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Racing to market leadership: Product launch and upgrade decisions

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ABSTRACT

Firms might not launch a next generation product as soon as a more efficient technology or a better product design is ready. We use a stylized model to analyze firms' product launch and upgrade decisions in an incumbent-vs-entrant setting. We find that large profit margins from the next generation product alone do not provide the entrant sufficient incentives to launch the next generation product, although small profit margins will deter the entrant from joining the competition. If the entrant intends to enter the market at an earlier time, it should consider process improvements that lower the firm's launch costs of the current generation product. In addition, the incumbent must respond strategically to the entrant's arrival. In particular, when anticipating a late arrival of the entrant, the incumbent should upgrade to the next generation earlier. The incumbent also has a cost advantage in the race to launch the next generation product.

1. Introduction

A product upgrade often requires the availability of either a new technology that enables more efficient production or a better product design that generates more revenue. Should a firm release a next generation product as soon as a more efficient technology (or a better product design) is available?

Empirical examples show that some firms appear to be technology chasers. Apple Inc.'s launch of the iPod Nano generated a great deal of buzz in September 2005. The sleek design of the Nano, undoubtedly, contributed to the publicity. On the other hand, the fact that the Nano was a replacement of the iPod Mini took the public completely by surprise and prompted much media coverage. On the same day the Nano was launched, Apple Inc. discontinued the sales of the Mini, despite the fact that the Mini was popular and had been on the market for only a year and eight months. Many industry analysts wondered whether Apple Inc. upgraded a cash-cow current generation product to the next generation too soon, given the company's market position as a powerful incumbent.

Microsoft Corporation took a different approach when launching its XBox series. The remarkable success of the Sony PlayStation worried Microsoft in the late 1990s. Microsoft, however, waited and launched its XBox in 2001 shortly after Sony's PlayStation 2 appeared. As an entrant, Microsoft chose to join the gaming console market not with a current generation product (equivalent to PlayStation) but with a next generation product (equivalent to PlayStation 2). This raises the question, is it always wise for an entrant to leapfrog?

This research aims to identify the driving forces behind a firm's product launch/upgrade decision, provided that the firm is technologically ready to produce the next generation product. We solve the optimal timing decisions for both the entrant and the incumbent, and then discuss market leadership (the first one to launch the next generation product) based on the optimal timings.

When launching the next generation product, a firm usually incurs a smaller launch cost if it has already

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launched the current generation product, because the firm can learn from its past experience. But if the benefit of building upon the current generation is outweighed by the superior profitability of the next generation product, then the entrant chooses to leapfrog (like Microsoft did with XBox) instead of entering with the current generation and then upgrading later. We also find that higher profitability of the next generation product provides the entrant with an incentive to launch the current generation product earlier if the firm prefers not to leapfrog.

The incumbent's monopolist status ends upon the arrival of the entrant. However, the incumbent may still find it optimal to upgrade as if it remained the monopolist throughout the planning horizon. If we interpret a late arrival of the entrant to the market as weak competition for the incumbent, then our results show that weaker competition leads the incumbent to an earlier upgrade. Therefore, the fact that Apple Inc. was far ahead of its competitors provides an incentive (not a disincentive) to upgrade as soon as possible. We also demonstrate the advantage of the incumbent in the race to launch the next generation product.

The rest of this paper unfolds as follows: Section 2 reviews relevant literature; Section 3 presents our model and explains the rationales behind our assumptions; Sections 4 and 5 analyze the firms' timing decisions; Section 6 discusses the incumbent's advantage on market leadership; Section 7 summarizes the implications of our findings and concludes the paper with future research directions.

2. Relevant literature

We analyze how a potential entrant firm determines its arrival time at the market, and this aspect links our model to market entry literature. The literature on market entry can be categorized into two groups: one group investigates the order-of-entry effect given that one firm moves first and others are later entrants, and the other group examines the timing decision regarding a firm's market entry.

"First-to-market" could lead to a market share advantage (see Lieberman and Montgomery, 1998 for an overview). However, the cost disadvantages of pioneer firms are also documented (Lieberman and Montgomery, 1998; Boulding and Christen, 2003). Bohlmann et al. (2002) provided a review of the literature on pioneer advantages and disadvantages, and constructed a game-theoretical model that incorporates a pioneer's preemption advantage and possible vintage effect, namely the phenomenon that later entrants can have lower costs and higher quality by utilizing improved technology. Bohlmann et al. (2002) demonstrated that the vintage effect can overcome the pioneer's first mover advantage. Theoretical models studying the order-of-entry effects focus on firms' entries to a new market. Those models often grant one firm the status of the first mover and characterize others later entrants, but they do not consider additional product generations. Our incumbent firm is not, automatically, the first one to launch the next generation product. Our entrant firm can compete with the incumbent by launching either the current generation product, or the next generation, or both sequentially. In such a setting, we analyze the incumbent's advantage in the race to launch the next generation product.

A firm's entry decision can be modeled as a discrete-time or continuous-time variable. Narasimhan and Zhang (2000) investigated two competing firms' entry decisions in a three-stage setting where firms face binary options at decision epochs. Firms are technologically ready to enter the market, but demand uncertainty is not resolved until the second stage. Narasimhan and Zhang (2000) showed that both the benefit of being the first and the disadvantage of lagging behind motivate a firm to enter a new market. Lin and Saggi (2002) studied how two firms choose their entry times (continuous variables) assuming that there is no technological or market uncertainty. Their analysis shows that when the initial entry generates positive externalities for the subsequent entry, a higher fixed cost of entry could benefit the first entrant by delaying the entry time of the later entrant. Like Lin and Saggi (2002), we adopt a continuous-time approach and let firms make simultaneous decisions at time zero. But our entrant's timing decision involves two generations of a product. Our finding that a higher launch cost of the current generation product delays the potential entrant's arrival is consistent with Lin and Saggi (2002)'s result, although network externalities do not play a role in our model.

The development of the next generation product could be driven by the adoption of a new technology. There is a rich literature on technology adoption. Hoppe (2002) provided a comprehensive survey of the literature on the timing of new technology adoption. A significant part of the technology adoption literature analyzes situations in which firms are uncertain about either the arrival time or the profitability of new technology. The uncertainty drives firms to wait and/or buy information (e.g. Jensen, 1982; McCardle, 1985; Mamer and McCardle, 1987; Jensen, 1988). Algorithms are devised for firms to determine the optimal timing of technology adoption under uncertainty (e.g. Chung and Tsou, 1998; Farzin et al., 1998; Doraszelski, 2004). Although uncertainties can affect a firm's product launch and upgrade decisions, we choose to disregard uncertainties (like Reinganum, 1981; Fudenberg and Tirole, 1985) and highlight other elements (e.g. competition and entry barrier) that also play a role in a firm's decision. Our model differs from that in Reinganum (1981) and Fudenberg and Tirole (1985) because they considered firms that have a single active choice, whereas our entrant chooses between two generations of the product.

Ofek and Sarvary (2003) and Souza (2004) studied the repeated introduction of technologically advanced next generation products in multi-period settings with uncertainty. A firm's single period decision is binary (to introduce or not) in Souza (2004), and the decision is an investment level concerning a single generation of a product in Ofek and Sarvary (2003). Again, our model is different because our entrant firm can choose between two active options. Rahman and Loulou (2001) and Huisman and Kort (2003) modeled two generations of the technology, but the newer technology is available only in the second period. The firms make adoption decisions in two periods based on the different availabilities of technologies. By allowing two generations of a product to be available at time zero, we analyze different timing decisions. In addition, our firms' decisions are continuous variables instead of discrete ones.

We contribute to the market entry and technology adoption literature by analyzing how firms choose product launch and/or upgrade times when they are technologically ready to release the next generation product. Such decisions are different from binary choices at each period and are needed as firms plan for the future.

3. The model

We consider a setting where two firms might become competitors. At time zero, Firm 1 is a monopolist incumbent producing the current generation product while Firm 2 is a potential entrant. Both firms have the capability to release the next generation of the product. The firms, however, will not do so until the right moment.

3.1. Decision variables

As an incumbent firm, Firm 1 determines whether and when to upgrade its current product to the next generation. We denote the incumbent's upgrade time by t_1^n, which can take any value from the interval $[0, \infty)$. Although such a setting implies that the firm's planning horizon is infinite, our results apply to situations where a firm's planning horizon is finite with minimal modifications. We also allow t_1^n to take a value of $\hbar$. $\hbar$ is not a real number, but a notation which indicates that the incumbent chooses never to launch the next generation product.

