European Journal of Operational Research 331 (2026) 292–305

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/eor

Innovative applications of O.R.

Dynamic pricing when consumers have real options

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ARTICLE INFO

Keywords:
Platforms
Real Options
Dynamic Pricing
Uncertainty

ABSTRACT

We study optimal dynamic pricing under uncertainty in a platform ecosystem subject to technological uncertainty. We highlight that users joining the platform before the full development of the complementary goods and services obtain real options to benefit from future improvements in platform quality and network effects. The platform owner influences the network effects and equilibrium outcomes through its dynamic price policy that trades off building an earlier consumer base versus extracting rents from early adopters. A price-skimming policy is optimal when the cost of developing a complementary good is small. Interestingly, price-skimming becomes optimal when the development cost is high, as long as the value of the improved platform is either small or relatively high. For intermediate values, however, the platform adopts a price-penetration policy. Our paper provides new insights for building markets subject to the network effect under uncertainty.

1. Introduction

Chicken-and-egg investment problems are common in two-sided markets. A new smartphone may introduce enhanced hardware and built-in capabilities, such as a higher-resolution camera or more accurate voice recognition. However, it may lack OS-specific applications that maximize its functionality for users. Once the phone is launched, app developers may consider creating software for it, and tech-savvy users may be interested in purchasing it for its advanced hardware. Yet both groups face uncertainty. Developers may worry that the phone will not attract enough customers, making investment in new apps risky and irreversible. At the same time, early adopters face the risk that app development for the device may be slow or challenging. In that case, they may end up with cutting-edge hardware that lacks a sufficient number of compatible applications.[1]

In the smartphone example, investment in apps, by the hardware producer or the developer community, improves the value of the bundle of phone and apps. Early buyers of the phone are betting on an "option" embedded in the value of bare-bone hardware, which benefits from direct (the same-side) and indirect (the cross-side) network effects. The same-side network effect refers to users community benefits due to the presence of other buyers: a larger number of buyers increases knowledge-sharing. The cross-side network effect refers to complementary goods: a larger number of applications improves the utility of the phone for the users. Noting these feedback effects, the smartphone producer also faces a non-trivial dynamic pricing of the hardware under uncertainty.

Motivated by many such real-life examples, we postulate a dynamic pricing problem in the presence of evolving *options* in platform markets.[2] We examine how uncertainty over the successful development of a platform bundle, such as the mall and support infrastructure, affects buyers' purchasing/investment decisions as well as the dynamic pricing policy of the platform owner. We highlight the fact that potential consumers of the platforms (smartphone buyers in the motivating example) face dynamic investment decisions because of multiple types of *real options*. As explained, the first real option is due to the (uncertain) enhanced functionality and larger network effects in case of better development of the bundle in the future (*growth option*). In other words, early smartphone buyers have a chance to enjoy a higher utility in the

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[1] A notable example occurred with the Apple III, introduced in 1980. Despite its improved hardware, it struggled due to limited software availability, as most developers continued supporting the dominant IBM PC platform. As a result, many early buyers of the Apple III found few compatible applications that resulted in a commercial failure of the product.

[2] The significance of the word "platform" in our paper comes from the fact that independent third-party firms typically invest in complementary goods. The platform owner does not directly control the development of the complementary good.

https://doi.org/10.1016/j.ejor.2025.09.034
Received 28 June 2024; Accepted 23 September 2025
Available online 26 September 2025

future in addition to the current level of their utility; in equilibrium, they are willing to pay for such an option, and the platform owner takes this into account. Some consumers, on the other hand, prefer to use their timing option (i.e., the *option to wait*) to make a purchasing decision after the resolution of uncertainty. The novel insight of our paper is that the value of both options depends on the dynamic pricing and investment decisions of the platform owner and the complementary good developers. The mass of initial buyers, as well as the expectation of future buyers, jointly determine the level of efforts to invest in developing the complementary good. Thus, to fully characterize the platform ecosystem problem, we jointly determine the equilibrium values of dynamic platform prices, developers' investment level, the endogenously resolved uncertainty, and buyers' purchase decisions.

To the best of our knowledge, our paper is among the first to consider the endogenous formation of real options on platform markets and the feedback effect of dynamic pricing policies on option values. Thus, we connect three lines of literature on (1) platform markets, (2) dynamic pricing, and (3) real options. One can consider the widespread applications of *platform real-options* in the modern economy. However, except for Lin, Pan et al. (2020) and Sui et al. (2024), we are not aware of any paper that explicitly models future indirect and direct network effects as various types of real options, and the resulting *coordination problem* due to such components. Besides the smartphone case, our model applies to a large range of practical problems in markets such as video games, virtual reality solutions, and electric vehicles. In these examples, early buyers (gamers, car owners, or businesses) are purchasing a basic product as well as an option for further development of the complementary goods/services (such as games, software, or charging stations) by a group of, potentially independent, developers.

Our model includes three key players: (1) a monopolistic platform owner that offers a durable *basic* good (e.g., smartphone or video game console), (2) a representative developer that offers a *complementary* good to the platform bundle (e.g., phone software or game packages) whose actual quality or even availability is only revealed in the next period, and (3) a mass of heterogeneous consumers (e.g., phone users or gamers) who differ in how much they value the basic platform. Consumers decide whether to join the platform earlier (before the outcome of the complementary good production is revealed) or later (when consumers learn if the complementary good is successfully developed).

By choosing different dynamic price paths, the platform owner affects the distribution of consumers' joining times, the mass of consumers, and the expectations of complementary good developers. Thus, the dynamic pricing policy affects both sides of the market due to network effects. Pricing not only affects customers' behavior but also controls developers' incentives to invest in complementary goods. As Zhou (2017) suggests, static models of expectation formation in platform markets might not provide sufficient intuition regarding dynamic pricing policies. We characterize two types of real options. First, the growth option reflects the incremental utility the consumer enjoys from both the direct and the indirect network effect. Second, the timing option captures the difference between the second and first-period utility functions (the consumers' flexibility to postpone the purchase of the basic product). We show that the combined effect of the option-to-wait and the growth options can result in endogenously determined upward or downward dynamic price paths for the platform.

We show that after noticing the option value and the pricing policies of the platform, consumers are segmented into three groups: (1) the high-value types who join the platform even before observing the outcome of the development of the complementary good, (2) the middle-value types who wait and join the platform only if the complementary good is successfully developed, and (3) the low-value types who do not join the platform at all. These results are consistent with observed consumer behavior in several markets. For instance, in the market for electric vehicles, consumers are divided into three groups: environmentally conscious or technology-oriented consumers who would purchase a vehicle even without a sufficiently developed network of charging stations, the "mass market" represented by consumers who buy a vehicle only if a high enough number of charging stations (i.e., complementary good) is available, and a third group that would rather buy a conventional vehicle (Egbue & Long, 2012; McKinsey, 2017).

We also demonstrate that the strength of the same-side network effect and the development cost drive the platform's optimal pricing policy. In equilibrium, the platform follows a *price-skimming* policy (i.e., consumer prices decline over time) if the indirect network effect is either too weak or too strong *and* the development cost is sufficiently low. Otherwise, the platform employs an increasing price schedule (i.e., *price-penetration* policy).

Intuitively, the platform's pricing policy is determined by the following trade-off. On the one hand, consumers who join the platform early either perceive a high intrinsic value for the basic platform or have a high option value (i.e., expect that the complementary product will enhance their product experience). Setting a high price initially (*price-skimming* policy) then allows extracting higher profits from early adopters. On the other hand, when the development cost is high, a price-skimming policy can discourage the developer from innovating and introducing the complementary product even when indirect network effects are relatively strong. The reason is that the price-skimming might incentivize some consumers to postpone their purchase decisions. This, in turn, reduces the developer's incentive to invest since its payoff is lower. The platform then has incentives to employ a *price-penetration* policy, holding the initial prices low to encourage more consumers to join the platform early on. As a result, the developer exerts more effort to develop the complementary product, and the probability of development increases.[3]

In the Extensions, we discuss variations of the baseline model that resemble additional features such as contingent second-period pricing, costly development of the basic good, several levels of the complementary product, and a more general utility function. In the Online Appendix, we also present two modifications of the core model: a model without commitment (Section A.2) and another one where the value of the complementary good is a function of consumer type (Section A.5). We illustrate that, for the platform, the benefit of commitment is twofold: commitment allows building a larger early consumer base and, in addition, commitment to a higher future price allows charging a higher earlier price. If the complementary good is a function of consumer type, the platform optimally sells the basic good only before the outcome of the complementary good is revealed. Therefore, consumers are segmented into two groups: high-value types who join the platform before observing whether the complementary good succeeds and low-value types who never join the platform.

The rest of the paper is organized as follows. Section 2 reviews the related literature. The main model and payoffs are introduced in Section 3. Section 4 presents the results of the equilibrium outcomes. The extensions are discussed in Section 5. Section 6 concludes.

2. Related literature

Our paper is related to three major streams of literature on (i) platform pricing and indirect network effects, (ii) dynamic pricing under uncertainty and strategic consumer behavior, and (iii) real options in platform ecosystems. Our key contribution lies in integrating platform pricing, developer-side innovation uncertainty, and forward-looking consumer adoption decisions within a unified dynamic framework, a feature that is mostly absent from the existing one-shot "chicken-and-egg" literature on platform formation.

[3] This price dynamic is consistent with the pricing policy adopted by electric vehicles and media service providers.

2.1. Network effect and optimal platform investment

The classic literature on platform markets has extensively studied how indirect network effects and pricing structures shape equilibrium outcomes (Armstrong, 2006; Bolt & Tieman, 2008; Rochet & Tirole, 2003). More recent work extends these insights to dynamic settings, including content release strategies under multi-homing, cooperation, and pricing optimization (Mardan & Tremblay, 2025; Tang et al., 2023; Wu & Chiu, 2023; Wu & Zha, 2025; Zhu et al., 2025). Similar to our paper, Gu et al. (2024) study differential pricing decisions on service platforms with capacity constraints. They show that platforms find it optimal to implement differential pricing in the presence of strong negative indirect network effects. Although we also explore platform pricing with both direct and indirect network effects, Gu et al. (2024) develop a static model. In contrast, we study intertemporal price dynamics and uncertainty on one side of the platform.

