state variable indicating the number of remaining buyers in the market in the beginning of period 2.

The timeline of events are as follows (Figure 1): In period 1, the firm sets price p_L, and buyers decide whether to purchase the low-quality product based on p_L and their rational expectations of the future price p_H of the high-quality product. In period 2, the firm sets price p_H according to the state of the market θ_2, and buyers who have not yet made the purchase (i.e, with valuations lower than θ_2 and higher than θ_H), decide whether to purchase the high-quality product.

The firm's profit functions in periods 2 and 1 are, respectively:

$$\begin{aligned}\Pi_2(p_H) &= (\theta_2 - \frac{p_H}{q_H})(p_H - \beta_2 q_H^2)\mu, \\ \Pi_1(p_L) &= (1 - \theta_2)(p_L - \beta_1 q_L^2)\mu + \alpha \Pi_2(\theta_2).\end{aligned}$$

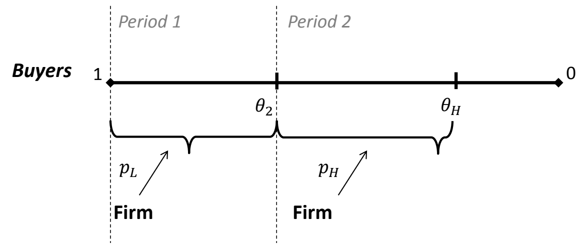

Figure 1: Overview with Buyer-Side Only

Without loss of generality, we normalize μ to 1 in the analysis.

We derive the optimal price in the each period (see Appendix B.1), based on which comparative statics yield the effect of future cost reductions on the firm's strategies and buyers' purchasing decisions. Firms commonly anticipate lower future costs as a result of technological advancement, learning-by-doing by the manufacturers, and contractual agreements with its suppliers in practice. Such reductions in future costs are critical to the firm's dynamic pricing decisions, and, consequently, buyers' strategic purchasing behaviors.

Proposition 1. *Cost reductions in period 2 induce the firm to raise the price (of the low-quality product) in period 1, which leads to a demand shift from period 1 (low-quality product) to period 2 (high-quality product).*

Reductions in future production costs increases profitability of the high-quality product; thus, the firm is inclined to expand the future market. The optimal strategy is then to raise the price in period 1, which not only extracts more surplus from the buyers who are early adopters but also creates a larger market for period 2. Facing a higher price in period 1, only buyers with the highest valuation purchase early, allowing the firm to price-discriminate more aggressively. More buyers are then willing to delay purchase – an expanded market emerges in period 2. The firm's pricing strategy in period 2 must align with buyers' rational expectations such that those who delay purchase are indeed better off giving up consumption in period 1.

The quality gap cross periods is a key factor in the effect of cost reductions on the price in period 2. To examine the conditions of quality gap, we first define an indicator function describing the quality ratio, $\frac{q_L}{q_H}$, relative to the discount factor, α: $f(\frac{q_L}{q_H}) = 5\alpha - 4\frac{q_L}{q_H}$. Notice that $f(\cdot)$ is monotonically decreasing in the quality ratio so that the indicator also increases when the quality gap increases. Moreover, we define the critical quality ratio $\delta \equiv \frac{5\alpha}{4}$, such that $f(\delta) = 0$. The (q_H, q_L)-space can be divided into three regions shown in Figure 2 and characterized in Table 1 (note that since $\alpha < \delta$, $f(\alpha) > f(\delta) = 0$).

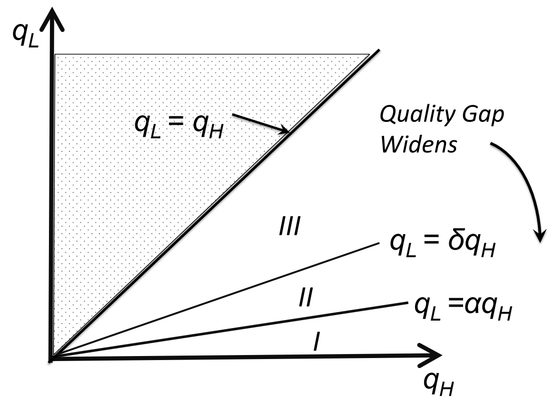

Figure 2: Three Regions in the (q_H, q_L)-Space

Table 1: Regions of the (q_H, q_L)-Space

Region	**Quality Ratio**	**Adj. Quality Gap**	**Extent of Quality Improvement**
Region I	$\frac{q_L}{q_H} < \alpha$	$--$	Not Feasible
Region II	$\alpha < \frac{q_L}{q_H} \leq \delta$	$f(\frac{q_L}{q_H}) \geq 0$	Major Quality Improvement
Region III	$\frac{q_L}{q_H} > \delta$	$f(\frac{q_L}{q_H}) < 0$	Minor Quality Improvement

In Figure 2, only the area below the 45-degree line ($q_L = q_H$) is feasible for the given quality levels to ensure $q_L < q_H$. Region I is also not feasible because we are interested in quality improvement in absolute terms only. The quality gap widens from Region III to Region II, leading to the following proposition.

Proposition 2. *2a. For a major quality improvement in period 2 (i.e., in Region II), cost reductions in period 2 induces the firm to raise the optimal price in period 2 (for the high-quality products). Meanwhile, the total demand across the two periods decreases.*

2b. For a minor quality improvement in period 2 (i.e., in Region III), cost reductions in period 2 induces the firm to lower the optimal price in period 2 (for the high-quality products). Meanwhile, *the total demand across the two periods increases.*

The firm can leverage cost reductions in period 2 either to position its product line to the high-end market or to increase the total market share. In the former strategy, the firm raises the price of the high-quality product in period 2 (as well as that of the low-quality product in period 1 as shown in Proposition 1) in response to cost reductions. This result contrasts sharply with the theory that lower costs lead to lower prices, which is applicable in a static setting. In a dynamic setting, the price increase in period 1 creates an forward demand shift that brings a group of buyers with high valuations to period 2; a sufficiently substantial quality improvement then allows the firm to exploit these buyers and raise the price in period 2. Even though the total market share is reduced, the price increase in both periods induces buyers to time their purchases such that the firm obtains a higher margin from all purchases.

The firm follows the latter strategy of lowering the price of the high-quality product in period 2 (while raising that of the low-quality product in period 1 as shown in Proposition 1) in response to cost reductions, only when the quality improvement in period 2 is not substantial. In this case, the firm cannot raise the price in period 2 high enough to extract sufficient surplus from the buyers with higher valuations; thus, instead, its optimal strategy is to lower the price to capture a bigger market.

Future cost reductions have several strategic implications for the firm. It may be a powerful leverage to raise all prices in the present and in the future (Propositions 1 and 2a), as long as the firm also anticipates major quality improvements for newer versions of the product. Through these pricing strategies, the firm in effect re-segments the market in favor of the future market, which is made more profitable due to cost reductions. In the spirit of second-degree price discrimination, the firm not only exploits buyers with sufficiently high valuations to purchase early, it may also extract more surplus from those who switch to delay purchase. The outcome of such strategic price adjustments is the exclusion of buyers with lower valuations. As a result, anticipating future cost reductions allows the firm to profit more from fewer buyers.

4 Two-Sided Pricing

In this section, we extend the analysis to examine a product that is a platform for two groups of users. For example, smartphones provide a marketplace for transactions of applications between the buyer-side and the seller-side (or developer-side). Building on the model in Section 3, we now also consider the seller-side of the platform. The two-sidedness significantly alters and complicates the platform's pricing problem. The platform not only faces a dynamic problem in setting the price of the hardware product on the buyer-side, it also prices the seller-side fee; in addition, the cross-side network externality is an important factor in the platform's optimal two-sided pricing decision. We investigate the effects of future cost reductions in the two-sided setting and contrast the results with those in Section 3.

In deriving analytical results, we focus on the case where the seller-side demand is increasing in the buyer-side network size, and the buyer-side demand is determined by their preference for quality following the setup in Section 3. This simplification allows the model to remain tractable as we examine the role of quality in the platform's dynamic, two-sided pricing strategy. To also incorporate the network externality from the seller-side to the buyer-side, we perform numerical analysis with network externalities on both sides in Section 5 and show that the findings are qualitatively consistent with the analytical results in this section. Thus, the analytical findings in the current section provides the theoretical insights for the impact of future cost reductions on the platform's two-sided pricing strategies. Furthermore, it is applicable to fully-developed platforms that have established a critical mass of sellers, in which case buyers' purchasing decisions are primarily reliant on the characteristics of the product itself. For example, given the large developer network in Apple's App Store, buyers' iPhone purchase decisions are mainly based on the functionality of the device. In another example, when consumers choose between Visa and Mastercard, their primary decision factor is not as much about the number of merchants honoring the card as it is about the quality of service and the promotions offered by the card.