As an entrant firm, Firm 2 can compete with the incumbent by launching the current generation product or the next generation product. The potential entrant (Firm 2), therefore, needs to determine not only whether and when to launch the next generation product, but also whether and when to launch the current generation product. We capture the entrant's decisions by t_2^c (the time to launch the current generation product) and t_2^n (the time to launch the next generation product). Similar to the specification of t_1^n, t_2^k can take any value from $[0, \infty) \cup \{\hbar\}$ for $k = c, n$. Since firms rarely launch an older version of a product after releasing the newer version, we require that $t_2^c \leqslant t_2^n$ when neither decision variable takes the value of $\hbar$.

Our focus is on the evolution of generations of the same product. We assume that once a firm has launched a newer generation of a product, the firm discontinues older versions of the same product. We also assume that the firms make their timing decisions simultaneously at time zero. The decisions are affected by the firms' cost structures, profit margin functions and the anticipated game play.

3.2. Launch costs

The launch or upgrade of a product is often associated with one-time fixed costs, for example, the cost of installing and implementing the necessary technology, and promotion cost. We refer to such fixed costs as "launch costs". It is worth noting that marketing and promotion costs, aiming to stimulate and improve awareness, positive perception and adoption of the product among potential consumers, could be a significant part of launch costs. For example, pharmaceutical companies spent about \$8 billion on sales and marketing, along with distributed samples that cost an additional \$7.95 billion in the US market in 2000 alone (Kyle, 2006). A typical razor costs Gillette Sensor \$200 million in research, engineering, and tooling, and an additional \$110 million in first-year television and print advertising (Hammonds, 1990).

The incumbent's launch costs of the current generation product are sunk at time zero when the firm determines whether and when to upgrade. The launch costs the incumbent should take into consideration are therefore those directly associated with the next generation product. We denote by $F_1^n(t_1^n)$ the launch costs the incumbent incurs at time t_1^n.

We denote by $F_2^c(t_2^c)$ the entrant's launch costs of the current generation product at time t_2^c. For the entrant's launch costs of the next generation product, we distinguish two situations: (i) if the entrant skips the current generation product and launches the next generation at time t_2^n, then the entrant incurs $F_2^n(t_2^n)$ at time t_2^n; (ii) if the entrant launches the current generation product at time t_2^c and upgrades it to the next generation at time t_2^n, then the entrant incurs $F_2^\delta(t_2^n - t_2^c)$ at time t_2^n. In the latter case, we assume that when the entrant launches the next generation product, it builds upon its past experience of launching the current generation product, and thus incurs lower launch costs given the same launch time of the next generation product in both situations.

Note that if a firm has no plan to launch the kth generation of the product, any launch cost associated with the generation is zero. Launch costs, in general, must be non-negative. Since we expect that the installation and implementation costs decrease over time as technologies mature and the marketing/promotion may cost less as consumers become increasingly aware of the product, we assume that launch costs decrease over time. Furthermore, we assume that the marginal decrease in launch costs declines over time, namely the cost reduction is diminishing as the launch time is postponed because technology improvements become more and more marginal and the learning effects decline as well.

The next generation product is supposed to be more technologically challenging for a firm than the current generation product. Because of this, if the entrant decides to launch only one generation of the product and the launch time is t, then the firm incurs a higher launch cost at time t if the product is of the next generation. That is, $F_2^n(t) > F_2^c(t)$. Furthermore, we set $F_2^\delta(0)$ to the difference between $F_2^n(t)$ and $F_2^c(t)$. The rationale is that if the entrant launches the current generation product and upgrades it to the next generation immediately, then the firm, effectively, launches only the next generation product.

In summary, we make the following assumptions about launch costs throughout this paper:

- (Assumption 1a): F_i^k is non-negative, continuously differentiable, strictly decreasing, and strictly convex in the launch time of the kth generation product.

- (Assumption 1b): F_2^{δ} is non-negative, continuously differentiable, strictly decreasing, and strictly convex in the time lapse between the two launches.
- (Assumption 2): $F_2^{\delta}(0) = F_2^n(t) - F_2^c(t)$.

3.3. Gross profit margins

Instead of modeling the formation of market prices through demand functions, we consider the impact of prices and revenues through a firm's gross profit margin. A firm's gross profit margin is its revenues minus variable costs.

A firm's gross profit margin is generated continuously as long as the firm has a product on the market. Similar to Fudenberg and Tirole (1985)'s approach, we assume that the state of the competition affects the firm's gross profit margins. Monopoly profit margins need not be the same as duopoly profit margins. Specifically, we denote by D_i^k Firm i's (instantaneous) current gross profit margin if Firm i offers the kth generation of the product in a duopoly market, and by M^k the incumbent's (instantaneous) current gross profit margin if the incumbent offers the kth generation of the product in a monopoly market. The entrant never earns monopoly profits because the incumbent is always a player on the market.

Given any point of time t, the generation of the product a firm has on the market can be inferred from the firms' timing decisions. Depending upon whether the entrant's product has arrived at the market by time t, the state of the competition at time t is either a duopoly or a monopoly. Table 1 summarizes the possible gross profit margins for each firm at time t and the conditions under which each possibility materializes.

Our modeling of the profit margins implies that in a duopoly market, a firm's gross profit margin does not change as the firm's competitor replaces one generation of the product with a newer generation. This is a strong assumption, but could be plausible. When brand name is the dominant factor driving consumers' choices, successions of product generations at competing firms do not affect a firm's profit margin much. For example, in the PC market, people who prefer Apple's Macintosh are not likely to purchase computers from other brand names regardless of the generation of the product others offer.

3.4. Profits

The firms make their launch and update decisions at time zero. While gross profit margins will be reaped in a continuous stream, the firms' launch costs will occur as one-time fixed costs. We convert future revenues and costs to present values given discount rate $r \in (0, \infty)$. A rational firm will prefer launch times that result in a higher present value of total profit. Depending on the firms' timing decisions, their gross profit margins and launch costs take different forms. We discuss the specifics later in Sections 4 and 5 when studying the entrant and the incumbent's decisions, respectively.

We recognize that our model focuses on the impact of fixed launch/upgrade costs among all the possible costs a firm might incur. But we do take into consideration a firm's variable/component costs by defining gross profit margin as the difference between revenue and variable costs. Since gross profit margins depreciate over time, as reflected by the discount rate r, we indirectly model variable costs that are decreasing over time.

4. The entrant's timing decisions

From the entrant's perspective, the state of the competition is always duopoly regardless of the incumbent's timing decision. As a result, the entrant's gross profit margin at time s depends only upon the generation of the product the entrant is offering at the moment. The present value of the entrant's profits is, hence, a function of the vector (t_2^c, t_2^n). Any well-defined vector (t_2^c, t_2^n) must belong to one of the following three categories:

(i) The entrant considers the launch of the current generation product with no plan to upgrade it to the next generation (i.e., $t_2^c \in [0, \infty) \cup \{\hbar\}$ and $t_2^n = \hbar$).
(ii) The entrant skips the current generation product and considers only the launch of the next generation (i.e., $t_2^c = \hbar$ and $t_2^n \in [0, \infty) \cup \{\hbar\}$).
(iii) The entrant launches the current generation product and upgrades it to the next generation at a later time (i.e., $t_2^c \in [0, \infty)$ and $t_2^n \in [t_2^c, \infty)$).

Note that the option $(t_2^c, t_2^n) = (\hbar, \hbar)$ is in both of the first two categories. Excluding this option, the three categories are non-overlapping. We look for the entrant's optimal timing decisions by examining options in each of these three categories.

4.1. The entrant considers only the current generation product

If the entrant decides not to launch the next generation product, t_2^n is fixed at $\hbar$. The entrant's decision is reduced to

Table 1
The firms' current gross profit margins at time t.