Within the platform literature, our paper is closest in spirit to Sui et al. (2023) and Zhu et al. (2023) examine how anticipated improvements in price or quality shape consumer decisions and developer incentives. However, our framework differs in three key ways. First, we model the development of complementary goods as an endogenous and stochastic process. Second, while Lin, Pan et al. (2020) emphasizes the platform's own product strategy, we focus on third-party developer innovation. Third, we analyze how platform price commitments shape the timing of consumer adoption. Furthermore, complementary services in Sui et al. (2023) are offered by platforms to both sides whereas in our model, the complementary product is developed by third-party developers under uncertainty.

While most models of indirect network effects emphasize participation size—i.e., the number of users on each side of the market (Boudreau, 2012), only a few consider the role of product quality and innovation. McIntyre and Srinivasan (2017) highlight this gap, while Jullien and Pavan (2019) and Roger and Vasconcelos (2014) address preference heterogeneity and information frictions. We build on this literature by examining how pricing can be used to incentivize uncertain innovation that enhances platform value.

2.2. Dynamic pricing

Our work also contributes to the large but still growing dynamic pricing literature, particularly models where consumer behavior is influenced by anticipated price changes or future product improvements (Kornish, 2001; Kumar & Sethi, 2009; Liu, 2010; Nair, 2007).

Relevant papers in this area examine how firms can mitigate revenue losses from strategic delay (Dasu & Tong, 2010; Kash et al., 2023; Liu et al., 2019; Liu & Zhang, 2013; Shum et al., 2017), often through pricing commitments or information design (Aviv & Pazgal, 2008; Drakopoulos et al., 2021; Lai et al., 2010; Su & Zhang, 2008). The advent of online businesses and platforms since the beginning of the century has given rise to a strand of literature that analyzes dynamic pricing and strategic consumer behavior. Ji et al. (2023) compare the impact of committed versus dynamic pricing schedules in a live-streaming platform, albeit absent uncertainty. Chen et al. (2025) explore dynamic pricing and price commitment for companies that market their products to strategic consumers on live-streaming platforms. Their model shows that live-streaming marketing enhances profitability under dynamic pricing when strategic consumers are less patient. Fan et al. (2025) investigate how product reviews and money-back guarantees affect strategic consumers' timing of purchases from online retailers. In these models, consumers' strategic behavior arises from their willingness to delay purchases. In contrast, strategic delay in our model arises from uncertainty over the development of complementary goods rather than expected price declines. We show that platform pricing affects not only consumer timing, but also developer incentives, creating a feedback loop between pricing, innovation, and adoption.

We also build on the literature that models forward-looking consumer expectations in platform settings (Hagiu & Hałaburda, 2014; Hagiu & Spulber, 2013; Halaburda & Yehezkel, 2013; Zhu & Iansiti, 2012). Zhu and Iansiti (2012), for instance, allow consumers to anticipate future app availability, governed by a discount factor. We extend this framework by modeling consumer heterogeneity and uncertainty over the quality and arrival of future complementary goods. Related work by Biglaiser et al. (2020) and Zhou (2017) explores platform switching and adoption timing, but does not explicitly model developer-side uncertainty as a driver of consumer delay.

2.3. Real options in platform eco-system

Platform markets are typically characterized by direct and indirect network effects and significant uncertainty regarding firm strategies. Network effects and uncertainty create valuable growth and timing options (Chintakananda & McIntyre, 2014; Chintakananda et al., 2025). As technology-driven and online businesses proliferate, recent work emphasizes the role of real options in platform development and pricing (Jia et al., 2018; Lin, Zhou et al., 2020; Sui et al., 2024). These models examine content bundling, pricing under installed base competition, and platform investment in value-added services. Toh and Agarwal (2023) examine the option value of uncertainty in complementary good for the entry of the platform. In Sui et al. (2024), platforms invest in value-added services to enhance network effects between manufacturers and suppliers. Jalili et al. (2025) similarly study strategic timing in the presence of future product upgrades. In general, the strand of literature that explores dynamic pricing in the presence of strategic consumers who may defer their purchases (e.g. Chen et al., 2025; Fan et al., 2025, among others) capture the idea of *timing options* without explicitly characterizing the option. In this paper, we characterize not only consumers' timing option but also their *growth option* that results from future product functionality. In addition, few of these studies explicitly model the uncertainty developers face in innovating complementary goods or how platforms can influence this process through pricing strategy.

To the best of our knowledge, our paper is the first to explicitly characterize both growth and timing options in platform markets. Our paper contributes to the small platform real options literature by modeling the developer's innovation process as a real option for consumers and studying how price commitment affects both developer investment and consumer adoption timing.

3. Model

Key players. We consider a model with three players: (1) a monopolistic platform, (2) a mass of heterogeneous consumers, and (3) a developer of the complementary product.[4] The platform offers a *basic* product and the developer offers a *complementary* product, i.e., features to be added on to the basic good. We assume that all the key parameters of the model are common knowledge among all the players at the beginning of the game.

[4] Although we treat the developer of the complementary product as a separate entity, our model captures the in-house production as well. The developer (i.e., internal engineers and scientists) must be incentivized to work hard (moral hazard problem). Rewards for successful innovative projects (bonuses, promotions, etc.) are widely used to incentivize internal innovations (see, e.g., Yanadori & Marler, 2006 and Lerner & Wulf, 2007).

Fig. 1. Time-line of the game.

Source of uncertainty. A key distinguishing feature of our paper is the uncertainty that is inherent in every innovation process.[5] In most platform markets, the development of complementary products is subject to various technical, legal, financial, organizational, market, and even political risks. For example, software developers face various technology risks and often experience failures (Boudreau, 2012). Risks might involve economy-wide shocks as well as idiosyncratic ones, i.e., losing to a rival developer. In the case of new physical products, numerous safety, zoning, and environmental regulations might be a source of uncertainty. For example, charging stations for electric cars might not receive construction permits from urban areas to build a large enough number of stations.

Timeline. The model is dynamic with three time periods $t \in \{0, 1, 2\}$. At $t = 0$, the platform produces the basic good and chooses an optimal pricing policy, i.e., prices p_t that consumers have to pay to join the platform at $t = 1$ and $t = 2$; in other words, the platform charges interaction-independent fixed fees (Rochet & Tirole, 2003). We normalize the marginal cost of producing the platform to zero and assume it does not change over time. In addition, the platform sets a reward $b > 0$ for the developer if the complementary product is successfully introduced. We normalize the developer's pay-off if the complementary good falls to zero. This is without loss of generality since the developer is risk-neutral. At $t = 1$, the developer determines the probability of successful development of the complementary product, denoted by $\lambda \in [0, 1]$. At $t = 2$, the outcome of the development process is revealed. The developer bears the full cost of development.

After observing the pricing policy chosen by the platform, consumers decide whether to join the platform at $t = 1$ or at $t = 2$ after paying price p_1 or p_2, respectively. Crucially, p_1 is the price consumers have to pay *before* observing whether or not the developer successfully introduces the complementary product. In contrast, p_2 is the price consumers pay to join the platform *after* observing the outcome of the development process.[6]

A representative timeline of the game is plotted in Fig. 1.

3.1. Payoffs

We now describe the payoff functions for the developer, consumers, and the platform.[7]

Developer. The development of the complementary product is a random process with a risky outcome. Therefore, the developer is facing a risky investment problem. With probability λ, the developer is successful and is paid b. However, with probability $1 - \lambda$, the complementary good fails, and the developer receives nothing. To achieve the probability of success λ, a certain level of effort (investment) is required. The cost of this effort is given by a quadratic function $c(\lambda)$:

$$c(\lambda) = A \times \lambda^2, \tag{1}$$

where $A > 0$ and $c'(\lambda) = 2A\lambda > 0$, $c''(\lambda) = 2A > 0$.[8]

Therefore, for a given b, the developer chooses the probability of success λ to maximize

$$\pi^D = \lambda b + (1 - \lambda) \times 0 - c(\lambda) = \lambda b - c(\lambda). \tag{2}$$

Consumers. The basic product (e.g., an electric vehicle or a smartphone) is durable, i.e., consumers who join the platform at $t = 1$, hold it, and get some utility from consumption of the basic good in both periods $t = 1$ and $t = 2$. Consumer utility at $t = 2$ represents a value function that summarizes the utility over the remaining life of the product.

The two-period model is used to capture the differential utility between early and late joiners. Consumers can live for an arbitrary number of T periods in a model. The early adopters then enjoy T periods of consumption of the basic good, whereas the late adopters enjoy $T-1$ periods only. The (relevant) marginal benefit from consumption of the basic product is then at $T-(T-1) = 1$ period. Given that T can also be a small number, specifically for electronic products, the one-period difference can be non-trivial. For example, early adopters may use the product for four years, while the late adopters use it for three years.[9]

The basic quality of the durable good does not depreciate between the two periods. We introduce two network effects to capture consumers' interaction with the platform and the developer of the complementary product.[10]

Direct Network Effect. A consumer gets a higher utility from joining the platform when more consumers are using the platform simultaneously. For example, users of an iPhone enjoy it more if their friends also have iPhones due to certain exclusive applications, such as FaceTime or, recently, Clubhouse. Consumers are heterogeneous in how much they value the basic product. For example, some consumers might have a higher willingness to pay for an iPhone. A consumer of type $\theta \in [0, 1]$, gets (per period) utility $u(\theta, N)$: $[0,1]\times[0,1] \rightarrow [0, +\infty)$ from consumption of the basic good, where θ denotes the intrinsic utility from the basic product, and N is the mass of current users of the basic product. In the benchmark model, we assume that[11]

$$u(\theta, N) = \theta \times N.$$

We normalize the utility of not joining the platform to zero for each consumer type.