4.1 Model Setup

In addition to the buyer-side price as in Section 3, in period t, $t \in \{1, 2\}$, the platform charges a fixed fee s_t to sellers upon joining. Let the seller-side demand decrease in s_i at the rate of k, as a result of the quantity effect. We adopt a linear demand function on the seller-side: For a buyer-side network of size Θ, the seller-side demand function is $v_t\Theta - ks_t$, where v_t is the marginal network effect exerted by the buyer-side in period t. We assume all agents have rational expectations about the future as they maximize utility (or payoffs).

The timeline is similar to that in Section 3 with the addition of seller-side fees in each period (Figure 3). In period 1, the platform sets prices charged on both sides s_1 and p_L; observing these prices, sellers and buyers make their participation and purchasing decisions, respectively. In period 2, the platform introduces a higher quality of device for buyers and sets s_2 and p_H; sellers and the remaining buyers make their participation and purchasing decisions, respectively.

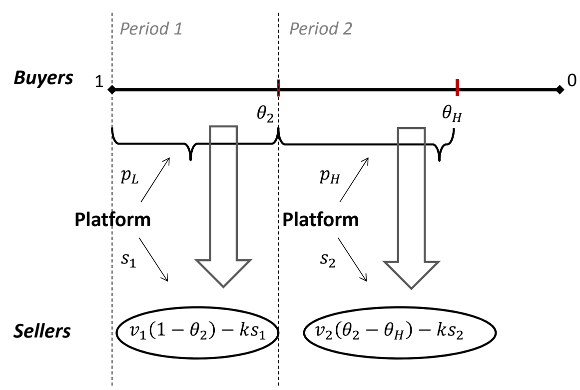

Figure 3: Overview in the Two-Sided Case

The platform's profit functions in two periods now include revenues generated on the seller-side:

$$\begin{aligned}
\Pi_2(p_H, s_2) &= (\theta_2 - \frac{p_H}{q_H})(p_H - \beta_2 q_H^2)\mu + s_2\left[v_2(\theta_2 - \frac{p_H}{q_H}) - ks_2\right], \\
\Pi_1(p_L, s_1) &= (1-\theta_2)(p_L - \beta_1 q_L^2)\mu + s_1\left[v_1(1-\theta_2) - ks_1\right] + \alpha\Pi_2(\theta_2).
\end{aligned}$$

As in the buyer-sided model, μ is normalized to 1; here, v_1, v_2 and k are also scaled accordingly.

4.2 Results

Here, the platform adopts a new set of strategies in period 2, in contrast with those when only the buyer-side is present. Lemma 1 characterizes the optimal buyer-side price, the valuation of the buyer who is indifferent between purchasing the high-quality product and consuming nothing, and the optimal seller-side fee in period 2. To simplify notation, we define $W \equiv \frac{v_2^2}{2kq_H}$.

Lemma 1. *Given θ_2 (the buyer with the highest valuation in period 2), the optimal price of the high-quality product, the buyer with the lowest valuation, and the optimal seller-side fee in this period are given by*

$$p_H^* = \frac{\theta_2 q_H + \beta_2 q_H^2 - \theta_2 \frac{v_2^2}{2k}}{2 - W} \tag{1}$$

$$\theta_H^* = \frac{\theta_2 + \beta_2 q_H - \theta_2 W}{2 - W} \tag{2}$$

$$s_2^* = \frac{v_2}{2k}(\theta_2 - \frac{p_H^*}{q_H}). \tag{3}$$

Let us inspect the optimal buyer-side price in period 2 with and without the seller-side (Eq. (2) and Eq. (9)). The comparison provides an illustration of the effect of network externality independent of intertemporal issues. The expressions of p_H^* in the two cases show that, with the seller-side, both the denominator and the numerator of p_H^* are reduced. These two differences create forces acting in opposite directions.

First, in the two-sided case, the platform's total profit is less sensitive to changes in the buyer-side price. With two-sided pricing, when the platform reduces the buyer-side price, it must also adjust the seller-side fee. Thus, a lower buyer-side price not only stimulates the buyer-side demand, but it also strengthens the network effect. Moreover, because of the expanding buyer-side demand the network effect intensifies at an increasing rate, as the buyer-side price further decreases. As a result, in the two-sided case, the platform reduces the buyer-side price at a higher rate than in the one-sided case to also take advantage of the seller-side profit gain. The similar intuition applies when the platform adjusts the buyer-side price upward. This price increase weakens the network effect and at a decreasing rate. Overall, the total profits from the two sides are less responsive to the changes in the buyer-side price, compared with the case when the platform derives revenues solely from the buyers. The intuition of the second force is straightforward. The seller-side introduces the incentive for the platform to obtain more buyers to generate profits on the seller-side; thus, the buyer-side price is shifted downward. The net effect determines the difference in the buyer-side price with and without the consideration for the seller-side.

From Equations (2) and (3), we also observe that the platform optimally adjusts the buyer-side price and the seller-side fee in opposite directions. Intuitively, an increase in the buyer-side price diminishes the network effect on the seller-side and reduces the optimal seller-side fee. When the buyer-to-seller network effect is weakened, the platform has less to gain on the seller-side; thus, the optimal seller-side fee decreases in order to generate more demand on the seller-side. The platform's optimal seller-side profits are also reduced.

Next we find the optimal results in period 1 and examine their properties.

Lemma 2. *In period 1, the optimal price for the low-quality product, the valuation of the buyer who is indifferent between purchasing the high-quality product and low-quality product, and the optimal seller-side fee are given by:*

$$p_L^* = \frac{((2-W)q_L - \alpha q_H)\left[(2-W)q_L - \alpha q_H + (2-W)\beta_1 q_L^2 - \frac{v_1^2}{2k}(2-W)\right] - \alpha^2\beta_2 q_H^3}{(2-W)[2(2-W)q_L - 3\alpha q_H] - \frac{v_1^2}{2k}(2-W)^2} - \frac{\frac{v_1^2}{2k}(2-W)\alpha\beta_2 q_H^2}{(2-W)[2(2-W)q_L - 3\alpha q_H] - \frac{v_1^2}{2k}(2-W)^2} \tag{4}$$

$$\theta_2^* = \frac{(2-W)q_L - \alpha q_H + (2-W)\beta_1 q_L^2 - 2\alpha\beta_2 q_H^2 - \frac{v_1^2}{2k}(2-W)}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} \tag{5}$$

$$s_1^* = \frac{v_1}{2k}(1-\theta_2^*) \tag{6}$$

Comparing p_L^* in the cases with and without the seller-side, the differences are similar to those for p_H^* – both the numerator and the denominator are reduced when the seller-side is introduced. Similar to the discussion for p_H^*, the seller-side helps to smooths out the sensitivity of the total profits generated in period 1, which leads to an increase in price. Meanwhile, the platform also has the incentive to reduce the price to attract more buyers and profit on the seller-side.

Aside from the same-period cross-side tradeoffs, the platform's pricing strategy in period 1 also depends on how the platform balances profits on the two sides in period 2. Notice that, in Eq. (5), the presence of the seller-side in period 2 affects buyers' intertemporal purchase decisions. Thus, introducing the seller-side complicates the platform's strategies due to the interactions between prices on the two sides as well as the dynamic effects. The combination of these forces generates the net difference in the price in period 1 compared to the case without the seller-side.

Proposition 3. *Cost reductions in period 2 shift demand from period 1 (low-quality product) to period 2 (high-quality product). In the meantime, the platform's optimal strategy is to raise the price (of the low-quality product) in period 1, given cost reductions in period 2.*

Proposition 1 from the one-sided setting applies to the current two-sided case. Considerations for the seller-side does not alter the qualitative effect of future cost reductions on the platform's pricing strategies in period 1: Cost reductions increase profitability in period 2 and induce a forward intertemporal demand shift. It is optimal for the platform to encourage buyers' tendency to delay purchase to the more profitable period by raising the buyer-side price in period 1. This also allows the platform to extract more surplus from those who remain in period 1.