(Incumbent, entrant)		The incumbent's product at time t	
		The current generation	The next generation
The entrant's product at time t	None	$(M^c, 0)$	$(M^n, 0)$
	The current generation	(D_1^c, D_2^c)	(D_1^n, D_2^c)
	The next generation	(D_1^c, D_2^n)	(D_1^n, D_2^n)

whether and when to launch the current generation product. For any $t_2^c \in [0,\infty)$, the present value of the entrant's total profits is

$$\Pi_2(t_2^c, t_2^n) = \Pi_2(t_2^c, \hbar) = \int_{t_2^c}^{\infty} D_2^c\, e^{-rs}\, ds - F_2^c(t_2^c)\, e^{-rt_2^c}. \qquad (1)$$

Note that if t_2^c takes the extreme value of $\hbar$, then the entrant earns zero profits, and we have $\Pi_2(\hbar,\hbar) = 0 = \lim_{t\to\infty}\Pi_2(t,\hbar)$.

The first derivative of the entrant's profit with respect to t_2^c is

$$\frac{d}{dt_2^c}\Pi_2(t_2^c,\hbar) = e^{-rt_2^c}\left(-D_2^c + rF_2^c(t_2^c) - \frac{d}{dt_2^c}F_2^c(t_2^c)\right). \qquad (2)$$

The sign of Eq. (2) determines whether or not the entrant's profit is increasing at a certain value of t_2^c. Lemma 1 tracks the sign of Eq. (2) and derives the optimal time for the entrant to launch the current generation product, given that the entrant has no plan to upgrade the product. (The proof of Lemma 1, together with proofs of other technical statements, is included in the appendix.)

Lemma 1. *Suppose the entrant rules out the possibility of launching the next generation product. Define* $\psi_2^c(t) = rF_2^c(t) - (d/dt)F_2^c(t)$.

(i) *If* $\lim_{t\to\infty}\psi_2^c(t) < D_2^c$, *the entrant's optimal launch time of the current generation product is* $\tau_2^{c\hbar} = \min\{t \mid \psi_2^c(t) \leqslant D_2^c\}$. *In particular,* $\psi_2^c(\tau_2^{c\hbar}) = D_2^c$ *if* $D_2^c \leqslant \psi_2^c(0)$, *and* $\tau_2^{c\hbar} = 0$ *if* $\psi_2^c(0) \leqslant D_2^c$.
(ii) *If* $\lim_{t\to\infty}\psi_2^c(t) \geqslant D_2^c$, *it is optimal for the entrant never to launch the current generation product.*

The intuition behind Lemma 1 is, essentially, a balancing act. The delay of launching the current generation product leads to savings in launch costs, but at the expense of delays in generating gross profit margins. The savings in launch costs come from two sources. First, due to the maturation of technologies over time, the firm's current launch cost $F_2^c(t)$ decreases over time. Second, taking a present value perspective means that the later the launch, the smaller the present value of the launch cost. The latter impact is measured by the discount factor r. From a present value perspective, the marginal cost of the launch is $e^{-rt}[rF_2^c(t) - (d/dt)F_2^c(t)] = e^{-rt}\psi_2^c(t)$ at time t. Meanwhile, the launch of the current generation product produces gross profit margins. The marginal benefit of the launch is $e^{-rt}D_2^c$ at time t from a present value perspective. The entrant must balance these two counteracting incentives. Lemma 1 above outlines the rule of thumb for the entrant: if there is a point in time at which the marginal cost of the launch equals the marginal benefit, then the entrant should launch the current generation product at that point in time; if such a time does not exist, then either the marginal cost always dominates the marginal benefit, or vice versa. If the marginal cost is indeed greater than the marginal benefit, the entrant always benefits from postponing the launch and, hence, prefers not to launch at all. Otherwise, the entrant should launch the current generation product as early as possible, and hence takes action at time zero.

4.2. The entrant considers only the next generation product

The entrant can skip the launch of the current generation product ($t_2^c = \hbar$) and enter the market with the next generation at t_2^n. In this case, for any $t_2^n \in [0,\infty)$, the present value of the entrant's total profits is

$$\Pi_2(t_2^c, t_2^n) = \Pi_2(\hbar, t_2^n) = \int_{t_2^n}^{\infty} D_2^n\, e^{-rs}\, ds - F_2^n(t_2^n)\, e^{-rt_2^n}.$$

The first derivative of $\Pi_2(\hbar, t_2^n)$ with respect to t_2^n is

$$\frac{d}{dt_2^n}\Pi_2(\hbar, t_2^n) = e^{-rt_2^n}\left(-D_2^n + rF_2^n(t) - \frac{d}{dt_2^n}F_2^n(t)\right).$$

The analysis here is similar to that in Section 4.1 in the sense that the entrant launches, at most, one generation of the product. Hence, the derivation of the entrant's optimal launch time of the next generation product in Lemma 2 is similar to the derivation in Lemma 1, which focuses on the entrant's optimal launch time of the current generation product.

Lemma 2. *Suppose the entrant skips the launch of the current generation product. Define* $\psi_2^n(t) = rF_2^n(t) - (d/dt)F_2^n(t)$.

(i) *If* $\lim_{t\to\infty}\psi_2^n(t) < D_2^n$, *the entrant's optimal launch time of the next generation product is* $\tau_2^{\hbar n} = \min\{t \mid \psi_2^n(t) \leqslant D_2^n\}$. *In particular,* $\psi_2^n(\tau_2^{\hbar n}) = D_2^n$ *if* $D_2^n \leqslant \psi_2^n(0)$, *and* $\tau_2^{\hbar n} = 0$ *if* $\psi_2^n(0) \leqslant D_2^n$.
(ii) *If* $\lim_{t\to\infty}\psi_2^n(t) \geqslant D_2^n$, *it is optimal for the entrant never to launch the next generation product.*

4.3. The entrant considers both generations

If the entrant launches the current generation product at $t_2^c \neq \hbar$ and upgrades the product to the next generation later at $t_2^n \neq \hbar$, then $\Delta = t_2^n - t_2^c$ (i.e., the lapse of time between the launches of two generations of the product) is well defined and $\Delta \in [0,\infty)$. In this case, finding the optimal launch times is equivalent to finding a vector (t_2^c, Δ) such that $(t_2^c, t_2^c + \Delta)$ maximizes the entrant's profit. For any $t_2^c \in [0,\infty)$ and any $\Delta \in [0,\infty)$, the present value of the entrant's total profits is

$$\begin{aligned}\Pi_2(t_2^c, t_2^n) &= \Pi_2(t_2^c, t_2^c + \Delta)\\ &= \int_{t_2^c}^{t_2^c+\Delta} D_2^c e^{-rs}\, ds + \int_{t_2^c+\Delta}^{\infty} D_2^n\, e^{-rs}\, ds - F_2^c(t_2^c)\, e^{-rt_2^c}\\ &\quad - F_2^\delta(\Delta)\, e^{-r(t_2^c+\Delta)}.\end{aligned} \qquad (3)$$

We first fix the launch time of the current generation product and examine how the entrant's profit changes with the lapse of time between the two launches. The first derivative of $\Pi_2(t_2^c, t_2^c + \Delta)$ with respect to Δ is

$$\frac{d}{d\Delta}\Pi_2(t_2^c, t_2^c + \Delta) = e^{-r(t_2^c+\Delta)}\left(D_2^c - D_2^n + rF_2^\delta(\Delta) - \frac{d}{d\Delta}F_2^\delta(\Delta)\right). \qquad (4)$$

Since $e^{-r(t_2^c+\Delta)}$ is always non-negative, the sign of Eq. (4) is not dependent upon the value of t_2^c. Instead, whether or not the entrant benefits from extending the lapse of time between the two launches at time $t_2^c + \Delta$ is determined by the value of $D_2^c - D_2^n + rF_2^\delta(\Delta) - (d/d\Delta)F_2^\delta(\Delta)$. Lemma 3 focuses on this value and derives the optimal time lapse between the two launches.

Lemma 3. *Suppose the entrant launches the current generation product at* $t_2^c \in [0,\infty)$. *Define* $\psi_2^\delta(\Delta) = rF_2^\delta(\Delta) - (d/d\Delta)F_2^\delta(\Delta)$.