Distribution of Types. The distribution of consumer preferences is given by a continuously differentiable distribution function $F(\theta)$ with

[5] To highlight the role of technological uncertainty and sharpen the intuition, our baseline model does not feature market uncertainty regarding consumer preferences or willingness to buy. We assume the distribution of consumer preferences is known to the platform. The case with market size uncertainty is discussed under the model extensions.

[6] For example, the price for an iPhone in 2007 with only a few hundred applications in the App Store was different from the price in 2010 when as many as 300,000 applications were available (Brochet et al., 2013).

[7] To simplify the exposition, we assume that all players have a common discount factor $\delta = 1$. None of our qualitative results hinge on this assumption.

[8] The cost of investment captures the cost of developing new performance features, adoption by the product, the cost of making that innovation includes marginal cost of development, and marketing costs and/or download purchases (Li et al., 2016). For the justification of cost being quadratic, see, e.g., Marjit et al. (2020) and references therein.

[9] Please note that our model is not a quantitative marketing model that accounts for the "level" effects.

[10] Almost all durable goods exhibit network effects in that they draw on common use and repair expertise. For example, the so-called "word of mouth" effect: more information is revealed regarding a good and its properties as more consumers buy it. Another example might be the so-called "learning by doing" effect: the developer improves the quality of the product as more consumers submit feedback.

[11] The multiplicative form of the direct externality is common in the literature on two-sided markets (see Goldfarb & Tucker, 2019 for a review and Sun et al., 2019, Zhu et al., 2023, and Xi et al., 2024 for more recent references). We discuss the robustness of our main results to a more general utility function in Section A.5.

Table 1
Key notation.

Variable	Definition
λ	Probability of Success in developing the complementary good
$c(\lambda)$	Developer's cost of efforts to achieve probability of Success λ
θ	Consumer type
$F(\theta), f(\theta)$	Distribution and density functions of types, respectively
π^D	developer's profit
N_1	Mass of consumers buying at $t = 1$
N_2^S	Mass of consumers buying the basic good at $t = 2$ in case of Success
N_2^F	Mass of consumers buying the basic good at $t = 2$ even in the case of Failure
N	Mass of current users of the product (*direct* network effect)
$u(\theta, N)$	Consumer utility
$h(\theta), \alpha$	Additional utility from the complementary good (*indirect* network effects)
p_1	Price of the basic good at $t = 1$
p_2	Price of the basic good at $t = 2$
b	Reward (bonus) for a successful development of the complementary good
$G(\theta)$	value of the growth option
$T(\theta)$	value of the timing option
$\hat{}$	The equilibrium value of variables

support $[0,1]$. A probability distribution $f(\theta) = F'(\theta)$ over the support defines the relative size of customers with valuation $\theta \in [0,1]$. We assume that the distribution of types is uniform, $f(\theta) = 1$ for $\theta \in [0,1]$.[12]

Indirect Network Effect. We introduce an *indirect* (positive) network effect between consumers and the developer of the complementary good as follows. Consumer's utility depends on the bundle, i.e., a combination of the basic and complementary products. In case the complementary product is successfully developed, each type of consumer obtains an additional utility $h(\theta) \geq 0$.[13] For example, the utility that current users derive from their electric cars is likely to increase when more charging stations become available in their area. As another example, the utility that current iPhone users will derive from their phones is likely to increase as new apps are developed and increase the phone's functionality.

Table 1 summarizes the key notation used throughout the paper.

3.2. Strategic choices

Consumer choice. Consumers decide whether to join the platform before observing if the complementary product is successfully developed ($t = 1$), or wait until the outcome of the development process is revealed ($t = 2$).[14] We denote by N_1, N_2^S (N_2^F) the mass of consumers who join the platform at $t = 1$ and at $t = 2$ if the development process is successful (fails), respectively.

When deciding the optimal time to join the platform, consumers form expectations regarding the probability of success λ and the relevant mass of consumers N_1, N_2^S, and N_2^F. Since each consumer is infinitely small, they do not take into account the effect of their own decision when to join the platform on the equilibrium values of λ, N_1, N_2^S, and N_2^F. Following the standard assumption in the network equilibrium models, we assume that each consumer correctly anticipates the values of λ, N_1, N_2^S, and N_2^F in equilibrium.

Optimal Timing of Joining the Platform. Consider a type-θ consumer who did not join the platform at $t = 1$ and decided to wait until $t = 2$. This consumer's utility at $t = 2$ is[15]:

$$\begin{cases} max\left\{\theta(N_1 + N_2^S) + h(\theta) - p_2, 0\right\}, & \text{if complementary product is developed} \\ max\left\{\theta(N_1 + N_2^F) - p_2, 0\right\}, & \text{if complementary product is not developed} \end{cases}$$

Therefore, at $t = 1$, a type-θ's expected utility of waiting until $t = 2$ is:

$$U_2(\theta) \equiv \lambda max\{\theta(N_1+N_2^S)+h(\theta)-p_2, 0\} + (1-\lambda) max\{\theta(N_1+N_2^F)-p_2, 0\}. \tag{3}$$

Consider now an arbitrary consumer θ who pays p_1 and joins the platform at $t = 1$. If the complementary product is introduced, the consumer gets $\theta(N_1+N_2^S)+h(\theta)$ at $t = 2$. If the complementary product fails, the consumer gets $\theta(N_1+N_2^F)$ only. Therefore, the expected utility from joining the platform at $t = 1$ is given by:

$$U_1(\theta) \equiv \theta N_1 - p_1 + \lambda\left[\theta(N_1 + N_2^S) + h(\theta)\right] + (1-\lambda)\theta(N_1 + N_2^F). \tag{4}$$

The individual rationality constraint implies that a consumer joins the platform at $t = 1$ if

$$U_1(\theta) \geq U_2(\theta),$$

and finds it optimal to wait until $t = 2$ otherwise (if $U_1(\theta) < U_2(\theta)$).[16]

Consumer real options. The expressions in Eqs. (3) and (4) enable us to define consumer θ's option value. In particular, each consumer has both a growth option and a timing option. The growth option arises due to the potential gain in utility as a result of enhanced product experience following the introduction of the complementary product.

The first period utility, $U_1(\theta)$ can be rewritten as:

$$U_1(\theta) = \theta N_1 + \theta(N_1 + N_2^F) + \lambda[\theta(N_2^S - N_2^F) + h(\theta)] - p_1. \tag{5}$$

The first and second terms in Eq. (5) reflect the direct network effect in the first and second periods, respectively. If the developer fails to introduce the complementary product, only a mass of consumers N_2^F joins the platform in the second period. Therefore, the first two terms characterize the *minimum* level of utility a consumer can expect by purchasing the basic product at $t = 1$.[17] The third term captures the value of the ***growth option***:

$$G(\theta) := \lambda[\theta(N_2^S - N_2^F) + h(\theta)]. \tag{6}$$

The expression in (6) reflects the incremental utility the consumer enjoys from both the direct network effect ($N_2^S - N_2^F$) and the indirect network effect ($h(\theta)$) if the complementary product is successfully introduced.

In addition to the growth option, each consumer also has a timing option (option to wait). In particular, $U_1(\theta)$ is similar to the net present value (NPV) of an investment in which consumer θ pays the price p_1 to obtain an "asset" that consists of a non-stochastic component (first-period direct network effects, θN_1) and a stochastic component (complementary product) weighted by the appropriate probabilities. In contrast, $U_2(\theta)$ represents the *contingent* NPV of an investment in which consumer θ has the flexibility to postpone the purchase and observe the outcome of the development process. Consumer θ has the option not to

[12] In Extensions, we discuss the implications of various other distributions.

[13] To highlight the effect of the uncertainty on the optimal pricing policy, we assume the indirect network effect is positive. It is also possible for the indirect network effect to be negative. This direction is left for future research.

[14] Consumers typically make a one-time purchase of a durable product such as a smartphone, an electric vehicle, or a point of sale (POS) terminal that they enjoy over several periods.

[15] The function $max\{\}$ reflects that consumers join the platform after the complementary good is successfully developed only if they find it optimal to do so, i.e., this decision has to be *ex-post* optimal.

[16] Without loss of generality, a consumer who is indifferent ($U_1(\theta) = U_2(\theta)$), joins the platform at $t = 1$.

[17] In real options terminology, these two terms constitute the "assets-in-place".

buy the product if the second-period price is too high relative to the utility. Thus, the difference between the second and first-period utility functions captures the value of the consumer's flexibility to postpone the purchase of the basic product. Accordingly, we define the value of consumers' ***timing option*** as:

$$T(\theta) := max\left\{U_2(\theta) - U_1(\theta), 0\right\}. \tag{7}$$

Optimal pricing. Given the mass of consumers N_1, N_2^S, and N_2^F, the platform collects $p_1 N_1$ from consumers buying the basic product at $t = 1$. In addition, with probability λ the complementary product is successful and the platform collects $p_2 N_2^S$ at $t = 2$, whereas the platform collects $p_2 N_2^F$ if the complementary good fails. Therefore, the platform chooses prices p_1, p_2, and b to maximize[18]

$$N_1 \times p_1 + \left[\lambda N_2^S + (1-\lambda) N_2^F\right] p_2 - \lambda \times b. \tag{8}$$

4. Equilibrium analysis

We now describe the equilibrium and the trade-offs involved. We present the results and the intuition, while all the proofs are delegated to Online Appendix. Our benchmark model assumes that the platform *commits* to price p_2 in advance, i.e., the platform announces p_2 at $t = 1$ (before observing the outcome of the complementary product development and consumer mass N_1) and cannot change it at $t = 2$.