The difference between the one-sided and two-sided business models is that adjustments of the buyer-side price in period 1 for a two-sided platform not only trigger an intertemporal demand shift but also affect the strengths of the network externality in both periods. Intuitively, the strength of the network externality is transferred in the direction of the intertemporal demand shift; in other words, as more buyers delay their purchases, the platform loses some buyer-side demand now but will gain a stronger network effect later. This does not impact the platform's pricing strategy *qualitatively* because the platform simultaneously optimizes the seller-side profit, which balances cross-period tradeoffs in network externalties. We identify the intertemporal seller-side tradeoffs in Proposition 4 and further contrast the two-sided business model with the case with only the buyer-side in the following propositions.

Proposition 4. *Cost reductions in period 2 raise the optimal fee and profits on the seller-side in period 2, but lower the optimal fee and profits on the seller-side in period 1.*

Future cost reductions not only incentivize the platform to shift the buyer-side demand to the future market, they also sharpen the difference in the seller-side profitability by weighing toward the future. The forward shift of the buyer-side demand transfers the strength of the network externality from period 1 to period 2. Thus, the platform is able to raise the seller-side fee in period 2, based on its offering of an expanded user base of buyers. As a result, for a two-sided business model, the platform gains from cost reductions of the future market in terms of both the sales of devices on the buyer-side and the revenues generated from the fees on the seller-side. The additional benefits from the seller-side in period 2 may increase the leverage that the platform obtains from future cost reductions compared to the one-sided case, as shown in Propositions 5 and 6.

Proposition 5. *In the two-sided setting, the intertemporal demand shift due to future cost reductions is more pronounced than in the one-sided case. Moreover, the platform raises the optimal price in period 1 more aggressively in the two-sided case than in the one-sided case.*

In the two-sided business model, the platform can raise the buyer-side price in period 1 more aggressively than in the one-sided case. Raising the buyer-side price in period 1 allows the platform not only to expand the buyer-side market in period 2 (same as in the one-sided case) but also to profit further on the seller-side in period 2 through the intensified buyer-to-seller network externality, as shown in Proposition 4. The latter (seller-side profits in period 2) increases the incentives for the former (creating more buyer-side demand in period 2); as a result, the platform's optimal strategy is to raise the buyer-side price in period 1 at a higher rate than in the one-sided case.

The implication is that, in a two-sided business model, the network externality empowers the platform to more aggressively price discriminate and more effectively segment the market intertemporally, when anticipating future cost reductions. As more focus is shifted to period 2, the platform only captures the most eager-to-buy consumers with the low-quality product and is able charge them a high premium for early adoption. The sales of the first iPhone highlight this point. While predicting a significant drop in production costs, Apple set a steep price for the first iPhone. The early adopters were mostly technology fanatics, who valued the revolutionary design of the iPhone at the time. In comparison, adopters of later versions of the iPhone were more driven by the hardware quality improvements and, very importantly, the rapidly growing App Store.

Proposition 6. *6a. For a major quality improvement in period 2 (i.e., in Region II), cost reductions in period 2 induce the platform to raise the buyer-side price (for the high-quality product). Furthermore, the rate of increase is higher with the consideration for the seller-side. And, the total demand across the two periods decreases.*

6b. For a minor quality improvement (i.e., in Region III), cost reductions in period 2 may nevertheless induce the platform to raise the buyer-side price (for the high-quality product), if the network effect in period 1, v_1*, is sufficiently strong. Under certain conditions of the strengths of network effects in both periods (*v_1 *and* v_2*), the platform may lower the price, given cost reductions in period 2.*

Consistent with the one-sided case, here a substantial quality improvement also enables the platform to raise the price of the high-quality product given cost reductions in period 2. Because the demand shift forward is more pronounced in the two-sided case, the future market is populated with more buyers with high valuations. This alone allows the platform to extract higher surplus from these additional buyers by raising the price in period 2 more aggressively. Furthermore, recall that, in the two-sided case, the platform's total profit is less sensitive to changes in the buyer-side price compared to the one-sided case; thus, the platform has more power to impose a higher price increase on the buyer-side to enjoy a higher profit.

Proposition 6b further suggests that the network externality allows the platform to raise the buyer-side price in scenarios where price increase is not possible for the one-sided business model. When the quality improvement is not sufficiently substantial, whereas in the one-sided case, anticipating cost reductions, the firm's optimal strategy is to cut the price of the high-quality product (Proposition 2b), the two-sided business model may enable the platform to raise the price nevertheless, depending on the strength of the network externality. This is a result of the intertemporal effects of network externality. In period 1, the network externality mitigates the responsiveness of the total profits to changes in the buyer-side price; thus, with a stronger network externality, the platform tends to raise the buyer-side price more aggressively while compensating for it by lowering the seller-side fee. The intensified shift of the buyer-side demand to period 2 provides the platform with the opportunity to extract additional surplus from buyers by raising the price higher, even when the quality improvement is not as significant. Therefore, with a sufficiently strong network externality, the intertemporal effect may reinforce the price increase despite the minor quality improvement.

On the other hand, when the network externality is sufficiently strong in period 2, the platform may lower the price of the high-quality product given reduced costs. This is intuitive because the more benefit each additional buyer generates, the more the platform is inclined to cut the buyer-side price so as to attract a larger buyer-side network and to raise the seller-side fee for a higher seller-side profit.

The network externality in a two-sided business model clearly plays an important role in the firm's pricing strategies. Thus far, for analytical tractability, we have only consider the buyer-to-seller externality, which yields fundamental insights on how such network externality impact the platform's and buyers' decisions. In the following section, we also incorporate the network externality from the seller-side to the buyer-side to examine the full picture of a two-sided platform's strategies.

5 Numerical Study

In this section, we consider a two-sided model with the network externalities in both directions between the buyer-side and the seller-side. Let γ_t denote each buyer's marginal utility for an additional seller on the other side of the platform; that is, γ_t measures the strength of the network effect of the seller-side on the buyer-side in period t. The utility function of a buyer with θ in period t is then $\theta q_t + \gamma_t(v_t\Theta_t - ks_t)q_t - p_t$, where $q_t = q_L, p_t = p_L$ for $t = 1$, $q_t = q_H, p_t = p_H$ for $t = 2$, and Θ_t is the buyer-side network size determined by all buyers' preferences based on this utility function. Hence, θ_H and θ_2 satisfy the following conditions:

$$\begin{aligned}(\theta_H + \gamma_2(v_2(\theta_2 - \theta_H) - ks_2))q_H - p_H &= 0,\\ (\theta_2 + \gamma_1(v_1(1-\theta_2) - ks_1))q_L - p_L &= \alpha((\theta_2 + \gamma_2(v_2(\theta_2 - \theta_H) - ks_2))q_H - p_H).\end{aligned}$$

The platform's profit in the two periods are:

$$\begin{aligned}\Pi_2(p_H, s_2) &= (\theta_2 - \theta_H)(p_H - \beta_2 q_H^2)\mu + s_2(v_2(\theta_2 - \theta_H) - ks_2),\\ \Pi_1(p_L, s_1) &= (1-\theta_2)(p_L - \beta_1 q_L^2)\mu + s_1(v_1(1-\theta_2) - ks_1) + \alpha\Pi_2.\end{aligned}$$

Without loss of generality, μ is normalized to 1, and v_1, v_2 and k are scaled accordingly. Following the method in Section 4, we obtain the expressions of p_H and s_2 in terms of θ_2 using the FOCs of Π_2 with respect to p_H and s_2. However, model complexity does not permit derivation of the expressions for p_L and s_1. Therefore, we use numerical analysis to compute these values and examine the effect of future cost reductions on the platform's and buyers' decisions.

We test a wide range of numerical values that satisfy the conditions to ensure concavity of the profit function and bounds of buyer valuations. In particular, the value of the indicator function $f(\cdot)$, which characterizes the relationship between quality levels and the discount factor, is an important determinant for the effect of cost reduction on the price of high-quality product. Thus, we consider different combinations of β_2 and α while fixing other parameters: $q_L, q_H, \beta_1, v_1, v_2, k, \gamma_1$, and γ_2. We verify the robustness of the qualitative results based on different feasible values of these parameters that satisfy conditions specified in Section 4. In accordance with these conditions, we vary β_2 values in the range of 0.05 to 0.3.

The numerical results show that the price of the low-quality product increases and the buyer demand of low-quality product decreases as the cost in period 2 decreases, which is consistent with Propositions 3. Figure 4 shows the result for $\alpha = 0.55$. When β_2 decreases, θ_2 increases, indicating that the demand is shifted from period 1 to period 2. Because cost reduction in period 2 increases the profitability of the high-quality product, the platform can generate a higher profit by raising the price of the low-quality product and thus pushing more buyers to the more profitable market.