(i) *If* $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) < D_2^n - D_2^c$, *it is optimal for the entrant to upgrade to the next generation at* $t_2^c + \delta^*$, *where* $\delta^* = \min\{\Delta \mid \psi_2^\delta(\Delta) \leqslant D_2^n - D_2^c\}$. *In particular,* $\delta^* = 0$ *if* $\psi_2^\delta(0) \leqslant D_2^n - D_2^c$, *and* $\psi_2^\delta(\delta^*) = D_2^n - D_2^c$ *if* $\psi_2^\delta(0) > D_2^n - D_2^c$.
(ii) *If* $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) \geqslant D_2^n - D_2^c$, *it is optimal for the entrant not to upgrade.*

Lemma 3 above describes how the entrant balances the incentive to spend less and the inventive to earn more. Given the launch of the current generation product at t_2^c, upgrading to the next generation product at time $t_2^c + \Delta$ costs the entrant a fixed cost of $e^{-r(t_2^c+\Delta)}F_2^\delta(\Delta)$ from a present value perspective. Delaying the upgrade will lower this cost. The marginal cost of the upgrade is $e^{-r(t_2^c+\Delta)}\psi_2^\delta(\Delta)$, which quantifies the entrant's incentive to spend less by delaying the upgrade. As the entrant replaces the current generation product with the next generation, the rate at which the entrant earns gross profit margins changes from $e^{-r(t_2^c+\Delta)}D_2^c$ to $e^{-r(t_2^c+\Delta)}D_2^n$. The marginal benefit of the upgrade is $e^{-r(t_2^c+\Delta)}(D_2^n - D_2^c)$. A positive $D_2^n - D_2^c$ allows the entrant to earn more and provides an incentive for the entrant to upgrade. Comparing $\psi_2^\delta(\Delta)$ to $D_2^n - D_2^c$, therefore, sheds light on how the entrant should strike a balance.

If $\psi_2^\delta(\Delta) > D_2^n - D_2^c$ for any $\Delta \in [0,\infty)$ (i.e., $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) \geqslant D_2^n - D_2^c$), then an upgrade to the next generation is never justified. In other words, the entrant's decision to launch both generations of the product is dominated by its optimal decision when considering only the current generation product. The latter case was analyzed earlier in Section 4.1.

Now, we consider the case in which $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) < D_2^n - D_2^c$. In this case, there exists a Δ such that the marginal benefit of the upgrade outweighs the marginal cost at time $t_2^c + \Delta$. If, however, the marginal benefit is large enough to cover the marginal cost at any point of time $t_2^c + \Delta$, then any delay of the upgrade lowers the entrant's profit and the optimal time lapse between the two launches (δ^*) should be zero. This action is equivalent to launching the next generation product at time t_2^c. Therefore, when $\delta^* = 0$, the entrant's optimization problem is reduced to finding the optimal time to launch the next generation product, which is a case studied earlier in Section 4.2.

If the marginal benefit of the upgrade equates the marginal cost for some $\Delta > 0$, such a Δ is the optimal time lapse between the two launches. That is, $D_2^n - D_2^c = \psi_2^\delta(\delta^*)$. We can fix the time lapse between the two launches at δ^*, and examine how the entrant's profit is affected by its launch time of the current generation product. With $\delta^* > 0$, the first order derivative of the entrant's profit with respect to t_2^c on the interval $[0,\infty)$ is

$$\frac{d}{dt_2^c}\Pi_2(t_2^c, t_2^c + \delta^*)$$
$$= e^{-rt_2^c}(-D_2^c + \psi_2^c(t_2^c)) + e^{-r(t_2^c+\delta^*)}(D_2^c - D_2^n + \psi_2^\delta(\delta^*) + \frac{d}{d\Delta}F_2^\delta(\delta^*))$$
$$= e^{-rt_2^c}(-D_2^c + \psi_2^c(t_2^c)) + e^{-r(t_2^c+\delta^*)}\frac{d}{d\Delta}F_2^\delta(\delta^*)$$

(the above equality follows because $\psi_2^\delta(\delta^*) = D_2^n - D_2^c$ for any $\delta^* \in (0,\infty)$)

$$= e^{-rt_2^c}(-D_2^c + \psi_2^c(t_2^c) + e^{-r\delta^*}\frac{d}{d\Delta}F_2^\delta(\delta^*)). \tag{5}$$

We have learned from Section 4.1 that $e^{-rt_2^c}\psi_2^c(t_2^c)$ is the entrant's marginal cost of launching the current generation product at time t_2^c. It measures the entrant's incentive to delay its launch of the current generation product. From time t_2^c to time $t_2^c + \delta^*$, the entrant earns an instantaneous gross profit margin of D_2^c at any moment. Beyond time $t_2^c + \delta^*$, the entrant earns a higher instantaneous gross profit margin of D_2^n. Taking into consideration the higher profit margins in the future, the entrant can treat $e^{-rt_2^c}[D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)]$ as the marginal benefit of launching the current generation product at time t_2^c. Therefore, a comparison of $\psi_2^c(t_2^c)$ and $D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$ determines whether and when the entrant should launch the current generation product given the optimal time lapse between the two launches. These intuitions are formalized in Lemma 4.

Lemma 4. *Suppose* $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) < D_2^n - D_2^c$. *The entrant considers launching the current generation product at* t_2^c *and upgrading the product to the next generation at* $t_2^c + \delta^*$.

(i) *If* $\delta^* = 0$, *any decision to launch both generations of the product sequentially is dominated by the maximizer of* $\Pi_2(\hbar, t_2^n)$ *over the region*: $t_2^n \in [0,\infty) \cup \{\hbar\}$.
(ii) *If* $\delta^* > 0$ *and* $\lim_{t\to\infty}\psi_2^c(t) \geqslant D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, *any decision to launch both generations of the product sequentially is dominated by* $(t_2^c, t_2^n) = (\hbar, \hbar)$.
(iii) *If* $\delta^* > 0$ *and* $\lim_{t\to\infty}\psi_2^c(t) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, *the entrant's optimal launch time of the current generation product is* $\tau_2^{c\delta} = \min\{t \mid \psi_2^c(t) \leqslant D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)\}$. *In particular,* $\tau_2^{c\delta} \leqslant \tau_2^{ch}$ if $\lim_{t\to\infty}\psi_2^c(t) < D_2^c$.

Lemma 4 points out that the entrant's optimal launch time of the current generation product would be earlier when an upgrade at a later time is guaranteed than when there is no plan to upgrade (i.e., $t_2^{c\delta} \leqslant t_2^{ch}$). This is because an upgrade brings in more gross profit margins, and hence strengthens the entrant's incentive to launch the current generation product. Recall that when an upgrade occurs δ^* time units after the launch of the current generation product, the marginal benefit of the launch at time t_2^c is $e^{-rt_2^c}[D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)] > e^{-rt_2^c}D_2^c$. The latter is the marginal benefit of launching the current generation product absent any plan to upgrade.

4.4. The entrant's overall decisions

We denote by $(t_2^c, t_2^n)^{opt}$ the vector that represents the entrant's optimal launch times. Based on our analysis in Sections 4.1–4.3, $(t_2^c, t_2^n)^{opt}$ must take one of these four values: $(\hbar,\hbar)$, $(\tau_2^{ch},\hbar)$, $(\hbar,\tau_2^{hn})$, or $(\tau_2^{c\delta}, \tau_2^{c\delta} + \delta^*)$. Our next step is to find out the necessary and sufficient conditions under which each of these vectors becomes the entrant's optimal decision.

We find that how the entrant's marginal benefit of the upgrade fares against its marginal cost of the upgrade plays an important role in determining the firm's overall product launch strategies. If the marginal benefit always dominates the marginal cost, then the lure of the next generation product is large enough for the entrant to skip the current generation product. If the marginal cost always dominates the marginal benefit, then it is not worthwhile for the entrant to pursue the next generation product at all. For cases in between, the entrant should consider launching both generations of the product sequentially. Proposition 1 combines this intuition with Lemmas 1–4, and formally states the entrant's optimal timing decisions.

Proposition 1. *The entrant's optimal timing decisions can be characterized as follows*:

(i) $(t_2^c, t_2^n)^{opt} = (\hbar, \tau_2^{\hbar n})$ *if and only if* $\psi_2^\delta(0) \leqslant D_2^n - D_2^c$ *and* $\lim_{t\to\infty}\psi_2^n(t) < D_2^n$.
(ii) $(t_2^c, t_2^n)^{opt} = (\tau_2^{c\delta}, \tau_2^{c\delta} + \delta^*)$ *if and only if* $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) < D_2^n - D_2^c < \psi_2^\delta(0)$ *and* $\lim_{t\to\infty}\psi_2^c(t) < D_2^c - e^{-r\delta^*}\frac{d}{d\Delta}F_2^\delta(\delta^*)$.
(iii) $(t_2^c, t_2^n)^{opt} = (\tau_2^{ch}, \hbar)$ *if and only if* $D_2^n - D_2^c \leqslant \lim_{\Delta\to\infty}\psi_2^\delta(\Delta)$ *and* $\lim_{t\to\infty}\psi_2^c(t) < D_2^c$.
(iv) *If none of the above sets of conditions are satisfied, then* $(t_2^c, t_2^n)^{opt} = (\hbar, \hbar)$.