The commitment eliminates the time inconsistency problem in the behavior of the platform owner. One of many examples of such commitment mechanisms is pre-orders of new products with a fixed price. In Section A.2, we relax the commitment assumption and allow the platform to determine p_2 after observing the outcome of the development process and the consumer base N_1. We solve the model using the solution concept of Rational Expectations Equilibrium.[19]

Definition (*Equilibrium (with commitment)*). Consumer prices $\hat{p}_1$ and $\hat{p}_2$, a reward $\hat{b}$; a success probability $\hat{\lambda}$; consumer mass $\hat{N}_1$, $\hat{N}_2^S$ and $\hat{N}_2^F$ constitute an equilibrium if

- *Developer*. Given $\hat{b}$, the developer of the complementary good chooses $\hat{\lambda}$ to solve

  $$\max_{\lambda \geq 0}\{\lambda \times b + (1-\lambda) \times 0 - c(\lambda)\}\ s.t.$$
  $$\lambda \times b + (1-\lambda) \times 0 - c(\lambda) \geq 0 \text{ (Positive expected profit)}.$$

- *Consumers*. Given $\hat{p}_1$, $\hat{p}_2$ and $\hat{\lambda}$,[20]

  $$\hat{N}_1 = \int_0^1 \mathbb{1}_{U_1 \geq U_2} dF(\theta),\ \hat{N}_2^S = \int_0^1 \mathbb{1}_{U_1 < U_2} \times \mathbb{1}_{\theta(\hat{N}_1 + \hat{N}_2^S) + h(\theta) - p_2 \geq 0} dF(\theta),$$
  and $$\hat{N}_2^F = \int_0^1 \mathbb{1}_{U_1 < U_2} \times \mathbb{1}_{\theta(\hat{N}_1 + \hat{N}_2^F) - p_2 \geq 0} dF(\theta).$$

- *Platform*. Prices $\hat{p}_1$ and $\hat{p}_2$, and a reward $\hat{b}$, are chosen as an optimal solution for

  $$\max_{b, p_1, p_2 \geq 0}\left\{\hat{N}_1 \times p_1 + \left[\hat{\lambda} \times \hat{N}_2^S + (1-\hat{\lambda}) \times \hat{N}_2^F\right] \times p_2 - \hat{\lambda} \times b\right\}.$$

To highlight the effect of the uncertainty on the optimal pricing policy, the benchmark model considers a case in which each consumer equally benefits from the complementary product. That is, the indirect network effect is type-independent[21]:

$$h(\theta) \equiv \alpha > 0 \text{ for all } \theta \in [0, 1].$$

In Section A.5, we relax this assumption and allow the additional benefit of the complementary good to be a function of the agent's type.

We now characterize the main elements of the equilibrium. In Proposition 4.1, we determine the optimal timing of joining the platform for each consumer type for given prices p_1 and p_2 as well as success probability λ. Next, in Section 4.2, we study the developer's optimal choice of the success probability for a given reward b. Section 4.3 solves for the platform's optimal pricing policy and the corresponding mass of consumers who join the platform at different times in equilibrium. Finally, in Section 4.4, we characterize the equilibrium option values.

4.1. Consumers

For a given pricing and development policy $\{p_1, p_2, b, \lambda\}$, a consumer of type θ decides whether to join at $t = 1$ (before the outcome of the development process is revealed) or to wait until $t = 2$ and observe the outcome of the development process.

If consumers join the platform at $t = 1$, they obtain both (i) the basic product that can be used for two periods, and (ii) the growth option described in Eq. (6) that provides an incremental utility if the development process is successful. For example, buyers of a video game console acquire a durable device as well as the opportunity to enjoy games that might be released in the future.[22] If consumers defer their decision to $t = 2$, they might join the platform only if the complementary good is successfully developed.

We perform the analysis backward by studying consumer choice at $t = 2$ first.

For arbitrary $N_1 \geq 0$, $N_2^S \geq 0$ and $N_2^F \geq 0$, consider the decision problem at $t = 2$ of a consumer of type θ who did not join the platform at $t = 1$. In the Online Appendix, we derive the following thresholds that characterize the equilibrium consumer space:

$$\underline{\theta} \equiv \frac{p_2 - h(\theta)}{N_1 + N_2^S} \text{ and } \overline{\theta} \equiv \frac{p_2}{N_1 + N_2^F}.$$

Fig. 2 shows that there are three relevant types of consumers at $t = 2$. First, "high-value" consumers who join the platform at $t = 2$ even if the complementary product fails to be developed: $\theta \geq \overline{\theta}$. Second, "middle-value" consumers who join the platform at $t = 2$ only if the complementary product is successfully developed: $\underline{\theta} \leq \theta < \overline{\theta}$. Third, "low-value" consumers who do not join the platform at $t = 2$ even if the complementary good is successfully developed: $\theta < \underline{\theta}$.

Therefore, $U_2(\theta)$ in Eq. (3) can be rewritten as

$$U_2(\theta) = \begin{cases} 0, & \theta < \underline{\theta} \\ \lambda \times \left(\theta(N_1 + N_2^S) + h(\theta) - p_2\right), & \underline{\theta} \leq \theta < \overline{\theta} \\ \lambda \times \left(\theta(N_1 + N_2^S) + h(\theta)\right) + (1-\lambda) \times \theta(N_1 + N_2^F) - p_2, & \theta \geq \overline{\theta} \end{cases} \tag{9}$$

[18] We assume that all payments are between consumers and the platform owner, i.e., there are no explicit transfers from consumers to the developer. In many markets such as electric vehicles and video games, it is indeed the case that the developer does not charge consumers directly. For instance, it is typical for the charging station services to be offered without any payment due. Our model is still applicable even when there are consumer-developer transfers if one treats p_t and b as *net* transfers between the platform and consumers and the complementary product developer, respectively.

[19] See Hagiu (2006) for the details.

[20] An indicator function $\mathbb{1}_{x\in\mathbb{X}}$ is defined as $\mathbb{1}_{x\in\mathbb{X}} = \begin{cases} 1, & x \in \mathbb{X} \\ 0, & x \notin \mathbb{X} \end{cases}$.

[21] For example, most gamers might benefit from a newly released game regardless of how much they enjoy playing other video games. Another example is a payment card system, such as MasterCard, that attracts a new merchant (a local cafe) and makes all cardholders (local coffee drinkers) equally better off.

[22] As another example, early buyers of an iPhone acquired a durable smartphone as well the opportunity to enjoy many features and apps that would be developed later.

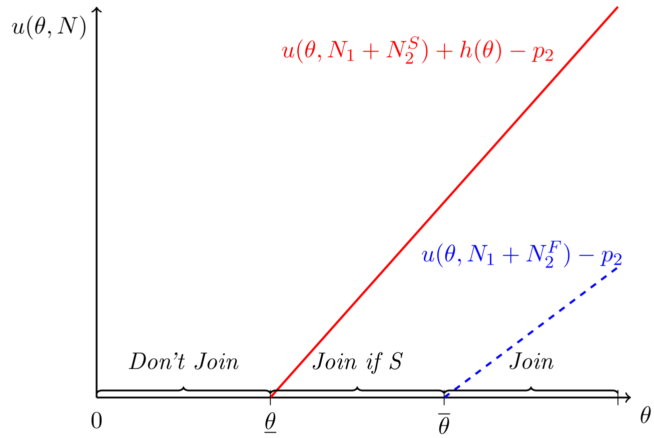

Fig. 2. Consumer's decision to join the platform at $t = 2$ for arbitrary N_1, N_2^F and N_2^S. The solid red line represents a consumer's utility if the complementary good is successfully developed, and the dashed blue line represents a consumer's utility if the complementary good fails. High-value consumers ($\theta \geqslant \overline{\theta}$) join the platform even if the complementary good fails, i.e., as long as $u(\theta, N_1 + N_2^F) - p_2 \geqslant 0$. Middle-value consumers ($\underline{\theta} \leqslant \theta < \overline{\theta}$) join the platform only if the complementary good is developed, i.e., only if $u(\theta, N_1 + N_2^S) + h(\theta) - p_2 \geqslant 0$. Low-value consumers ($\theta < \underline{\theta}$) do not join the platform.

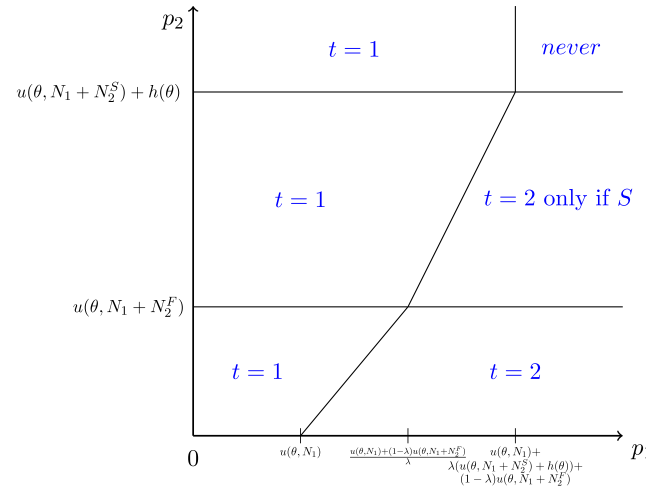

Fig. 3. Consumer decision to join the platform for arbitrary prices p_1 and p_2. A consumer might find it optimal to join the platform before observing the development of the complementary good ($t = 1$), wait and join only if the complementary good is developed at ($t = 2$ *only if* S), wait and join the platform regardless of the complementary good development ($t = 2$), or not to join the platform (*never*).