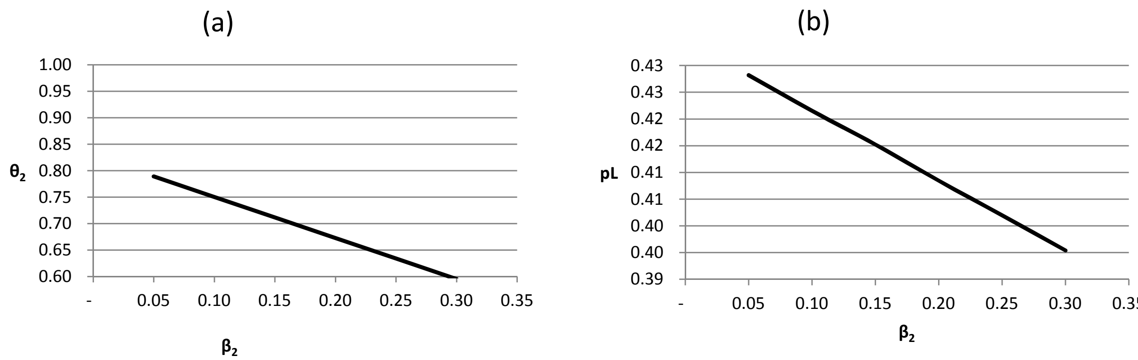

Figure 4: Demand and Price of Low-Quality Product in Period 1

Figure 5 illustrates the results for the price and profit on the seller-side in period 1. Since more buyers are inclined to delay their purchase, the network externality enables the platform to raise the seller-side fee in period 2 but lower the fee in period 1, which coincides with Proposition 4. As a result, the profit on the seller-side decreases in period 1 and increases in period 2.

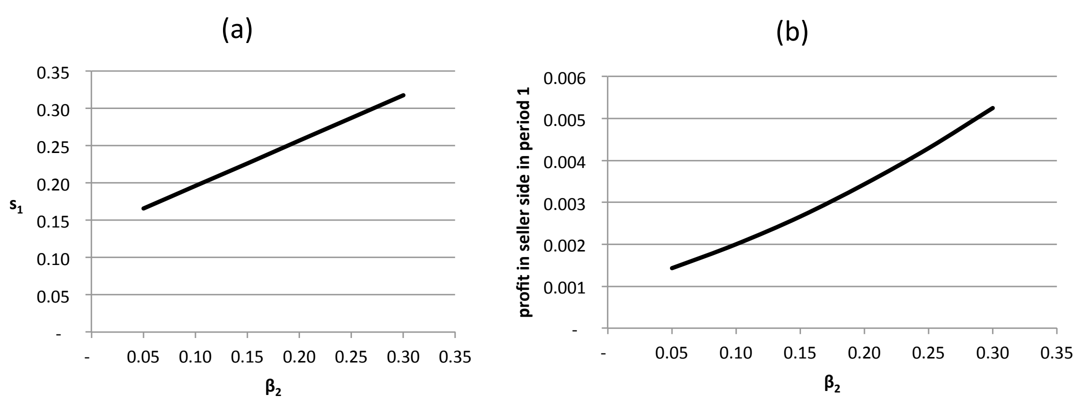

Figure 5: Optimal Fee and Profit on Seller-Side in Period 1

Figure 6 compares the changes in the price of the low-quality product and the demand in period

1 in the cases of one-sided and two-sided business models, as the cost in period 2 decreases. Again, the finding revealed is consistent with that in Section 4 (Proposition 5): The two-sided business model provides the platform additional benefits of setting a higher price of the low-quality product and shifting more buyers from the low-quality product market to the high-quality product market. With the seller-side, more buyers tend to purchase the high-quality product for a higher surplus; and the platform enjoys a higher profit generated on the seller-side due to the network externality and thus raises the price of the low-quality product further.

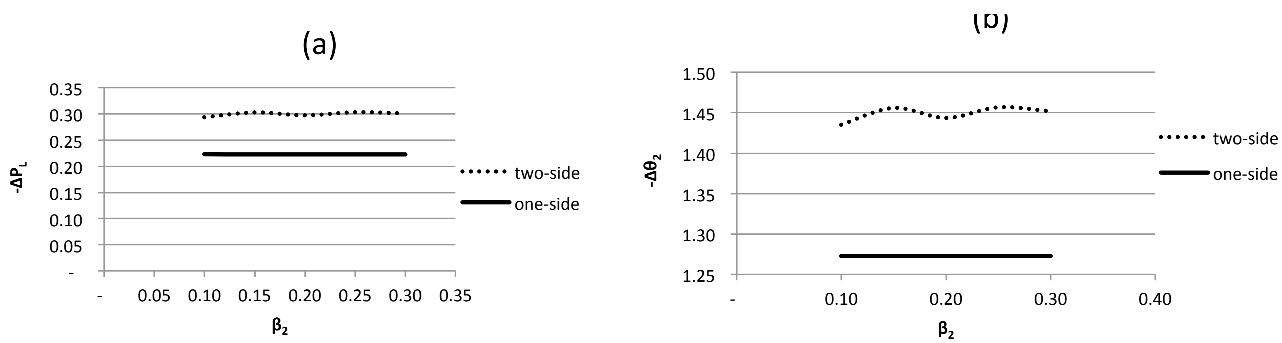

Figure 6: Demand and Price of low-quality Product for One-sided and Two-sided Model

Following Proposition 6, here cost reductions in period 2 lead to a higher price of the high-quality product due to the demand shift from period 1 to period 2 if the higher quality product improves the quality substantially (Region II). Moreover, the rate of increase is higher with the consideration of the seller-side. However, when the quality improvement is less substantial (in Region III), the firm may lower the price of the high-quality product since the quality improvement is not sufficiently appealing to attract more buyers at a higher price. Figure 7 demonstrates the results for Region II ($\alpha = 0.7$) and Region III ($\alpha = 0.55$).

Although considering the network externalities in both directions significantly complicates the model, we derive the same insights as those obtained analytically based on unidirectional externality in Section 4. The intuitions offered by the analytical model can be extended to understand the consistency in findings. The addition of the seller-to-buyer network externality does not conflict with the platform's intertemporal incentives. In Section 4, we find that in the two-sided case the platform induces more buyers to delay purchase by raising prices higher compared to the one-sided case, because buyers in period 2 can indirectly generate additional profits for the platform

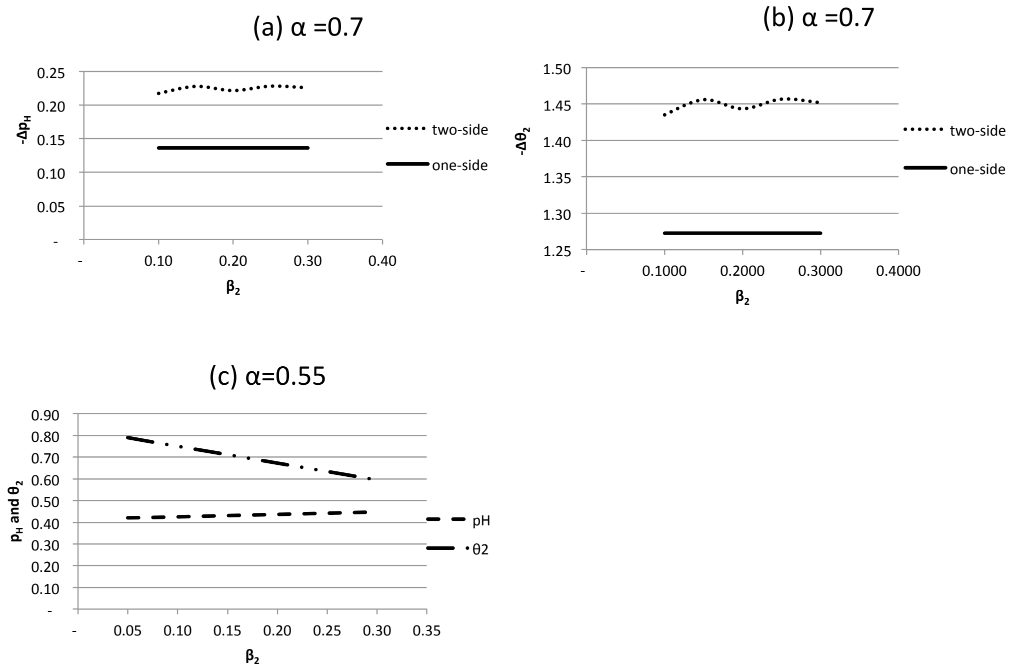

Figure 7: Price of high-quality Product in Region II and III

by attracting more sellers. Here, when sellers also have this effect on the buyer-side demand, the platform nevertheless relies more on period 2 for profits relative to period 1. In fact, shifting buyers to period 2 not only stimulates the seller-side demand, the effect also feeds back on the buyer-side and induces more buyers to purchase in period 2. Whereas qualitative insights are consistent whether the externality is unidirectional or bidirectional, there may be quantitative differences depending on the strength of each network externality. Based on our parameter values, such quantitative differences are insignificant compared to the values that lead to the qualitative results.