We try to visualize the entrant's optimal timing decisions as shown in Fig. 1. In the figure, we use D_2^c and $D_2^n - D_2^c$ as horizontal and vertical axes, respectively, and compare them to different thresholds relating to the entrant's launch costs. For any given D_2^n, all the feasible combinations of $(D_2^c, D_2^n - D_2^c)$ are represented by a 45° line (diagonal) that links the vertical and the horizontal axes. Each point on the diagonal presents a unique combination of $(D_2^c, D_2^n - D_2^c)$ but all the points share the same D_2^n. As D_2^n gets smaller (larger), the position of the corresponding diagonal moves toward (away from) the origin.

There are four regions of different shades shown in Fig. 1, each representing a potential optimal decision for the entrant. Depending on the value of D_2^n, the corresponding diagonal intersects with different regions. For any pair of D_2^c and D_2^n, the entrant's optimal decision can be found by drawing the diagonal that represents D_2^n and locating the point $(D_2^c, D_2^n - D_2^c)$ on the diagonal. By identifying the region that hosts the point $(D_2^c, D_2^n - D_2^c)$ we find the entrant's optimal decision.

The exact shape and size of each region depend upon how the values of the cost thresholds rank against each other and the gross profit margins. What we show in Fig. 1 is simply one possibility. For example, if $\lim_{t\to\infty}\psi_2^c(t)$ gets smaller, then both the line that separates Region (III) from Region (IV) and the line that separates Region (II) from Region (IV) will move toward the vertical axis. The movements will result in a smaller Region (IV).

If we fix the cost thresholds and move the 45° line (diagonal) that represents the next generation product's gross profit margin (D_2^n), we can see how gross profit margins affect the entrant's timing decisions. Here are a

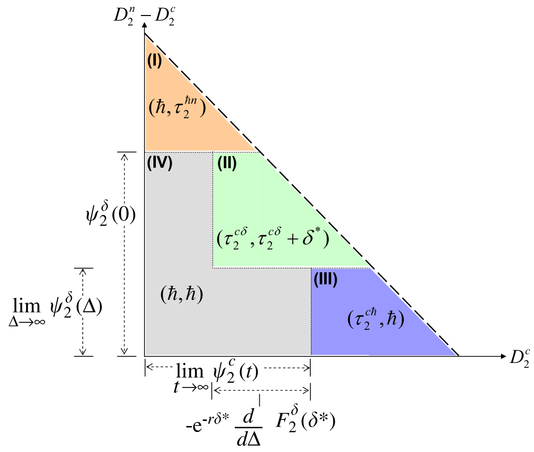

Fig. 1. The entrant's optimal timing decisions.

few observations. (a) If D_2^n is not sufficiently large, the entrant will not launch any generation of the product. (b) It is also interesting to note that a large D_2^n does not guarantee the entrant's launch of the next generation product. When both D_2^n and D_2^c are large, we can have a small difference between the gross profit margins for both generations of the product, which can spoil the launch of the next generation product. (c) The entrant is motivated to launch both generations of the product in a sequential manner only if the firm earns enough profit margins from the current generation product and can improve its profit margins sufficiently by upgrading to the next generation.

If we experiment with the cost thresholds, it is easy to see that the existence of the four regions illustrated in Fig. 1 is not automatic. At one extreme, if $\lim_{t\to\infty}\psi_2^c(t) = 0$, then Region (IV) no longer exists, which implies that the entrant will always join the competition. In this sense, $\lim_{t\to\infty}\psi_2^c(t)$ can be thought of as an entry barrier: the bigger $\lim_{t\to\infty}\psi_2^c(t)$ is, the more lucrative the next generation product (i.e., the bigger the D_2^n) has to be in order to justify the entry.

The entry–barrier effect of $\lim_{t\to\infty}\psi_2^c(t)$ can also be verified by noticing that a sufficient condition to guarantee the entrant's arrival at the market is $\lim_{t\to\infty}\psi_2^c(t) < \min\{D_2^c, D_2^n - rF_2^\delta(0)\}$. This condition follows from Proposition 1. The proposition indicates that if $\lim_{t\to\infty}\psi_2^c(t) < D_2^c$, $\lim_{t\to\infty}\psi_2^n(t) < D_2^n$, and $\lim_{t\to\infty}\psi_2^c(t) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$ all hold, then the entrant will enter the market. Meanwhile, $0 < -e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$ and $\psi_2^n(t) = rF_2^\delta(0) + \psi_2^c(t)$, where the second equality follows from Assumption 2: $F_2^\delta(0) = F_2^n(t) - F_2^c(t)$. Thus, the sufficient condition described at the beginning of this paragraph emerges. Using similar logic, we find that if the entrant can reduce its launch cost $\psi_2^c(t)$ consistently through some process improvement, then the entrant's possible entry times, $\tau_2^{c\delta}$, τ_2^{ch}, and $\tau_2^{\hbar n}$, will be advanced. This result is formally established in Corollary 1.

Corollary 1. *If the entrant can lower its launch costs of the current generation product* $F_2^c(t)$ *by* $\varepsilon > 0$ *for any* $t \in [0, \infty)$, *then the entrant is more likely to enter the market, and with an earlier entry time.*

Corollary 1 confirms that small launch costs of the current generation product are a competitive advantage.

5. The incumbent's timing decisions

Whether the incumbent (Firm 1) upgrades its product to the next generation depends upon its anticipation as to whether and when the entrant (Firm 2) joins the competition. If the entrant is expected to stay out of the market, the incumbent's upgrade decision must fit its status as a monopolist. Otherwise, the incumbent's status will be changed from a monopolist to a duopolist upon the arrival of the entrant. We analyze, in this section, the incumbent's optimal response given the entrant's product launch and upgrade strategies.

5.1. The incumbent's decision when facing no competitors

When the entrant stays out of the market (i.e., $t_2^c = t_2^n = \hbar$), the incumbent remains a monopolist producing either the current or the next generation product. We refer to such an incumbent as a pure monopolist. Being a pure monopolist, the incumbent's decision of upgrading at $t_1^n \in [0, \infty)$ results in the present value:

$$\Pi_1(t_1^n, t_2^c, t_2^n) = \Pi_1(t_1^n, \hbar, \hbar) = \int_0^{t_1^n} M^c\, e^{-rs}\, ds + \int_{t_1^n}^{\infty} M^n\, e^{-rs}\, ds - F_1^n(t_1^n)\, e^{-rt_1^n}. \tag{6}$$

If the incumbent chooses not to upgrade, the present value of its total profits becomes $\int_0^\infty M^c\, e^{-rs}\, ds = \lim_{t\to\infty} \Pi_1(t, \hbar, \hbar)$. The first derivative of the profit with respect to t_1^n is

$$\frac{d}{dt_1^n}\Pi_1(t_1^n, \hbar, \hbar) = e^{-rt_1^n}\left(M^c - M^n + rF_1^n(t_1^n) - \frac{d}{dt_1^n}F_1^n(t_1^n)\right). \tag{7}$$

Like the entrant, the incumbent wants to balance two counteracting forces: the marginal benefit of upgrading to the next generation product and the marginal cost of doing so. Proposition 2 characterizes the optimal upgrade time for the incumbent when it is a pure monopolist.

Proposition 2. *Suppose the entrant stays out of the market. Define* $\psi_1^n(t) = rF_1^n(t) - (d/dt)F_1^n(t)$.

(i) *If* $\lim_{t\to\infty}\psi_1^n(t) \geqslant M^n - M^c$, *the incumbent is better off never to upgrade.*
(ii) *If* $\lim_{t\to\infty}\psi_1^n(t) < M^n - M^c$, *the optimal time for the incumbent to upgrade its product to the next generation is* $\tau_1^m = \min\{t | \psi_1^n(t) \leqslant M^n - M^c\}$.