Consider now the decision to join the platform at $t = 1$. In equilibrium, a consumer of type θ (who correctly anticipates the equilibrium values of $\hat{N}_1$, $\hat{N}_2^S$, and $\hat{N}_2^F$) joins the platform at $t = 1$ if $U_1(\theta) \geq U_2(\theta)$, where

$$U_1(\theta) = \theta N_1 - p_1 + \left[\lambda \times \left(\theta(N_1 + N_2^S) + h(\theta)\right) + (1-\lambda) \times \theta(N_1 + N_2^F)\right].$$

Comparing $U_1(\theta)$ and $U_2(\theta)$, a consumer of type θ joins the platform at $t = 1$ if

$$\begin{cases} \theta N_1 + \lambda\left(\theta(N_1 + N_2^S) + h(\theta)\right) + (1-\lambda)\theta(N_1 + N_2^F) \geq p_1 & \theta < \underline{\theta} \\ \theta N_1 + (1-\lambda)\theta(N_1 + N_2^F) \geq p_1 - \lambda p_2 & \underline{\theta} \leq \theta < \overline{\theta} \\ \theta N_1 \geq p_1 - p_2 & \theta \geq \overline{\theta} \end{cases}$$

Using the definition in Eq. (7), we can now express the value of the **timing option** as:

$$T(\theta) = \begin{cases} 0, & \theta < \underline{\theta} \\ p_1 - \lambda p_2 - (2-\lambda)\theta N_1 - (1-\lambda)\theta N_2^F, & \underline{\theta} \leq \theta < \overline{\theta} \\ p_1 - p_2 - \theta N_1, & \theta \geq \overline{\theta} \end{cases} \tag{10}$$

Eq. (10) shows that the platform's pricing policy and network effects determine the value of the consumers' timing option. In particular, a high first-period price p_1 and/or a low second-period price p_2 increase the value of the timing option: consumers have the incentive to postpone their purchase decision. This effect is countervailed by the magnitude of the direct network effect, θN_1: the greater the direct network effect, the lower the option value. Consumers are more likely to join the platform at $t = 1$.

In Fig. 3, we illustrate the optimal timing of joining the platform for various combinations of prices p_1 and p_2. When both prices are relatively high (the upper-right corner), consumers do not join the platform at all. If p_2 is relatively higher than p_1 (the upper-left corner), consumers join the platform immediately at $t = 1$. Intuitively, the value of the option to delay purchase is low when the second-period price p_2 is relatively high. Therefore, for this combination of prices, consumers prefer to join the platform without waiting and observing whether the complementary product is successfully developed or not. Finally, if p_2 is relatively smaller than p_1, consumers wait and join the platform only after the complementary product is successfully developed at $t = 2$. For these consumers, the option value of postponing the purchase to the subsequent period is high enough.

The equilibrium mass of consumers who join the platform at $t = 1$ or $t = 2$ is determined by the platform's pricing policy. In particular, the platform's policy dictates (i) whether the platform makes it optimal for some consumers to wait and join the platform only after the successful development of the complementary product at $t = 2$, and (ii) whether the platform excludes some consumers from the market completely (make it optimal to never join).

We prove that in equilibrium all consumers are segmented into three adjacent groups according to their type: (i) "high-value" consumers who join the platform at $t = 1$, (ii) "middle-value" consumers who wait until $t = 2$ and join the platform only if the complementary product is successfully developed, and (iii) "low-value" consumers who never join the platform (see Fig. 4).[23]

When deciding how many consumers to attract at $t = 1$, the platform faces the following trade-off. On the one hand, attracting more consumers at $t = 1$ allows charging future consumers who join the platform at $t = 2$ a higher price. This is a consequence of the direct network effect. On the other hand, to attract a sufficient mass of early consumers, the platform must charge a small enough price at $t = 1$. Therefore, the platform trades off building an earlier mass of consumer base and extracting profits from early adopters. As a result, there is an optimal mass of consumers $\hat{N}_1$ that balances these two forces. In addition, we find that it might be optimal for the platform to exclude some consumers from the market completely. This is the case only if the value of the complementary good is relatively small ($\hat{N}_1 + \hat{N}_2^S < 1$ if $\alpha < 1$). We summarize the results in Proposition 4.1 below.

Proposition 4.1. *If the indirect network effect is type-independent,* $h(\theta) \equiv \alpha$, $\forall \theta \in [0, 1]$, *then the equilibrium mass of consumers is given by*

[23] It is straightforward that $\hat{N}_2^F = 0$. Suppose there is an equilibrium with $\hat{N}_2^F > 0$, i.e., where some consumers find it optimal to wait until $t = 2$ and then join the platform even if the complementary product fails. Necessarily, $p_1 > p_2$ in such an equilibrium, and at least some of these consumers retain a strictly positive surplus. The platform can then make a higher profit by extracting this surplus by increasing p_2.

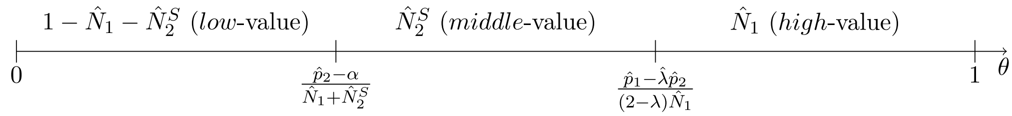

Fig. 4. Optimal timing of joining the platform if $h(\theta)=\alpha>0$.

$$\hat{N}_1=\frac{2}{3},\ \hat{N}_2^F=0,\ \hat{N}_2^S=min\left\{\frac{\sqrt{1+3\alpha}-1}{3},\frac{1}{3}\right\}.$$

Proof. See Online Appendix A.1. □

Our result that $\hat{N}_1=\frac{2}{3}$ is due to the assumption that the indirect network effect is type-independent. In general, the mass of consumers $\hat{N}_1$ might vary with other parameters, as we illustrate in Online Appendix 6.2, where we consider an extension of the main model and allow the additional benefit of the complementary good to be a function of the agent's type.

4.2. Developer

Consider now the developer's optimization problem for a given reward b. The developer determines the optimal probability of success $\hat{\lambda}$ as a solution to

$$max_{\lambda\geq 0}\{\lambda\times b-c(\lambda)\}\ s.t.$$
$$\lambda b-c(\lambda)\geq 0.$$

Since the developer correctly anticipates when each type of consumer joins the platform, the choice of $\hat{\lambda}$ is determined by the equilibrium values of $\hat{N}_1$ and $\hat{N}_2^S$. In the Online Appendix, we formally prove that the platform's profit is:

$$\lambda\alpha(N_1+N_2^S)+\lambda(N_1+N_2^S)^2(1-N_1-N_2^S)+(2-\lambda)N_1^2(1-N_1)-\lambda c'(\lambda).$$

A higher probability of success for the complementary product changes the optimal timing of joining the platform for some consumer types. For example, consider a type $\tilde{\theta}$ who is just indifferent between joining the platform at $t=1$ and $t=2$. Suppose now the probability increases. Then type $\tilde{\theta}$ consumer strictly prefers joining the platform at $t=1$ rather than waiting until $t=2$. The platform then can increase price p_1 accordingly to extract the expected surplus from type $\tilde{\theta}$. Therefore, the platform jointly adjusts prices and the probability to maximize profit. Intuitively, the equilibrium $\hat{\lambda}$ equalizes the marginal benefit of increasing the probability of success and the marginal cost of efforts.

Proposition 4.2 characterizes the equilibrium solution to the developer's problem.

Proposition 4.2. *The equilibrium probability of success $\hat{\lambda}(b)$ is given by:*

$$\hat{\lambda}(b)=\frac{b}{2A}. \tag{11}$$

Given the equilibrium mass of consumers in Proposition 4.1, the equilibrium probability can also be expressed as[24]*:*

$$\hat{\lambda}=\frac{\alpha(\hat{N}_1+\hat{N}_2^S)+(\hat{N}_1+\hat{N}_2^S)^2(1-\hat{N}_1-\hat{N}_2^S)-\hat{N}_1^2(1-\hat{N}_1)}{4A}. \tag{12}$$

[24] Formally, $\hat{\lambda}$ is determined by
$\alpha(\hat{N}_1+\hat{N}_2^S)+(\hat{N}_1+\hat{N}_2^S)-\hat{N}_1(1-\hat{N}_1)+(1-\hat{N}_1-\hat{N}_2^S)=\hat{N}_1(1-\hat{N}_1)+c'(\lambda)+\lambda c''(\lambda)$.
The condition is derived by differentiating the platform's profit given by
$\lambda\alpha(N_1+N_2^S)+\lambda(N_1+N_2^S)^2(1-N_1-N_2^S)+(2-\lambda)N_1^2(1-N_1)-\lambda c'(\lambda)$.

Proof. Eq. (11) follows from the first-order necessary condition, which is also sufficient since the objective function is concave. □

Note that because $c(\lambda)$ is convex, $\hat{\lambda}(b)$ is an increasing function, $\frac{d\hat{\lambda}(b)}{db}>0$. Intuitively, by promising a higher price for the complementary good, the platform makes a successful development more likely. We also find that $\hat{\lambda}$ is an increasing function of α and a decreasing function of A. These two results should appear intuitive. The higher the value added by the complementary product (high α), the higher the surplus that can be extracted from the consumers and, therefore, the higher the benefit of success for the developer. When the effort necessary for achieving success is costlier (high A), a marginal increase in the probability of success becomes less beneficial.

Proposition 4.2 also illustrates that the level of uncertainty in the market is endogenously determined as a consequence of the platform's pricing policy. The level of uncertainty is greatest if the probability of development hovers around 0.5. As the platform incentivizes the developer to innovate by either offering more attractive compensation or building a greater mass of consumer base in the first period, the probability of a successful development increases. Accordingly, the level of uncertainty in the market is expected to decrease.

4.3. Platform

We now determine prices $\hat{p}_1$ and $\hat{p}_2$ that the platform chooses in equilibrium. A critical question for the platform is whether to use a *price-penetration* ($\hat{p}_2>\hat{p}_1$) or a *price-skimming* ($\hat{p}_1>\hat{p}_2$) policy. When determining whether to charge a lower price at $t=2$ than at $t=1$, the platform is facing the following trade-off.