6 Discussion and Conclusion

In this paper, we examine a monopolistic firm's dynamic pricing decisions facing future cost reductions, when it introduces quality-improving products sequentially. We compare strategies of a firm that only sells to buyers with those of a platform that markets to both buyers and sellers, where cross-side network externalities are present. Contrary to the conventional wisdom, we find that future cost reductions enable the firm to raise the price of the current product and as well as that of the future product that has a sufficiently high quality. Thus, future cost reductions shift the demand forward and enable high-end positioning of the product line. Furthermore, whereas the one-sided and two-sided business models allow the firm to adopt the similar strategy, in the two-sided case the network externalities offer the platform a stronger leverage to raise price because the the network externalities further stimulate the demand and profits in the future market.

This study underscores important factors, in addition to network externality, to be considered by platform owners that are entering the hardware market. Driven by innovative technologies, platform owners' pricing decisions not only depend on the strength of network externalities between different groups of users, successful two-sided pricing strategies also account for intricate interplays between network externality and other hardware-relevant factors. In the case of Apple, securing future cost discounts through negotiation with hardware factories upfront has enabled the company to optimally segment the market across multiple releases through strategic pricing. Anticipating future cost reductions, Apple paces consumers' adoption of different versions of iPad to gradually achieve a remarkable market saturation. A steep price of the first iPad (relative to other tablets) achieves both the positioning of the product as a premium tablet and sufficient market demand for more attractive, later versions. In the meantime, the cross-side network externality spurs the growth of the App Store, which currently features over 500,000 applications. In the emerging trend of platform-owned hardware devices, Google, Microsoft and other major players also face dynamic decisions for pricing hardware for their types of platforms. We provide guidelines for considering the key factors jointly.

Our findings also offer new theoretical insights into cannibalization in an intertemporal context. When high-quality product cannot be offered before the low-quality product, we can leverage future cost reductions to mitigate the intertemporal cannibalization problem. The firm's strategy to raise price in response to future cost reductions suggests that *over*estimating future costs may lead to product *under*pricing. Anticipating a higher future cost drives the firm to capture more demand early on by cutting the price. A suboptimally low price of the product introduced early cannibalizes the demand for the future product, which in turn leads to further underpricing. This is because buyers with high valuation opt for the underpriced product early on, and the buyers remaining in the market have low willingness to pay when the higher-quality product becomes available. Therefore, without accurately anticipating future costs, the firm could face a severe intertemporal cannibalization problem, which incurs profit losses due to underpricing.

By comparing the one-sided and two-sided cases, our results suggest that it is even more important for a firm with a two-sided business model to reduce and accurately estimate future costs. Here the potential cost of intertemporal cannibalization is exacerbated because the buyer-side demand in the future market has an additional effect of attracting more sellers; the cross-side network externality feeds back on the buyer-side demand, expanding the market significantly and yielding profit gains for the platform. As the platform balances its intertemporal tradeoffs, the presence of network externalities further emphasizes the more profitable market, inducing the platform to allocate more demand to the market where cost reduction occurs. Therefore, a two-sided platform enjoys a greater advantage by lowering and anticipating future costs and holds more market power to position its current and future products to the high-end market.

A few limitations exist in the current paper and point to several directions for future research. First, we assume that the firm discontinues the low-quality product when the high-quality product is introduced. In practice, the low-quality product may continue to be on market. Appendix B.2 formulates an extension of the model from Section 3 and shows that our findings still hold when the low-quality product remains in period 2. However, studying this scenario in a two-sided model requires additional assumptions about compatibility issues on both sides of the platform for co-existing qualities. The topic of this extension is beyond the scope of this work. Another interesting extension is to consider variations in buyers' purchasing behavior beside the typical "unit demand" for durable goods. One possibility is for some buyers to demand multiple products of different qualities. A related direction is that in the second-hand market, which emerges through many online channels for many types of products. Existing users then have the option of upgrading their current device by selling their products and then buying a newer and better version. The firm faces strategic policy decisions when the second-hand market becomes sufficiently dominant.

Appendix

A Proofs

Proof of Lemma 3 The firm's profit function is:

$$\Pi_2(p_H) \quad = \quad (\theta_2 - \theta_H)(p_H - \beta_2 q_H^2) = (\theta_2 - \frac{p_H}{q_H})(p_H - \beta_2 q_H^2).$$

The first-order condition gives $p_H^* = \frac{\theta_2 q_H + \beta_2 q_H^2}{2}$ and $\theta_H^* = \frac{p_H}{q_H} = \frac{\theta_2 + \beta_2 q_H}{2}$. $\square$

Proof of Lemma 4 Taking into account θ_2^*, the firm's expected profit in period 1 is

$$\Pi_1(p_L) \quad = \quad (1-\theta_2^*(p_L))(p_L - \beta_1 q_L^2) + \frac{\alpha q_H}{4}(\theta_2^*(p_L) - \beta_2 q_H)^2$$

The FOC wrt p_L is

$$(2q_L - \alpha q_H - 4p_L + 2\beta_1 q_L^2 + \alpha\beta_2 q_H^2)(2q_L - \alpha q_H) + \alpha q_H(2p_L - \alpha\beta_2 q_H^2) - \alpha\beta_2 q_H^2(2q_L - \alpha q_H) \quad = \quad 0$$

From our assumption of moderate innovation with $q_L > \alpha q_H$, we have $-8q_L + 6\alpha q_H < 0$ and the SOC is $\frac{\partial^2 \Pi_1}{\partial p_L^2} = \frac{-8q_L + 6\alpha q_H}{(2q_L - \alpha q_H)^2} < 0$. We can obtain the optimal price as shown in Eq. (12). By substituting p_L^* into Eq. (11), we get expression for θ_2^* as shown in Eq. (13).

Notice that θ_2 must satisfy $\theta_H \leq \theta_2 \leq 1$, therefore we need the following conditions.

$$\beta_2 q_H \leq \frac{2q_L - \alpha q_H + 2\beta_1 q_L^2 - 2\alpha\beta_2 q_H^2}{4q_L - 3\alpha q_H} \leq 1 \tag{7}$$

$\square$

Proof of Proposition 1 In period 1, the demand for the low-quality product is $1 - \theta_2^*$.

$$\frac{\partial(1-\theta_2^*)}{\partial\beta_2} = \frac{2q_H^2\alpha}{4q_L - 3\alpha q_H} > 0.$$

The demand for the high-quality product in period 2 is $\theta_2^* - \theta_H^*$.

$$\frac{\partial(\theta_2^* - \theta_H^*)}{\partial\beta_2} = \frac{-q_H^2\alpha}{4q_L - 3\alpha q_H} < 0 \text{ and } \frac{\partial p_{1,L}^*}{\partial\beta_2} = \frac{-\alpha^2 q_H^3}{8q_L - 6\alpha q_H} < 0$$

$\square$

Proof of Proposition 2 In Region II

$$\frac{\partial p_H^*}{\partial\beta_2} \quad = \quad \frac{-2q_H^3\alpha}{8q_L - 5\alpha q_H} + \frac{q_H^2}{2} = \frac{q_H^2}{2}\left[\frac{4q_L - 5\alpha q_H}{4q_L - 3\alpha q_H}\right] = \frac{q_H^3}{2}\left[\frac{f_1(\frac{q_L}{q_H})}{4q_L - 3\alpha q_H}\right] \geq 0.$$

The total demand is $1 - \theta_H^*$, and

$$\frac{\partial(1-\theta_H^*)}{\partial\beta_2} = -\frac{\partial(\theta_H^*)}{\partial\beta_2} = -q_H\frac{\partial p_H^*}{\partial\beta_2} \geq 0.$$

In Region III,

$$\frac{\partial p_H^*}{\partial\beta_2} = \frac{q_H^3}{2}\left[\frac{f_1(\frac{q_L}{q_H})}{4q_L - 3\alpha q_H}\right] < 0 \text{ and } \frac{\partial(1-\theta_H^*)}{\partial\beta_2} = -\frac{\partial(\theta_H^*)}{\partial\beta_2} = -q_H\frac{\partial p_H^*}{\partial\beta_2} < 0.$$