Proposition 2 suggests that the incumbent's launch of the next generation product is not automatic even if the firm is the monopolist. Ultimately, it is the comparison between the marginal benefit and cost of upgrading that determines the course of action.

5.2. The incumbent's decision in anticipation of competition

The incumbent becomes a duopolist upon the entrant's arrival. We denote the entrant's arrival time by $\tilde{t}_2$. If the entrant plans to launch the current generation product, its launch time of the current generation product is $\tilde{t}_2$. Otherwise, the entrant's launch time of the next generation product is $\tilde{t}_2$. That is,

$$\tilde{t}_2 = \begin{cases} t_2^c & \text{if } t_2^c \in [0, \infty); \\ t_2^n & \text{if } t_2^c = \hbar \quad \text{and} \quad t_2^n \in [0, \infty). \end{cases} \tag{8}$$

$\tilde{t}_2$ is well defined as long as the entrant competes with the incumbent, namely $(t_2^c, t_2^n) \neq (\hbar, \hbar)$. An extreme case is that $\tilde{t}_2 = 0$. In this case, the entrant rushes to the market and competes with the incumbent from time zero. Hence, the incumbent becomes a duopolist since time zero. We refer to such an incumbent as a pure duopolist. Similar to the definition of τ_1^m in Proposition 2, we define $\tau_1^d = \min\{t | \psi_1^n(t) \leqslant D_1^n - D_1^c\}$. Note that τ_1^d is well defined only if $\lim_{t\to\infty}\psi_1^n(t) < D_1^n - D_1^c$. If the incumbent is a pure duopolist, then the optimal time for the incumbent to upgrade would be τ_1^d provided that the incumbent was better off with an upgrade (i.e, $\lim_{t\to\infty}\psi_1^n(t) < D_1^n - D_1^c$). The derivations are the same as those for Proposition 2 with minimal adaptations.

We find that a pure monopolist's optimal upgrade time is earlier than a pure duopolist's as long as $D_1^n - D_1^c < M^n - M^c$. The inequality implies that a monopolist enjoys a larger increase in gross profit margins from a product upgrade than a duopolist does, which is a plausible scenario. This result is formalized in Lemma 5.

Lemma 5. *If* $\lim_{t\to\infty}\psi_1^n(t) < D_1^n - D_1^c < M^n - M^c$ *then* $\tau_1^m \leqslant \tau_1^d$. *In particular, if* $\tau_1^d > 0$ *then* $\tau_1^m < \tau_1^d$.

It is perhaps more often the case that $\tilde{t}_2 > 0$. Now the incumbent is neither a pure monopolist, nor a pure duopolist. For any $t_1^n \in [0, \infty)$, with the expectation of becoming a duopolist from being a monopolist, the incumbent reaps both monopoly gross profit margins from the current generation product and duopoly gross profit margins from the next generation product, although during different periods of time. The incumbent, however, is able to enjoy monopoly gross profit margins from the next generation product only if its upgrade precedes the entrant's arrival. On the other hand, the incumbent will earn duopoly gross profit margins from the current generation product only if it upgrades after the entrant's arrival. Therefore, if the incumbent upgrades at some $t_1^n \in [0, \infty)$, then the present value of the firm's total profits is

$$\Pi_1(t_1^n, t_2^c, t_2^n) = \begin{cases} \int_0^{t_1^n} M^c\, e^{-rs}\, ds + \int_{t_1^n}^{\tilde{t}_2} M^n\, e^{-rs}\, ds \\ \quad + \int_{\tilde{t}_2}^{\infty} D_1^n\, e^{-rs}\, ds - F_1^n(t_1^n)\, e^{-rt_1^n} \quad \text{for } t_1^n \in [0, \tilde{t}_2]; \\ \int_0^{\tilde{t}_2} M^c\, e^{-rs}\, ds + \int_{\tilde{t}_2}^{t_1^n} D_1^c\, e^{-rs}\, ds \\ \quad + \int_{t_1^n}^{\infty} D_1^n\, e^{-rs}\, ds - F_1^n(t_1^n)\, e^{-rt_1^n} \quad \text{for } t_1^n \in [\tilde{t}_2, \infty). \end{cases}$$

If the incumbent never upgrades, the present value of its total profits is $\Pi_1(\hbar, t_2^c, t_2^n) = \int_0^{t_2^n} M^c\, e^{-rs}\, ds + \int_{t_2^n}^{\infty} D_1^c\, e^{-rs}\, ds$, which equals $\lim_{t\to\infty}\Pi_1(t, t_2^c, t_2^n)$.

The first derivative of the incumbent's profit with respect to t_1^n is

$$\frac{d}{dt_1^n}\Pi_1(t_1^n,\hbar,t_2^n)=\begin{cases} e^{-rt_1^n}(M^c-M^n+\psi_1^n(t_1^n)) & \text{if } t_1^n\in[0,\tilde{t}_2);\\ e^{-rt_1^n}(D_1^c-D_1^n+\psi_1^n(t_1^n)) & \text{if } t_1^n\in[\tilde{t}_2,\infty). \end{cases} \tag{9}$$

When $\tilde{t}_2>0$, the incumbent starts off as a monopolist but becomes a duopolist upon the arrival of the entrant. We have derived the optimal upgrade time for a pure monopolist and a pure duopolist, respectively. Should the incumbent choose its upgrade time as if it were a pure monopolist, or a pure duopolist? Will there be circumstances in which the incumbent is better off never to upgrade? Proposition 3 below attempts to answer these questions.

We assume that $D_1^n-D_1^c<M^n-M^c$. The incumbent, therefore, has a stronger incentive to upgrade as a pure monopolist than as a pure duopolist. From Proposition 2 we have learned that a pure monopolist prefers not to upgrade if $M^n-M^c\leqslant\lim_{t\to\infty}\psi_1^n(t)$. Hence, a pure duopolist will not have any incentive to upgrade if $M^n-M^c\leqslant\lim_{t\to\infty}\psi_1^n(t)$. Consequently, in this case, the incumbent, whose status changes from a monopolist to a duopolist, is better off never to upgrade.

As M^n-M^c surpasses $\lim_{t\to\infty}\psi_1^n(t)$, a pure monopolist is willing to upgrade while a pure duopolist prefers not to do so as long as $D_1^n-D_1^c$ is below $\lim_{t\to\infty}\psi_1^n(t)$. We find that if a pure monopolist's optimal upgrade time (i.e., τ_1^m) arrives after the incumbent has actually become a duopolist (i.e., $\tilde{t}_2$), the incumbent is better off acting like a duopolist (instead of a monopolist) and prefers not to upgrade at all.

When $D_1^n-D_1^c$ is sufficiently large to justify the upgrade for a pure duopolist, the incumbent will upgrade. The question now is whether the incumbent should upgrade at the time that is best for a pure monopolist (i.e., τ_1^m) or at the time that is best for a pure duopolist (i.e., τ_1^d). From Lemma 5 we know that $\tau_1^m\leqslant\tau_1^d$. We find that if τ_1^d is earlier than the entrant's arrival (namely when the incumbent is still a monopolist), then adopting τ_1^d is dominated by the decision to go with τ_1^m. Similarly, we also conclude that if τ_1^m arrives after the incumbent becomes a duopolist, then the incumbent should act like a duopolist, as opposed to a monopolist.

The above results are formally established in Proposition 3.

Proposition 3. *Suppose the incumbent anticipates a competition with the entrant starting at $\tilde{t}_2$. Let $D_1^n-D_1^c<M^n-M^c$.*

(i) *When $M^n-M^c\leqslant\lim_{t\to\infty}\psi_1^n(t)$, the incumbent is better off never to upgrade.*
(ii) *When $D_1^n-D_1^c\leqslant\lim_{t\to\infty}\psi_1^n(t)<M^n-M^c$, the incumbent's optimal decision is either upgrading the product at τ_1^m or never upgrading, whichever results in a larger profit. In particular, if $\tilde{t}_2\leqslant\tau_1^m$, the incumbent is better off never upgrading.*
(iii) *When $\lim_{t\to\infty}\psi_1^n(t)<D_1^n-D_1^c$, the incumbent's optimal decision is to upgrade the product at either τ_1^m or τ_1^d, whichever results in a larger profit. In particular, if $\tilde{t}_2\leqslant\tau_1^m$, the incumbent's profit is maximized by $t_1^n=\tau_1^d$; if $\tau_1^d\leqslant\tilde{t}_2$, the incumbent's profit is maximized by $t_1^n=\tau_1^m$.*

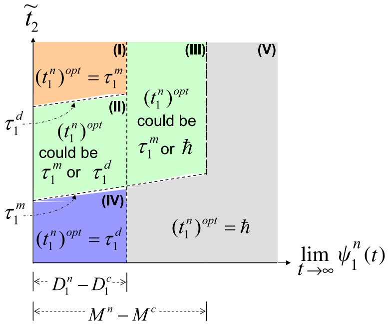

Fig. 2. The incumbent's optimal time to upgrade.