On the one hand, there are two reasons to lower the price at $t=2$. First, consumers who join the platform at $t=1$ enjoy the basic product over two periods rather than just one. Given that early buyers are high-value consumers, the platform may extract surplus from them and then use a low-price strategy at $t=2$. Second, due to the indirect network effect, early consumers at $t=1$ buy not only the basic product itself but also the (growth) option to benefit from the complementary product if it is successfully developed in the future. The platform extracts this surplus at $t=1$ by charging a higher price. Then, at $t=2$, the platform lowers the price and serves the middle-value consumers who are willing to join only if the complementary product is successfully developed.

On the other hand, there are two reasons to increase the price of the basic product at $t=2$. First, a lower price at $t=1$ increases the number of early consumers. As a result, the value of the basic product in the future increases due to the direct network effect. Second, consumers join the platform at $t=2$ only if they can benefit from the indirect network effect after the complementary product is successfully developed. Thus, future price $\hat{p}_2$ should be high enough to extract surplus from the combination of both the basic and the complementary products.

We plot graphically a combination of optimal pricing policies for various parameters α (value of the complementary product) and A (cost of developing the complementary product) in Fig. 5. We observe that the price-skimming policy ($\hat{p}_1>\hat{p}_2$) is optimal for relatively small values of A. Intuitively, if the cost of development of the complementary product is sufficiently low, then the probability of success is high in equilibrium. Since consumers have a greater likelihood of experiencing enhanced functionality from the complementary product, they are more likely to join the platform at $t=1$. The platform is then better off extracting its surplus earlier.

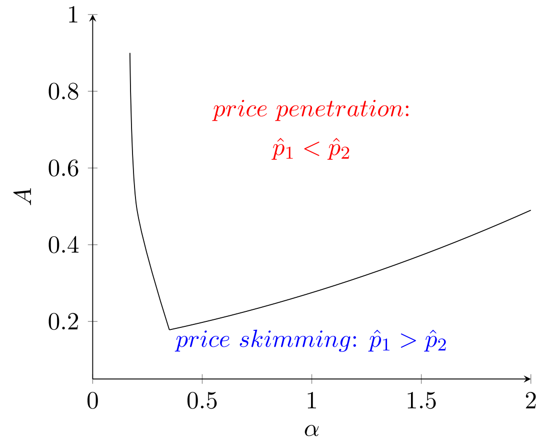

Fig. 5. Optimal pricing policy for various combinations of α and A. For all levels of development costs A except sufficiently low, the platform alternates between price-skimming and price-penetration. For low enough development costs A, price-skimming is optimal.

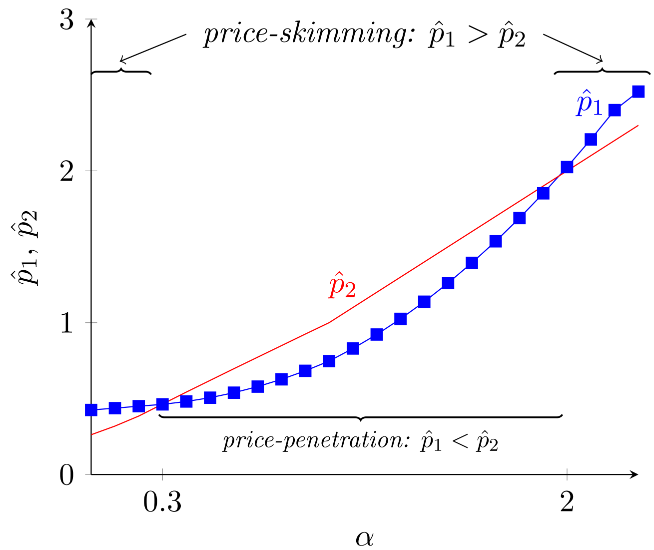

Fig. 6. Optimal prices if $A = \frac{1}{2}$.

In contrast, if the cost of development of the complementary product is relatively high, the complementary product is less likely to be developed. Then the platform might not charge a high price before the uncertainty is resolved. As a result, a price-penetration ($\hat{p}_1 < \hat{p}_2$) policy might become optimal. The equilibrium probability that the complementary product is successfully developed, $\hat{\lambda}$, which is increasing in α. Therefore, we expect and indeed find that the platform uses a price-skimming ($\hat{p}_1 > \hat{p}_2$) policy if the value of the complementary product is relatively small, i.e., $\hat{p}_2 < \hat{p}_1$ for small α and $\hat{p}_2 > \hat{p}_1$ as α becomes higher. We illustrate this price dynamics in Fig. 6, where $\hat{p}_2 < \hat{p}_1$ for $\alpha < 0.3$ and $\hat{p}_2 > \hat{p}_1$ if $\alpha \geq 0.3$.

Interestingly, we also identify another effect. When α becomes sufficiently large ($\alpha \geq 2$ in Fig. 6), it is again optimal to employ price-skimming ($\hat{p}_1 > \hat{p}_2$).[25] Intuitively, if the benefit of the complementary product is large, it will be successfully developed with high probability. Since the complementary product is very likely to succeed, consumers who join the platform at $t = 1$ are almost certain to benefit from the indirect network effect. Put differently, the consumers' growth option is more likely to be realized. The platform is then better off by extracting this surplus from the growth option value earlier. Note that this is the case if consumers have a high intrinsic value for the complementary product. For example, gamers may buy a video game console to play a particular game: Soccer fans may buy a PlayStation to enjoy FIFA 19 and its upgrades. Another example is a consumer who buys a smartphone to mostly use a particular app (Uber or Lyft).

We summarize this discussion in Proposition 4.3 below.

Proposition 4.3. *Given the equilibrium mass of consumers who join the platform at $t = 1$ and $t = 2$ and the equilibrium probability of development $\hat{\lambda}$, the platform's equilibrium pricing and reward policy $\{\hat{p}_1, \hat{p}_2, \hat{b}\}$ is given by:*

$$\left.\begin{array}{l} \hat{b} = \dfrac{\alpha(\hat{N}_1 + \hat{N}_2^S) + (\hat{N}_1 + \hat{N}_2^S)^2(1 - \hat{N}_1 - \hat{N}_2^S) - \hat{N}_1(1 - \hat{N}_1)}{2} \\ \hat{p}_2 = \alpha + (\hat{N}_1 + \hat{N}_2^S)(1 - \hat{N}_1 - \hat{N}_2^S) \\ \hat{p}_1 = \hat{\lambda}\hat{p}_2 + (2 - \hat{\lambda})\hat{N}_1(1 - \hat{N}_1) \end{array}\right\} \tag{13}$$

Proof. See Online Appendix A.1. □

Elaborating on the relation between the equilibrium prices further, we present the following necessary and sufficient conditions for price penetration/skimming to be optimal.

Proposition 4.4. *If $\alpha \geqslant 1$, then there exists A^* and $\alpha^* > 1$, such that:*

$$\left.\begin{array}{l} \text{If } A \leqslant A^*, \text{ then price penetration } (\hat{p}_2 \leqslant \hat{p}_1) \text{ is optimal;} \\ \text{If } A > A^*, \text{ then price penetration (skimming) } \hat{p}_2 \leqslant (>) \hat{p}_1 \\ \quad \text{if } \alpha \leqslant (>) \alpha^* \text{ is optimal.} \end{array}\right\} \tag{14}$$

Proof. See Online Appendix A.1 □

4.4. Equilibrium option values

Given the equilibrium outlined in Proposition 4.1 along with Eqs. (6) and (10), we present now consumer θ's equilibrium option values in Corollary 4.5.

Corollary 4.5. *The equilibrium value of consumer θ's growth option is:*

$$G(\theta) = \hat{\lambda}[\theta(\hat{N}_2^S - \hat{N}_2^F) + \alpha] = \hat{\lambda}(\theta\hat{N}_2^S + \alpha) \tag{15}$$

The equilibrium value of consumer θ's timing option is:

$$T(\theta) = \begin{cases} 0, & \theta < \underline{\theta} \\ (2 - \hat{\lambda})\hat{N}_1(1 - \hat{N}_1 - \theta), & \underline{\theta} \leq \theta < \overline{\theta} \\ \hat{p}_1 - \hat{p}_2 - \theta\hat{N}_1, & \theta \geq \overline{\theta} \end{cases} \tag{16}$$

Proof. The corollary follows from substituting the equilibrium values from Propositions 4.1–4.3 in Eqs. (6) and (10). □

Eq. (15) shows that the value of the growth option is higher for high-value consumers. It is an increasing function of the equilibrium probability of development and indirect network effects. We note that the growth option always has a non-zero value for each consumer type θ as long as the indirect network effects are present and the development process is undertaken. In contrast, Eq. (16) shows that the timing option is valuable only for consumers with a relatively low valuation of the product.[26] In particular, for high-value consumers ($\theta \geq \overline{\theta}$) who normally join the platform early at $t = 1$, the timing option is valuable only if the platform follows a price-skimming policy in which the first period price net of the direct network effects is higher than

[25] Our results are robust to different parameter settings.

[26] $\theta \leq \frac{1}{3}$ for $\underline{\theta} \leq \theta < \overline{\theta}$ and $\theta \leq \frac{\hat{p}_1 - \hat{p}_2}{\hat{N}_1}$ for $\theta \geq \overline{\theta}$.