$\square$

Proof of Lemma 1 The expected profit function is

$$\Pi_2(p_H, s_2) = (\theta_2 - \frac{p_H}{q_H})(p_H - \beta_2 q_H^2) + s_2\left[v_2(\theta_2 - \frac{p_H}{q_H}) - ks_2\right]$$

By taking the FOC w.r.t. s_2, we get

$$s_2^* = \frac{v_2}{2k}(\theta_2 - \frac{p_H}{q_H}).$$

Substituting s_2^* into the profit function yields,

$$\Pi_2(p_H, s_2) = (\theta_2 - \frac{p_H}{q_H})(p_H - \beta_2 q_H^2) + \frac{v_2^2}{4k}(\theta_2 - \frac{p_H}{q_H})^2.$$

The FOC wrt to p_H gives us

$$p_H^* = \frac{\theta_2 q_H + \beta_2 q_H^2 - \theta_2 \frac{v_2^2}{2k}}{2 - W}.$$

The SOC wrt to p_H requires the concavity condition: $2 - W > 0$. □

Proof of Lemma 2 Plugging Eq. (2) for p_H^* into the profit function, we have

$$\Pi_2^*(\theta_2) \quad = \quad \frac{(\theta_2 - \beta_2 q_H)^2}{[2 - W]^2}\left[q_H - \frac{v_2^2}{4k}\right]$$

Notice that to ensure positive demand and marginal profit, the following conditions must be satisfied:

$$\theta_2 - \beta_2 q_H > 0 \text{ and } q_H - \frac{v_2^2}{2k} > 0.$$

Furthermore, we derive the following to be substituted into the FOC of Π_1.

$$\frac{\partial \Pi_2}{\partial \theta_2} = \frac{2(q_H - \frac{v_2^2}{4k})}{[2 - W]^2}(\theta_2 - \beta_2 q_H) = \frac{q_H}{2 - W}(\theta_2 - \beta_2 q_H)$$

The indifferent buyer θ_2^* must satisfy the following:

$$[2 - W](\theta_2^* q_L - p_L) \quad = \quad \alpha\left[\theta_2^* q_H - \beta_2 q_H^2\right]$$

$$\theta_2^* = \frac{(2 - W)p_L - \alpha\beta_2 q_H^2}{(2 - W)q_L - \alpha q_H},$$

where $(2 - W)q_L - \alpha q_H > 0$. Notice that, similar to the one-sided case, a reduction in the period-2 cost would induce buyers to delay purchase (higher θ_2^*).

The platform's profit function in period 1 is

$$\Pi_1(p_L, s_1) = (1 - \theta_2^*)(p_L - \beta_1 q_L^2) + s_1\left[v_1(1 - \theta_2^*) - ks_1\right] + \alpha\Pi_2^*(\theta_2^*).$$

The FOC wrt s_1 gives $s_1^* = \frac{v_1}{2k}(1 - \theta_2^*)$. We can rewrite the profit in period 1 as,

$$\Pi_1(p_L) = (1 - \theta_2^*)(p_L - \beta_1 q_L^2) + \frac{v_1^2}{4k}(1 - \theta_2^*)^2 + \alpha\Pi_2^*(\theta_2^*)$$

By taking the FOC wrt p_L, we get

$$-2(2-W)p_L + (2-W)\beta_1 q_L^2 + (2-W)q_L - \alpha q_H + \alpha\beta_2 q_H^2 - \frac{v_1^2}{2k}(1-\theta_2^*)(2-W) + \alpha q_H(\theta_2^* - \beta_2 q_H) = 0.$$

Therefore,

$$\begin{aligned} p_L^* &= \frac{((2-W)q_L - \alpha q_H)\left[(2-W)q_L - \alpha q_H + (2-W)\beta_1 q_L^2 - \frac{v_1^2}{2k}(2-W)\right] - \alpha^2\beta_2 q_H^3}{(2-W)[2(2-W)q_L - 3\alpha q_H] - \frac{v_1^2}{2k}(2-W)^2} \\ &\quad - \frac{\frac{v_1^2}{2k}(2-W)\alpha\beta_2 q_H^2}{(2-W)[2(2-W)q_L - 3\alpha q_H] - \frac{v_1^2}{2k}(2-W)^2} \end{aligned}$$

To ensure concavity of the profit function, we have the following condition:

$$(2-W)[2(2-W)q_L - 3\alpha q_H] - \frac{v_1^2}{2k}(2-W)^2 > 0,$$

which implies that $q_L - \frac{v_1^2}{4k} > 0$.

Using

$$((2-W)q_L - \alpha q_H)\theta_2^* = (2-W)p_L^* - \alpha\beta_2 q_H^2,$$

we get

$$\theta_2^* = \frac{(2-W)q_L - \alpha q_H + (2-W)\beta_1 q_L^2 - 2\alpha\beta_2 q_H^2 - \frac{v_1^2}{2k}(2-W)}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)}$$

To ensure $\theta_H^* \leq \theta_2^* \leq 1$, we need the following condition.

$$\beta_2 q_H \leq \frac{(2-W)q_L - \alpha q_H + (2-W)\beta_1 q_L^2 - 2\alpha\beta_2 q_H^2 - \frac{v_1^2}{2k}(2-W)}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} \leq 1$$

□

Proof of Proposition 3

$$\frac{\partial\theta_2^*}{\partial\beta_2} = \frac{-2\alpha q_H^2}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} < 0. \tag{8}$$

Since the demand in period 1 is $1-\theta_2^*$, it decreases as β_2 decreases.

$$\frac{\partial p_L^*}{\partial\beta_2} = \frac{q_H^2\left[-\alpha^2 q_H - \frac{v_1^2\alpha}{2k}(2-W)\right]}{(2-W)[2(2-W)q_L - 3\alpha q_H] - \frac{v_1^2}{2k}(2-W)^2} < 0.$$

□

Proof of Proposition 4

$$\begin{aligned}\frac{\partial s_1^*}{\partial \beta_2} &= \frac{v_1}{2k}\left[-\frac{\partial \theta_2^*}{\partial \beta_2}\right] > 0,\\ s_2^* &= \frac{v_2}{2k}\left[\theta_2^* - \frac{p_H^*}{q_H}\right] = \frac{v_2}{2k}\left[\frac{\theta_2^* - \beta_2 q_H}{2-W}\right] \text{ and } \frac{\partial s_2^*}{\partial \beta_2} = \frac{v_2}{2k(2-W)}\left[\frac{\partial \theta_2^*}{\partial \beta_2} - q_H\right] < 0.\end{aligned}$$

Since the seller-side profits is ks_i^{*2} in period i, $i \in \{1,2\}$; the results for the seller-side profits follow immediately. □

Proof of Proposition 5

$$\frac{\partial \theta_2^*}{\partial \beta_2} = \frac{-2\alpha q_H^2}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)},$$

which is greater in magnitude compared to $\frac{\partial \theta_2^*}{\partial \beta_2}$ in the one-sided case because the numerators are equal and $2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W) < 4q_L - 3\alpha q_H$.

To compare the intensity of the price increase on p_L^* in one-sided and two-sided cases, we find the difference of the magnitude of $\frac{\partial p_L^*}{\partial \beta_2}$, i.e. $\left|\frac{\partial p_L^*}{\partial \beta_2}\right| = -\frac{\partial p_L^*}{\partial \beta_2}$, in the two cases. Let Δ denote the amount that $\left|\frac{\partial p_L^*}{\partial \beta_2}\right|$ is greater in the two-sided case than in the one-sided case; and denote by D the product of the denominators of $\frac{\partial p_L^*}{\partial \beta_2}$ in the two cases.

$$\begin{aligned}\frac{D\cdot\Delta}{q_H^2} &= \left[\alpha^2 q_H + \frac{v_1^2\alpha}{2k}(2-W)\right]\cdot[8q_L - 6\alpha q_H] - \left[\alpha^2 q_H\right]\cdot\left[(2-W)[2(2-W)q_L - 3\alpha q_H] - \frac{v_1^2}{2k}(2-W)^2\right]\\ &= W(4q_L - 3\alpha q_H)\alpha^2 q_H + \frac{v_1^2\alpha}{2k}(2-W)\left[8q_L - 6\alpha q_H\right] + \left[(\alpha^2 q_H\right]\left[2W(2-W)q_L\right] + \left[\alpha^2 q_H\right]\frac{v_1^2}{2k}(2-W)^2 > 0\end{aligned}$$

□

Proof of Proposition 6

$$\frac{\partial p_H^*}{\partial \beta_2} = \left(\frac{q_H - \frac{v_2^2}{2k}}{2-W}\right)\frac{\partial \theta_2^*}{\partial \beta_2} + \frac{q_H^2}{2-W} = \frac{q_H^2}{2-W}\left[\frac{-2\alpha(q_H - \frac{v_2^2}{2k})}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} + 1\right]$$

We first need to show that $\frac{\partial p_H^*}{\partial \beta_2} \le 0$. To do that, we combine the numerator of the terms in the parentheses:

$$4q_L - 5\alpha q_H + 2\alpha\frac{v_2^2}{2k} - 2Wq_L - \frac{v_1^2}{2k}(2-W) = (1-W)(4q_L - 5\alpha q_H) + W(2q_L - 3\alpha q_H) - \frac{v_1^2}{2k}(2-W)$$

where $4q_L - 5\alpha q_H \le 0$ in Region II; thus, $2q_L - 2.5\alpha q_H \le 0$, implying that $2q_L - 3\alpha q_H < 0$. Also, notice that $1 - W > 0$ because $q_H - \frac{v_2^2}{2k} > 0$. Therefore, $\frac{\partial p_H^*}{\partial \beta_2} < 0$.