Fig. 2 illustrates the incumbent's optimal upgrade timing. We fix the values of M^n-M^c and $D_1^n-D_1^c$ in the figure. Since the values of τ_1^m and τ_1^d are affected by the function ψ_1^n, the values of τ_1^m and τ_1^d will change as the value of $\lim_{t\to\infty}\psi_1^n(t)$ changes. Thus, the straight lines shown in Fig. 2 that represent the values of τ_1^m and τ_1^d are not parallel to the horizontal axis that represents $\lim_{t\to\infty}\psi_1^n(t)$. These two straight lines are upward sloping as $\lim_{t\to\infty}\psi_1^n(t)$ increases because ψ_1^n decreases with time.

A few observations follow from Fig. 2. As $\tilde{t}_2$ gets sufficiently large, the incumbent's optimal upgrade time becomes either τ_1^m or $\hbar$. This is the same outcome as when the entrant stays out of the market (see Section 5.1).

Although the entrant's arrival time ($\tilde{t}_2$) is a key element in the incumbent's upgrade decision, $\tilde{t}_2$ does not always affect whether the incumbent upgrades or not. Regions (I), (II) and (IV) shown in Fig. 2 cover all the possible events as long as $\lim_{t\to\infty}\psi_1^n(t)<D_1^n-D_1^c$. The incumbent may choose different times to upgrade but will upgrade eventually in all three regions. At the other end of the spectrum where $M^n-M^c\leqslant\lim_{t\to\infty}\psi_1^n(t)$, the incumbent finds it optimal never to upgrade regardless of the value of $\tilde{t}_2$ (see Region (V)). Therefore, the value of $\lim_{t\to\infty}\psi_1^n(t)$ in relation to $D_1^n-D_1^c$ and $M_1^n-M_1^c$ is the determinant of the incumbent's upgrade.

When it is optimal for the incumbent to upgrade regardless of $\tilde{t}_2$ (see Regions (I), (II) and (IV)), the value of $\tilde{t}_2$ affects the incumbent's choice of the time to upgrade. $\tilde{t}_2$ takes smaller values in Region (IV) than in Region (I). The incumbent's optimal time to upgrade, however, is earlier in Region (I) than in Region (IV). Does an earlier arrival of the entrant prompt the incumbent to delay its upgrade? In order to answer this question, we need to analyze how the incumbent's preference of τ_1^m changes with $\tilde{t}_2$ in Regions (II) and (III).

In Region (II) the incumbent's optimal upgrade time is either τ_1^m or τ_1^d, whichever results in a higher present value of the incumbent's total profits. The incumbent's preference of τ_1^m increases with the difference: $\Pi_1(\tau_1^m,t_2^c,t_2^n)-\Pi_1(\tau_1^d,t_2^c,t_2^n)$. We show in Corollary 2 that this difference can be expressed as a monotonically increasing function of $\tilde{t}_2$. Therefore, the anticipated impact of $\tilde{t}_2$ can be established for Region (II). A similar pattern can be shown for Region (III).

Corollary 2. *Let $D_1^n-D_1^c<M^n-M^c$. In both Regions* (II) *and* (III) *shown in Fig. 2, the incumbent's preference of τ_1^m as its optimal upgrade time increases with $\tilde{t}_2$.*

If the incumbent upgrades its product to the next generation, there are only two choices for the optimal upgrade time: τ_1^m and τ_1^d. Recall from Lemma 5 that $\tau_1^m < \tau_1^d$. Corollary 2 suggests that an earlier arrival time of the entrant will delay the incumbent's upgrade time.

Combining Corollary 2 and what has been shown in Fig. 2, we conclude that as long as $\lim_{t\to\infty}\psi_1^n(t) < D_1^n - D_1^c \leqslant M^n - M^c$, the incumbent will upgrade its product to the next generation, and the optimal upgrade time is postponed from τ_1^m to τ_1^d as the arrival time of the entrant becomes earlier. When $D_1^n - D_1^c \leqslant \lim_{t\to\infty}\psi_1^n(t) \leqslant M^n - M^c$, the entrant's arrival time can determine whether the incumbent should upgrade at all. When the entrant arrives early enough the incumbent will be deterred from upgrading.

6. Discussions on market leadership

Market leadership refers to a firm's ability to lead the launch of a new generation of a product. In our setting, the incumbent leads the launch of the current generation product. Will the incumbent also be the first one to launch the next generation product? We explore this question based on structural results obtained earlier.

In order to understand whether the position of an incumbent provides a firm any edge over its entrant competitor, let us consider for the moment firms with equivalent cost and profit margin structures. The incumbent has already launched the current generation product at time zero. To put the incumbent and the entrant on the same footing in terms of launch costs, the incumbent's launch costs of the next generation product should be regarded as upgrade costs. Equivalent launch costs of the next generation product imply that $F_1^n(t) = F_2^\delta(\Delta)$ for any $t = \Delta \in [0,\infty)$. Similarly, we would like to establish an equivalence between the two firms' gross profit margins. When replacing the current generation product with the next generation, the entrant's gross profit margin improves from D_2^c to D_2^n, and the incumbent's gross profit margin improves from D_1^c to D_1^n, or from M_1^c to M_1^n. We assume that $D_2^n - D_2^c = D_1^n - D_1^c < M^n - M^c$.

If the entrant finds it optimal not to launch the current generation product at all, the incumbent can never be the laggard in terms of the next generation product. We are, however, more interested in situations where the entrant chooses to launch the next generation product. There are two possibilities, either the entrant launches only the next generation product or the entrant launches the current generation and then upgrades to the next generation at a later time.

If the entrant launches the current generation product at $\tau_2^{c\delta}$ and upgrades to the next generation δ^* time units later, Proposition 1 tells us that the optimal time lapse between the two launches (δ^*) must equate the marginal cost of the upgrade to the marginal benefit for the entrant (i.e., $e^{-r(t_2^c+\delta^*)}\psi_2^\delta(\delta^*) = e^{-r(t_2^c+\delta^*)}(D_2^n - D_2^c)$). Since the two firms are equivalent in terms of costs and gross profit margins, we know that from the incumbent's perspective the marginal cost of the upgrade at time δ^* (i.e., $e^{-r\delta^*}\psi_1^n(\delta^*)$) equals the marginal benefit a pure duopolist earns (i.e., $e^{-r\delta^*}(D_1^n - D_1^c)$). From the definition of τ_1^d, we know that $\tau_1^d = \delta^*$. The incumbent's optimal launch time of the next generation product need not be τ_1^d. When both τ_1^m and τ_1^d are well defined the incumbent's optimal launch time is either $\tau_1^m \leqslant \tau_1^d$ or τ_1^d (from Proposition 3). Since the entrant's launch time of the next generation product is $\delta^* = \tau_1^d$ time units after its launch of the current generation product, we conclude that the entrant cannot launch the next generation product earlier than the incumbent does.

If the entrant skips the launch of the current generation product and launches the next generation product at $\tau_2^{\hbar n}$, Proposition 1 tells us that we must have $\psi_2^\delta(0) \leqslant D_2^n - D_2^c$. Given the cost and profit margin equivalence, we know that $\psi_1^n(0) \leqslant D_1^n - D_1^c$, which implies that $\tau_1^m = \tau_1^d = 0$. Again, the entrant cannot launch the next generation product earlier than the incumbent does.

Proposition 4 demonstrates the incumbent's advantage in the race to market leadership under a more general condition ($\psi_1^n(t) \leqslant \psi_2^\delta(\Delta)$). Note that $F_1^n(t) = F_2^\delta(\Delta)$ is an extreme case of $\psi_1^n(t) = \psi_2^\delta(\Delta)$.