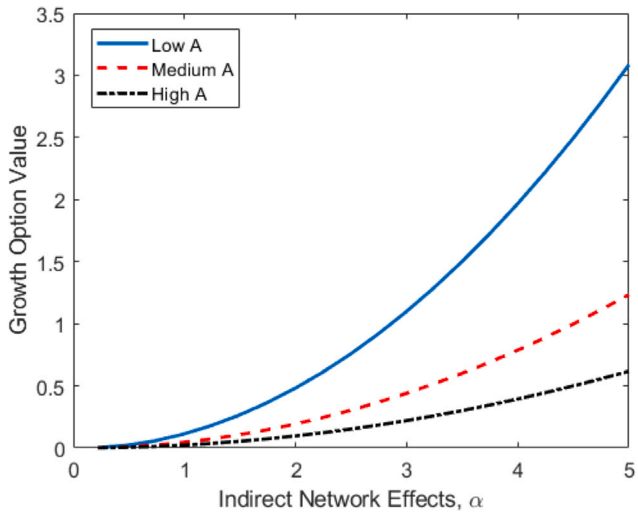

Fig. 7. Growth option value as a function of indirect network effects and cost of development.

the second price ($\hat{p}_1 - \theta \hat{N}_1 \geq \hat{p}_2$). Similarly, for mid-value consumers ($\underline{\theta} \leq \theta < \bar{\theta}$), the option to delay is valuable only for consumers $\theta \leq \frac{1}{3}$.

Fig. 7 illustrates the value of the growth option as a function of indirect network effects α for various levels of development cost A. The growth option is *increasing* in the magnitude of the indirect network effect and is inversely associated with the development cost.

Fig. 8 compares the values of the growth option (*the right axis*) and the timing option (*the left axis*) over the consumer space. The panels combine different scenarios for indirect network effects and development costs.[27] In both panels, the timing option is most valuable for consumers with a lower intrinsic value for the basic product. In contrast, the value of the growth option increases in consumers' intrinsic valuation of the basic product. Importantly, Fig. 8 highlights the interaction between the platform's optimal pricing policy and the value of consumers' options. When the indirect network effect is weak (Panel A), the growth option is virtually worthless. Therefore, consumers who join the platform in the first period are those with a high intrinsic value for the basic product. In this case, the platform does not serve the whole market (Proposition 4.1) and pursues a skimming policy to extract the surplus from the high-value consumers.

The pattern reverses when the indirect network effect becomes strong (Panel B). The value of the growth option to consumers turns significant and dominates the timing option. In this setting, the platform attracts more early consumers by lowering the first-period price and pursuing a market penetration strategy.

In the results not presented in the figure, we also document that as the indirect network effect becomes stronger, the value of the growth option increases even further, and the platform switches again to a price-skimming policy. This result further corroborates the result in Fig. 6.

To summarize, the results suggest that the platform resorts to a price-skimming strategy when the value of consumers' growth options is either very low (low indirect network effect) or very high (high indirect network effect). In the former case, the platform's role as an intermediary between the developer and consumers is insignificant, and offering incentives to the developer is of secondary concern to the platform. In the latter case, for a given level of development cost, sufficiently high growth option values driven by high indirect network effects induce consumers to join the platform early. The presence of high indirect network effects countervails the negative effect of high development costs on the developer's incentives to innovate. Therefore, the platform charges a high first-period price to extract the surplus from consumers with either a high valuation of the intrinsic good (i.e., low growth option value) or a high valuation of the indirect network effect (i.e., high growth option value). In the intermediate range of growth option values, the platform incentivizes the developer by following a price-penetration policy.

5. Extensions

In this section, we offer variations of the baseline model that resemble additional features observed in certain markets. Although none of the extensions alter the fundamental results of the paper, they provide further insights.

5.1. Optimal policy with contingent pricing

In the base model, we assumed the platform commits to a fixed second-period price. The second-period price is the same regardless of whether the complementary good is developed. What if the platform announces the committed second-period prices *contingent* on the outcome of the complementary good development? We now explore the implications of the platform using a contingent second-period price. Formally, we augment the base model with two possible prices the platform picks after success and failure of the complementary good, denoted by p_2^S and p_2^F, respectively. We present the key result below, and all the derivations are in the Online Appendix A.3.

Proposition 5.1. *If the platform can use contingent pricing, then the equilibrium mass of consumers is given by*

$$\hat{N}_1 = \frac{1}{2},\ \hat{N}_2^F = \frac{1}{6},\ \hat{N}_2^S = min\left\{\frac{1}{3}, \frac{\sqrt{9+48\alpha}-3}{12}\right\}.$$

The key novel effect in comparison with the base model (see Proposition 4.1) is that some consumers wait till period $t = 2$ and join the platform if the complementary good fails, $\hat{N}_2^F > 0$. Intuitively, the platform optimally charges a higher price p_2^S to those who decided to wait and join the platform if the complementary good is successful. In addition, the platform charges a smaller second-period price p_2^F to those who decided to wait and join the platform if the complementary good fails. This additional instrument, i.e., a contingent second-period price, allows attracting consumers with relatively low value who would otherwise not join the platform. As a result, the mass of consumers joining the platform at $t = 1$ is smaller, and the entire market is served for a smaller value of α compared to the base model. In summary, allowing for a contingent pricing in the second period, enhances efficiency and social surplus.

5.2. Costly development of the basic good

In the baseline model, we assume the cost of producing the basic good is zero. This is a reasonable approximation for a market where the platform collects a sufficiently high markup and, therefore, the production cost structure is less relevant for the optimal product pricing. This is the case, for example, due to brand loyalty or significant market power.

We now discuss the base model extension with production cost for the basic good. For instance, in some markets, research and development costs for the basic product might play an important role in the platform's pricing policy. Without loss of generality, we can normalize the first-period production cost to zero, similar to the baseline model. Then, we introduce a cost function $C_2(N_2^S + N_2^F)$ capturing the basic product cost for a total mass of consumers $N_2^S + N_2^F$ joining the platform

[27] Alternative specifications for the development cost produce similar qualitative results. These results are available upon request.

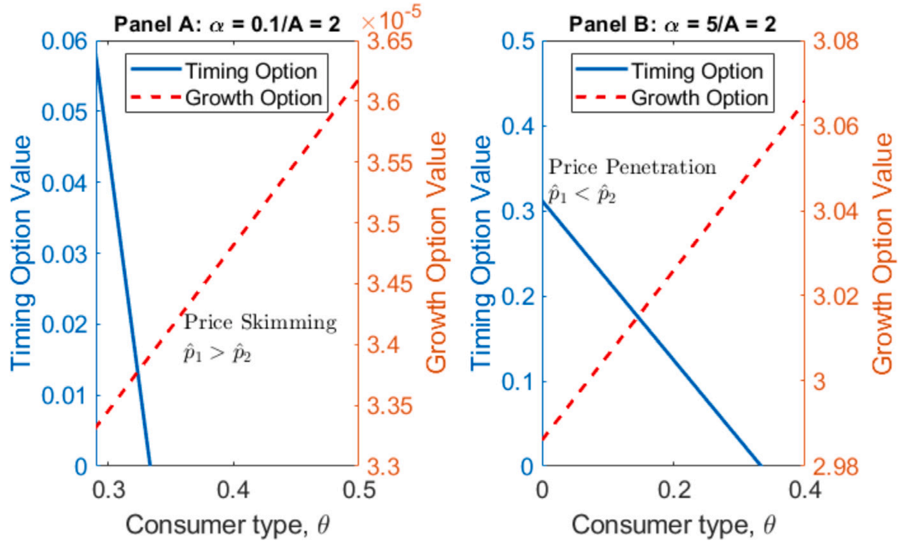

Fig. 8. Value of the timing option(left scale) and the growth option (right scale) for various combinations of indirect network effects and cost of development. Each panel indicates the platform's optimal pricing policy.

at $t = 2$. We let C_2 to be positive or negative to represent two scenarios. If $C_2 < 0$, the production cost declines relative to the first period, for example, due to learning-by-doing or the economies of scale effects. If $C_2 > 0$, the production cost increases due to factors such as supply chain constraints, new regulations, higher cost of materials, etc.

Although our qualitative predictions remain intact, the basic product production cost provides additional insights. For example, if the platform at $t = 1$ expects future costs at $t = 2$ to increase, $C_2(N_2^S + N_2^F) > 0$, it anticipates a smaller leverage for the second-period optimal price. As a result, the platform optimally attracts fewer customers at $t = 2$. To fix the ideas, recall the platform's profit function,

$$N_1 p_1 + \left[\lambda N_2^S + (1-\lambda) N_2^F\right] p_2 - \lambda b - C_2(N_2^S + N_2^F),$$

that we augment with the function $C_2(N_2^S + N_2^F)$ capturing the basic product cost at $t = 2$. If the marginal cost at period $t = 2$ is positive, $C_2'(N_2^S + N_2^F) > 0$, it is straightforward from the first-order conditions that the platform optimally attracts fewer consumers. Similarly, if the platform at $t = 1$ expects future costs at $t = 2$ to decrease, $C_2(N_2^S + N_2^F) < 0$, it optimally attracts more consumers at $t = 2$ than in the baseline model.

5.3. Levels of the complementary good development

In the baseline model, we assumed that the innovation is either successful or fails overall. In some applications, there might be several "levels" of the complementary good (i.e., bad, good, very good outcome, etc.) These levels may correspond to the quality or the varying levels of functionality of the complementary good developed. It is straightforward to incorporate this new feature into our baseline model. To fix the ideas, suppose that there are $L \geqslant 2$ levels of the complementary good, with the corresponding consumer values $0 < h_1 < \cdots < h_L$. That is, in the baseline model, we have $L = 1$ with $h_0 = 0$ after a failure and $h_1 = h$ after success.

If all the levels of the complementary good are observable and contractable, the platform can offer a sequence of rewards $\{b_i\}_{i=1}^L$, one for each corresponding level of the complementary good. The developer chooses the optimal value of λ to maximize $\sum_{i=1}^L Pr(i|\lambda) b_i - c(\lambda)$, where $Pr(i|\lambda)$ is the probability of level i for a given λ. The risk-neutral developer then chooses λ given the *expected* bonus $\sum_{i=1}^L Pr(i|\lambda)\, b_i$ instead of λb in the baseline model.