To compare with the one-sided case, recall that in the one-sided case:

$$\frac{\partial p_H^*}{\partial \beta_2} = \frac{q_H^2}{2}\left[\frac{-2\alpha q_H}{4q_L - 3\alpha q_H} + 1\right]$$

If $\frac{2\alpha(q_H - \frac{v_2^2}{2k})}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} > \frac{2\alpha q_H}{4q_L - 3\alpha q_H}$, then the increase in p_H^* is more pronounced in the two-sided

case than in the one-sided case. After multiplying the product of the numerators ($\left[2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W\right.$
$[4q_L - 3\alpha q_H]$) on both sides, LHS - RHS is the following:

$$
\begin{aligned}
& 2\alpha(q_H - \frac{v_2^2}{2k}) \cdot [4q_L - 3\alpha q_H] - 2\alpha q_H \cdot \left[2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)\right] \\
= \; & 2\alpha q_H \left[4q_L - 3\alpha q_H\right] - 2\alpha \frac{v_2^2}{2k}\left[4q_L - 3\alpha q_H\right] - 2\alpha q_H \left[4q_L - 3\alpha q_H\right] + 2\alpha q_H \left[2Wq_L + \frac{v_1^2}{2k}(2-W)\right] \\
= \; & 2\alpha q_H \frac{v_1^2}{2k}(2-W) + 2\alpha W q_H \left[-2q_L + 3\alpha q_H\right]
\end{aligned}
$$

In Region II, $f(\frac{q_L}{q_H}) \geq 0$, meaning $2q_L \leq 2.5\alpha q_H$. Thus, $[-2q_L + 3\alpha q_H] > 0$, implying that $LHS - RHS > 0$. Therefore, the increase in p_H^* is more pronounced in the two-sided case than in the one-sided case.

$$
\begin{aligned}
\frac{\partial p_H^*}{\partial \beta_2} &= \frac{q_H^2}{2-W}\left[\frac{-2\alpha(q_H - \frac{v_2^2}{2k})}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} + 1\right] \\
&= \frac{q_H^2}{2-W}\left[\frac{(2-W)(2q_L - 2.5\alpha q_H) - \frac{\alpha W q_H}{2} - \frac{v_1^2}{2k}(2-W)}{4q_L - 3\alpha q_H - 2Wq_L - \frac{v_1^2}{2k}(2-W)}\right]
\end{aligned}
$$

where $2q_L - 2.5\alpha q_H > 0$ in Region III and the numerator is decreasing in v_1. Therefore, for v_1 sufficiently high, $\frac{\partial p_H^*}{\partial \beta_2} \leq 0$.

$$
\begin{aligned}
& \left[2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)\right] \cdot [4q_L - 3\alpha q_H] * \left[\frac{2\alpha(q_H - \frac{v_2^2}{2k})}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} - \frac{2\alpha q_H}{4q_L - 3\alpha q_H}\right] \\
= \; & \frac{2\alpha}{2k}\left[v_1^2 q_H(2-W) - v_2^2(2q_L - 3\alpha q_H)\right] < 0
\end{aligned}
$$

Therefore,

$$
\frac{q_H^2}{2-W}\left[\frac{-2\alpha(q_H - \frac{v_2^2}{2k})}{2(2-W)q_L - 3\alpha q_H - \frac{v_1^2}{2k}(2-W)} + 1\right] > \frac{q_H^2}{2}\left[\frac{-2\alpha q_H}{4q_L - 3\alpha q_H} + 1\right] > 0
$$

□

B Optimal Characterization of Buyer-Side Pricing

B.1 Baseline Model with Only High-Quality Product in Period 2

We first analyze the subgame in period 2. The remaining buyers in this period have valuations over $[0, \theta_2)$. Given state θ_2 and prices p_L and p_H, a buyer with valuation $\theta < \theta_2$ purchases if doing so yields positive surplus. Therefore, buyers with valuations in the interval $[\theta_H, \theta_2)$ purchase the high-quality product, where $\theta_H = \frac{p_H}{q_H}$. Lemma 3 characterizes the optimal price for the high-quality product and the valuation of the buyer who is indifferent between purchasing the high-quality product and consuming nothing.

Lemma 3. *Given that the remaining buyers in the second period have valuations in the interval* $[0, \theta_2)$*, the optimal price for the high-quality product and the lowest valuation of the buyer purchasing the high-quality product are given by:*

$$p_H^* = \frac{\theta_2 q_H + \beta_2 q_H^2}{2}, \tag{9}$$

$$\theta_H^* = \frac{\theta_2 + \beta_2 q_H}{2}. \tag{10}$$

Now we examine the firm's pricing decision for the low-quality product in period 1. Buyers time their purchases by comparing their utilities of consuming the products offered in the two periods. Let θ_2^* denote the valuation of the buyer who is indifferent between purchasing in the two periods under the optimality condition. Thus, buyers with valuation $\theta \geq \theta_2^*$ purchase in period 1. From $\theta_2^* q_L - p_L = \alpha(\theta_2^* q_H - p_H^*(\theta_2^*))$, we define the indifference buyer by the following expression:

$$\theta_2^* = \frac{2p_L - \alpha\beta_2 q_H^2}{2q_L - \alpha q_H}, \tag{11}$$

where $2q_L - \alpha q_H$ is positive.

A number of factors directly influence the value of θ_2^*. Ceteris paribus, a lower product cost in period 2 would induce buyers to delay purchase; also, a lower quality or a higher price in period 1 would have the similar effect. Using the first-order condition (FOC) of the firm's expected profit function in period 1, we can obtain the optimal price for the low-quality products and the optimal indifference buyer θ_2^* as shown in Lemma 4.

Lemma 4. *In period 1, the optimal price for the low-quality product and the valuation of a buyer who is indifferent between purchasing the high-quality product and low-quality product are given by*

$$p_L^* = \frac{(2q_L - \alpha q_H + 2\beta_1 q_L^2)(2q_L - \alpha q_H) - \alpha^2 \beta_2 q_H^3}{8q_L - 6\alpha q_H} \tag{12}$$

$$\theta_2^* = \frac{2q_L - \alpha q_H + 2\beta_1 q_L^2 - 2\alpha\beta_2 q_H^2}{4q_L - 3\alpha q_H}. \tag{13}$$

B.2 Coexistence of High- and Low-Quality Products in Period 2

The firm's objective is to find p_H^* and p_L^* such that $\Pi^* = max_{p_H, p_L}\Pi(p_H, p_L)$. Since there is a one-to-one correspondence between (p_H, p_L) and (θ_H, θ_L), the firm's profit function in the second period can be written as the following:

$$\Pi_2(\theta_H, \theta_L) = (\theta_2 - \theta_H)(p_H - \beta_2 q_H^2) + (\theta_H - \theta_L)(p_L - \beta_2 q_L^2)$$

The firm's maximization problem is

$$max_{\theta_H, \theta_L}\Pi_2(\theta_H, \theta_L)$$
$$s.t.\ 0 \leq \theta_L \leq \theta_H \leq 1$$

Based on the FOCs, we derive:

$$\begin{aligned} \theta_L^* &= \frac{\theta_2 + \beta_2 q_L}{2}, \theta_H^* = \frac{\theta_2 + \beta_2(q_H + q_L)}{2}, \\ p_L^* &= \frac{\theta_2 q_L + \beta_2 q_L^2}{2}, \text{ and } p_H^* = \frac{\theta_2 q_H + \beta_2 q_H^2}{2}. \end{aligned}$$

Notice that p_H^* remains unchanged compared to that in Section 3; as a result, θ_2^*, the indifference buyer between purchasing in the two periods, and p_L^* are also identical to those in the main model – Proposition 1 holds for this setting.

Reductions in the costliness of quality provide more cost savings for a product of a higher quality; thus, cost reductions in period 2 raise profitability of the high-quality product more significantly than that of the low-quality product. It is intuitive that, within period 2, the optimal strategy is to induce a demand shift from the low-quality product to the high-quality product. The intertemporal demand shift, however, further depends on the platform's optimal strategy in setting the price of the low-quality product in period 1.

We also need to derive the optimal price for the low-quality product in period 2, p_L^*. To examine the effect of cost reductions on this price, we first define two indicator functions that are analogous to $f(\cdot)$ defined in Section 3:

$$\begin{aligned} f_1(\frac{q_L}{q_H}) &= 5\alpha - 4\frac{q_L}{q_H} = \tilde{f}(\frac{q_L}{q_H}) + 2\alpha \\ f_2(\frac{q_L}{q_H}) &= 2\alpha + 3\alpha(\frac{q_L}{q_H}) - 4(\frac{q_L}{q_H})^2 = \frac{q_L}{q_H}\tilde{f}(\frac{q_L}{q_H}) + 2\alpha \end{aligned}$$

where $\tilde{f}(\frac{q_L}{q_H}) = 3\alpha - 4\frac{q_L}{q_H}$. Notice that $f_1'(\cdot) < 0$ and $f_1''(\cdot) = 0$; and, $f_2'(\cdot) < 0$ when $\frac{q_L}{q_H} > \frac{3\alpha}{8}$ and $f_2''(\cdot) < 0$.

Define $\delta_1 \equiv \frac{5\alpha}{4}$, so that $f_1(\delta_1) = 0$; also, let $\delta_2 \equiv \frac{3\alpha + \sqrt{(3\alpha)^2 + 32\alpha}}{8}$, so that $f_2(\delta_2) = 0$. The (q_H, q_L)-space can be divided into four regions shown in Figure 8: Region I with $\frac{q_L}{q_H} < \alpha$, region II with $\alpha < \frac{q_L}{q_H} \leq \delta_1$, region III with $\delta_1 < \frac{q_L}{q_H} \leq \delta_2$, and region IV with $\delta_2 < \frac{q_L}{q_H} < 1$.

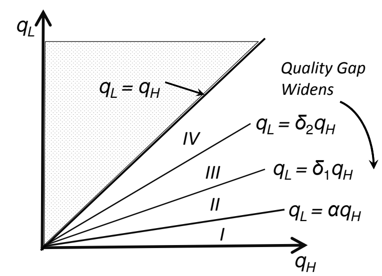

Figure 8: Four Regions in the (q_H, q_L)-Space

Lemma 5. *The values of $f_1(\cdot)$ and $f_2(\cdot)$ depend on the quality gap (i.e., the quality ratio) as described in Table 2.*

Table 2: Regions of the (q_H, q_L)-Space

Region I	$\frac{q_L}{q_H} < \alpha$	Not Feasible
Region II	$\alpha < \frac{q_L}{q_H} \leq \delta_1$	$f_1(\frac{q_L}{q_H}) \geq 0, f_2(\frac{q_L}{q_H}) > 0$
Region III	$\delta_1 < \frac{q_L}{q_H} \leq \delta_2$	$f_1(\frac{q_L}{q_H}) < 0, f_2(\frac{q_L}{q_H}) \geq 0$
Region IV	$\frac{q_L}{q_H} > \delta_2$	$f_1(\frac{q_L}{q_H}) < 0, f_2(\frac{q_L}{q_H}) < 0$

In Region II, $f_1(\delta_1) = 0$ and $f_1'(\cdot) < 0$, so $f_1(\frac{q_L}{q_H}) \geq 0$. Since $\tilde{f}(\frac{q_L}{q_H}) < 0$ and $\frac{q_L}{q_H} < 1$, $f_1(q) < f_2(q)$ for all feasible values of q and thus $f_2(\frac{q_L}{q_H}) > 0$.

In Regions III & IV, $f_1(\frac{q_L}{q_H}) < 0$. Since $f_2(\delta_2) = 0$ and $f_2'(\cdot) < 0$, we can get $f_2(\frac{q_L}{q_H}) \geq 0$ for

$\delta_1 < \frac{q_L}{q_H} \leq \delta_2$ (Region III). For $\frac{q_L}{q_H} > \delta_2$ (Region IV), since $\delta_2 > \frac{q_L}{q_H} > \frac{3\alpha}{8}$, $f_2(\cdot)$ is decreasing and $f_2(\frac{q_L}{q_H}) < 0$. □

Propositions 2 from the main model can be extended to apply to the result regarding the low-quality product in period 2.

Proposition 7. *7a. For a major quality improvement in period 2 (i.e., in region II), cost reductions in period 2 induce the firm to raise the optimal price for both the low-quality and high-quality products in period 2. As a result, the total demand over two periods decreases.*

7b. For a minor quality improvement in period 2 (i.e., in region IV), cost reductions in period 2 induce the firm to lower the optimal price for both the low-quality and high-quality products in period 2. As a result, the total demand over two periods increases.

7c. When the quality improvement is moderate (i.e., in region III), cost reductions in period 2 induce the firm to lower (raise) the optimal price for the high-quality (low-quality) product in period 2. As a result, the total demand over two periods decreases.

7a. From Lemma 5, we have $f_1(\frac{q_L}{q_H}) \geq 0, f_2(\frac{q_L}{q_H}) > 0$, so

$$\frac{\partial p_H^*}{\partial \beta_2} = \frac{-q_H^3\alpha}{4q_L - 3\alpha q_H} + \frac{q_H^2}{2} = \frac{q_H^3}{2}\left[\frac{-f_1(\frac{q_L}{q_H})}{4q_L - 3\alpha q_H}\right] < 0 \text{ and } \frac{\partial p_L^*}{\partial \beta_2} = \frac{q_L^2}{2} - \frac{q_H^2 q_L \alpha}{4q_L - 3\alpha q_H} = -\frac{q_L q_H^2}{8q_L - 6\alpha q_H} f_2(\frac{q_L}{q_H}) < 0.$$

The total demand is $1 - \theta_L^*$, and $\frac{\partial(1-\theta_L^*)}{\partial \beta_2} = \frac{q_H^2\alpha}{4q_L - 3\alpha q_H} - \frac{q_L}{2} = -q_L \frac{\partial p_{2L}^*}{\partial \beta_2} > 0$

7b. Lemma 5 shows $f_1(\frac{q_L}{q_H}) < 0, f_2(\frac{q_L}{q_H}) < 0$, so

$$\begin{aligned}
\frac{\partial p_H^*}{\partial \beta_2} &= \frac{q_H^3}{2}\left[-\frac{f_1(\frac{q_L}{q_H})}{4q_L - 3\alpha q_H}\right] > 0 \text{ and } \frac{\partial p_L^*}{\partial \beta_2} = -\frac{q_L q_H^2}{8q_L - 6\alpha q_H} f_2(\frac{q_L}{q_H}) > 0, \\
\frac{\partial(1-\theta_L^*)}{\partial \beta_2} &= \frac{q_H^2\alpha}{8q_L - (4\gamma + 2\alpha)q_H} - \frac{q_L}{2} = -q_L \frac{\partial p_{2L}^*}{\partial \beta_2} < 0.
\end{aligned}$$

7c. Lemma 5 shows $f_1(\frac{q_L}{q_H}) < 0, f_2(\frac{q_L}{q_H}) \geq 0$, so

$$\begin{aligned}
\frac{\partial p_H^*}{\partial \beta_2} &= \frac{q_H^3}{2}\left[-\frac{f_1(\frac{q_L}{q_H})}{4q_L - 3\alpha q_H}\right] > 0 \text{ and } \frac{\partial p_{2,L}^*}{\partial \beta_2} = -\frac{q_L q_H^2}{8q_L - 6\alpha q_H} f_2(\frac{q_L}{q_H}) < 0, \\
\frac{\partial(1-\theta_L^*)}{\partial \beta_2} &= \frac{q_H^2\alpha}{4q_L - 3\alpha q_H} - \frac{q_L}{2} = -q_L \frac{\partial p_{2L}^*}{\partial \beta_2} > 0.
\end{aligned}$$

□

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