The platform's profit then becomes

$$N_1 p_1 + \left[\sum_{i=1}^L Pr(i|\lambda) N_i^S + \left(1 - \sum_{i=1}^L Pr(i|\lambda)\right) N_2^F\right] p_2 - \sum_{i=1}^L Pr(i|\lambda)\, b_i,$$

where N_i^S is the mass of consumers joining the platform at $t = 2$ given the corresponding level of the complementary good $i = 1, \ldots, L$.

Given that all the players are risk-neutral, the new problem is, in fact, identical to the one in our baseline model. Indeed, when deciding on the optimal level of λ, the platform takes into account the *expected* number of consumers joining the platform after some level of the complementary good, $\sum_{i=1}^L Pr(i|\lambda) N_i^S$, instead of λN_2^S in the base model. Similarly, the expected number of consumers joining the platform after failure is $\left(1 - \sum_{i=1}^L Pr(i|\lambda)\right) N_2^F$ instead of $(1-\lambda) N_2^F$.

5.4. Market size uncertainty

In the baseline model, technological uncertainty was the sole source of risk. We now extend the model to allow for *market size uncertainty*, where the realized size of the consumer base at $t = 2$ is itself stochastic and unknown at $t = 1$. Specifically, we assume that the realized mass of second-period consumers is multiplied by a random variable $\omega \in [1-\epsilon, 1+\epsilon]$ drawn from a known distribution $G(\omega)$, independent of technological success. A tractable case will be a binary case of $\omega \in \{\underline{\omega}, \overline{\omega}\}$.

This extension introduces a second layer of real options for consumers, developer, and platform owner: *demand risk*. Consumers now face uncertainty both about whether the complementary product will be developed and about how large the same-side network effect for it will be even if development succeeds. Accordingly, the consumer's timing option (7) is altered: the expected utility from waiting now incorporates $\mathbb{E}[\omega]$ effect, not just the success probability λ. Consumers have a stronger incentive to delay adoption to resolve both sources of uncertainty since they have less desire to be the owner of the product in a small user community.

The developer's payoff is also modified: the bonus b for a successful complementary product is scaled proportionally with the realized ω. Thus, the developer now chooses effort anticipating an expected bonus $\mathbb{E}[\omega] \times b$, rather than a fixed b. As a result, greater market size uncertainty generally reduces equilibrium effort λ, unless the platform adjusts the reward upward to compensate.

Introducing market size uncertainty amplifies the real option value of waiting, reduces early platform adoption, and forces the platform to

Table 2
Impact of market size uncertainty on equilibrium outcomes.

Variable	Baseline (Technological uncertainty only)	Technology and market size uncertainty
Consumer timing option $T(\theta)$	Moderate	Higher (waiting option more valuable given network effect uncertainty)
Developer effort λ	Higher	Ceteris Paribus, Lower (unless the incentive contract offsets the dis-utility of risk)
Equilibrium N_1 (early adopters)	Larger mass	Smaller mass given the value of waiting
Equilibrium pricing policy (p_1 vs. p_2)	Depends on α, A	p_1 needs to compensate a higher option value but also faces stronger type consumers; likely, to see higher price skimming effort.
Platform profit sensitivity	Sensitive to A and α	Sensitive to Var(ω) as well

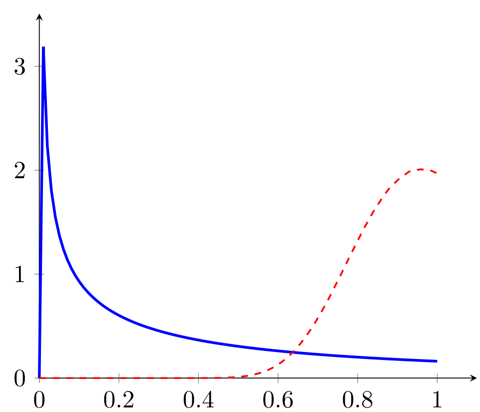

Fig. 9. Various distributions of consumer type (niche markets).

adjust pricing and reward strategies more aggressively. In particular, price-skimming becomes more likely as early adopters must be compensated for bearing dual uncertainty. The details of model extension are provided in Online Appendix A.4. Table 2 summarizes the key qualitative changes.

5.5. Type-dependent utility

To focus on the effect of uncertainty, we have assumed that the utility function is linear in both the consumer type and the current consumer base. We should note that our main results can be extended to a more general utility function that might be relevant in other applications. For example, one may assume that the marginal utility of a type θ consumer is a non-linear function of their type. Our main results that all consumers are divided into (at most) three groups remain intact with any more general utility function as long as the direct externality is non-negative, i.e., $\frac{\partial u(\theta,N)}{\partial N} \geq 0$. However, a more general utility function will not allow us to derive the explicit characterization of the relevant mass of consumers and corresponding price levels.

5.6. Distribution of consumer preferences ($Niche$ markets)

We presented the benchmark model assuming the uniform distribution of consumer type. While considering a mass market allows us to derive the explicit solution, our results give some guidance into possible equilibria in niche markets. We discuss now the implications of our model for various distributions of consumer type.

First, suppose there are many low-type consumers and higher types are almost uniformly distributed (see the blue solid curve in Fig. 9). An example might be a low-temperature country where only a few people find electric cars desirable. This type of distribution makes excluding low-type consumers costlier and, consequently, some of the results from the main model might change. In particular, charging a higher price at $t = 1$ and then lowering it at $t = 2$ may become sub-optimal.[28] The reason is that now the platform must make its profit from the low-type consumers. Since charging a higher price earlier can attract only a few high-value consumers, the platform might be better off lowering the price of the basic good at $t = 1$ to establish a sufficient consumer base early.

Second, suppose consumer-type distribution is skewed so that there are many high-type consumers and lower types are almost uniformly distributed (see the red dashed curve in Fig. 9). An example might be a high-temperature country where richer people find electric cars attractive, whereas poorer consumers prefer conventional cars due to cheap gasoline. Then, our intuition and results from the main model remain intact. In particular, recall that the platform optimally excludes the low-value consumers when the value of the complementary good is small (see Proposition 4.1). This is still optimal since the platform first attracts high-value consumers to build an early consumer base. However, when there are many low-type consumers, the platform will find it optimal to charge a relatively smaller price at $t = 2$ to maximize second-period profit.

6. Conclusion

We offer a novel view of endogenous real options formation and its interaction with the dynamic platform pricing. Our model examines optimal pricing policies for a platform that faces uncertainties regarding developing its complementary goods/services. We show that the early buyers obtain the basic product and a real option to benefit from possible enhanced functionality in the future (i.e., a *growth option*). The late buyers, on the other hand, decide to use a *waiting option* to make the purchase decision after observing the outcome of the development process. The platform alters the incentives of both types of consumers as well as developers by varying the optimal dynamic pricing policy.

We show that consumers are divided into at most three groups: early adopters, late adopters, and those who never join the platform. Under the assumed specification, we find that the mass of early adopters does not depend on the value of the complementary product, whereas the mass of late adopters increases if the value of the complementary product goes up. When the value of the complementary product is sufficiently large, the platform serves the whole market.

The platform's pricing policy is determined by the value of the complementary product (i.e., indirect network effects) as well as the costs of its development. If the development costs are sufficiently low, then the platform follows a price-skimming policy and charges a higher price for those consumers joining the platform earlier. For higher development costs, the platform alternates between price-skimming and price-penetration. In this case, the developer has fewer incentives to engage in the development of the complementary product, and thus the probability of success is also lower. To incentivize the developer, the platform might employ a price-penetration strategy and reduce the price it charges earlier.

Our paper provides a theoretical framework for better understanding the decisions of consumers and platform owners. The framework can be applied beyond the classic examples of electronic devices. To succeed, a large shopping center requires a portfolio of support infrastructures, such as parking lots, transit facilities, and sometimes nearby hotels and entertainment. However, stakeholders of this market face

[28] Recall that this was the optimal pricing policy for small and sufficiently high values of α.

uncertainty. Investors in support infrastructure are concerned that the shopping center will not attract enough retail businesses and customers. Thus, they might not be motivated to commit to risky, irreversible investments. On the other side, retail businesses that purchase attractive spots also face uncertainty: What if the mall is completed, but the required support infrastructure is not built or fails to receive required permits? In that case, they end up having purchased space in a low-value mall.

As we discuss in the paper, investment in support infrastructures improves the value of the bundle of mall and infrastructure for retail shops. Early investors in retail space are betting on an "option" embedded in the value of retail space, which benefits from direct and indirect network effects. Noting these feedback effects, the mall owner also faces the dynamic pricing of space under uncertainty that we characterize in the paper.

This paper can be extended by explicitly modeling the contractual relationship between the platform and developers. For tractability, we have abstracted the contractual specifics and assumed a fixed reward structure. Although this simplifies the analysis, it does not reflect the variety of contractual arrangements observed in real-world platform ecosystems. Future research could explore the comparative performance of different mechanisms, such as fee-based models, royalties, revenue-sharing agreements, and sales guarantees, as well as policies governing development governance (e.g., make-or-buy decisions and multi-homing constraints). Each contractual form introduces varying degrees of risk sharing and incentive alignment, thereby influencing developer effort and platform pricing strategies, especially in the presence of uncertainty in product development.

In particular, transitioning from fixed bonuses to revenue-sharing contracts alters the developer's payoff by tying compensation to realized outcomes. This shift introduces an output risk to the developer and affects both effort provision and the platform's optimal contracting decision. While a formal analysis of such mechanisms is beyond the current scope, it represents a valuable avenue for future theoretical and empirical research. A rigorous modeling of diverse contractual forms can yield deeper insights into developer behavior and explain the heterogeneity of incentive schemes used across platform industries.

Second, the framework can be combined with data from a specific market to empirically test the predictions of the model and to produce quantitative results.

CRediT authorship contribution statement

Hamed Ghoddusi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Alexander Rodivilov:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Baran Siyahhan:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ejor.2025.09.034.

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