Proposition 4. *Assume $\psi_1^n(t) \leqslant \psi_2^\delta(\Delta)$ for any $t = \Delta$, and $D_2^n - D_2^c = D_1^n - D_1^c < M^n - M^c$. If it is optimal for the entrant to set $t_2^n \neq \hbar$, then the incumbent's next generation product appears on the market no later than the entrant's counterpart.*

Proposition 4 shows that for competing firms with equivalent launch costs of the next generation product and gross profit margins, the position of incumbent provides an advantage as far as market leadership is concerned. In order to be the incumbent, a firm must have launched the current generation product by time zero. The launch costs of the current generation product are sunk before decisions about the next generation are made at time zero. Sunk costs are no longer part of the firm's cost–benefit analysis. Hence, the incumbent has a stronger incentive to launch the next generation product than the entrant, even if both firms have equivalent cost functions and gross profit margins.

It is likely that the incumbent can launch the next generation product more efficiently than the entrant does due to the learning effect. It is also plausible that the incumbent earns more from the product upgrade than the entrant due to consumer loyalty to an enduring brand. Our research implies that if any of the above scenarios occur, the incumbent's market leadership still holds and is actually strengthened. From the entrant's perspective, market leadership is not attainable unless the entrant is superior, either at launching products efficiently, or at generating more gross profit margins. For an established firm with dominating brand powers, the latter is a possible and realistic way to take over market leadership from the incumbent.

7. Conclusion and future research

We analyze firms' product launch and upgrade timings in an incumbent-vs-entrant setting. Using a stylized model, we characterize the optimal time for the incumbent to upgrade the current generation product and the optimal times for the entrant to launch and upgrade a competing product.

Although the entrant firm should not base its entry decision solely on gross profit margins, we find that small profit margins generated by the next generation product are likely to deter the entrant from joining the competition. Microsoft skipped launching an equivalent product to Sony's PlayStation and leapfrogged to the next generation product. This is because Microsoft was capable of extracting enough profit margins from the next generation product to outweigh the benefit of learning. In general, the entrant need not leapfrog to the launch of the next generation product. As a matter of fact, large profit margins generated by the next generation product do not guarantee the optimality of launching the next generation product. If an entrant would like to advance its entry time to the market, it should consider process improvements that can lower the firm's launch costs of the current generation product.

The incumbent firm must respond strategically to the arrival of the entrant. The incumbent is better off upgrading earlier when anticipating the late arrival of its competitor. This result explains the speed with which Apple Inc. replaced the iPod Mini with the iPod Nano. As a dominant player that is technologically advanced, Apple did not anticipate any significant rivalry any time soon and, hence, preferred to enjoy the (near) monopoly profit margins generated by the iPod Nano earlier rather than later.

Although the incumbent is not automatically the first one to launch the next generation product, the incumbent is better positioned in the race of market leadership. Having already invested in the current generation product allows the incumbent to materialize the learning effects. Meanwhile, sunk costs need not be factored into future planning. Thus, the incumbent has a cost advantage over the entrant as far as market leadership is concerned. Nevertheless, a powerful entrant with superior market power can overcome the incumbent's cost advantage.

In the interest of tractability, we assume in this paper that a firm's profit margins are determined by the generation of the product the firm offers and the competition status of the market, namely monopoly or duopoly. Doing so, however, implies that the two firms are essentially offering their products to separate market segments (decided by brand name). One interesting extension for future research is to consider a more general setting. For example, the firms' profit margins can be modeled as a result of a pricing and market share game like the one in Filippini (1999). In such a general setting, more strategic decisions are to be expected. In our current research, the incumbent reacts strategically to the entrant's market entry timing, but the entrant's optimal timings are not dependent upon the specific generation of the product offered by the incumbent. When a pricing and market share game is directly modeled, both the incumbent and the entrant will have to respond strategically to each other's actions.

This research can be further extended by relaxing the assumption that each firm has at most a single generation of the product on the market. Moorthy and Png (1992) found examples where firms offered both high-end and low-end versions of a product in order to capture different market segments. Given our current profit margin setting, a firm would not have any incentive to replace a high-end version with a low-end one because the low-end version has an inferior profit margin. If the firms do not have to discontinue existing generations/versions of a product when introducing other generations/versions, and if the firms' profit margins are determined by a pricing and market share game, based on what we have learned from this research we envision that various introduction timings could become an equilibrium outcome. Ultimately, the firms must balance the fixed costs of offering a product and a stream of profit margins reaped from the product. Different combinations of cost and market condition parameters will generate different points of balance.

Appendix

Proof of Lemma 1. Note that $\psi_2^c(t) = rF_2^c(t) - (d/dt)F_2^c(t)$ is continuous and strictly decreasing because F_2^c is continuously differentiable, strictly decreasing, and strictly convex (see Assumption 1a).

If $\lim_{t\to\infty}\psi_2^c(t) \geqslant D_2^c$ then for any $t_2^c \in [0,\infty)$ we have $-D_2^c + \psi_2^c(t_2^c) > -D_2^c + \lim_{t\to\infty}\psi_2^c(t) \geqslant 0$. It follows that $(d/dt_2^c)\Pi_2(t_2^c, \hbar)$ in Eq. (2) is always positive. That is, $\Pi_2(t_2^c, \hbar)$ is strictly increasing in t_2^c. For any $t_2^c \in [0,\infty)$ we have $\Pi_2(t_2^c, \hbar) < \lim_{t\to\infty}\Pi_2(t, \hbar) = 0$. Meanwhile, $\Pi_2(\hbar, \hbar) = 0$. Therefore, $t_2^c = \hbar$ maximizes the entrant's profit when $\lim_{t\to\infty}\psi_2^c(t) \geqslant D_2^c$.

If $\lim_{t\to\infty}\psi_2^c(t) < D_2^c$ then the continuity and monotonicity of ψ_2^c imply that either $\psi_2^c(t_2^c) < D_2^c$ for any $t_2^c \in [0,\infty)$ or there exists a unique $t_2^c \in [0,\infty)$ such that $\psi_2^c(t_2^c) = D_2^c$.

When $\psi_2^c(t_2^c) < D_2^c$ for any $t_2^c \in [0,\infty)$ we have $(d/dt_2^c)\Pi_2(t_2^c, \hbar) < 0$. That is, Π_2 is strictly decreasing. Hence, Π_2 is maximized at $t_2^c = 0 = \min\{t|\psi_2^c(t) \leqslant D_2^c\} = \tau_2^{ch}$. So, τ_2^{ch} is the maximizer of Π_2 when $\psi_2^c(t_2^c) < D_2^c$ for any $t_2^c \in [0,\infty)$. On the other hand, when there exists a unique $t_2^c \in [0,\infty)$ such that $\psi_2^c(t_2^c) = D_2^c$, we know that $\psi_2^c(\tau_2^{ch}) = D_2^c$ from the definition of τ_2^{ch}. Due to the monotonicity of ψ_2^c, we have

$$\psi_2^c(t_2^c)\begin{cases} > D_2^c & \text{if } t_2^c < \tau_2^{ch}; \\ = D_2^c & \text{if } t_2^c = \tau_2^{ch}; \text{ and, thus,} \\ < D_2^c & \text{if } t_2^c > \tau_2^{ch}; \end{cases}$$

$$\frac{d}{dt_2^c}\Pi_2(t_2^c, \hbar) = -D_2^c + \psi_2^c(\tau_2^{ch})\begin{cases} > 0 & \text{if } t_2^c < \tau_2^{ch}; \\ = 0 & \text{if } t_2^c = \tau_2^{ch}; \\ < 0 & \text{if } t_2^c > \tau_2^{ch}. \end{cases}$$

Hence, τ_2^{ch} is the maximizer of the entrant's profit when there exists a unique $t_2^c \in [0,\infty)$ such that $\psi_2^c(t_2^c) = D_2^c$. This completes the proof of the lemma. □

Proof of Lemma 2. The derivations are the same as those in the proof of Lemma 1 except that the current generation is replaced by the next generation. That is, F_2^c in the proof of Lemma 1 is replaced by F_2^n, D_2^c is replaced by D_2^n, and τ_2^{ch} is replaced by τ_2^{hn}. □

Proof of Lemma 3. Note that $\psi_2^\delta(\Delta) = rF_2^\delta(\Delta) - (d/d\Delta)F_2^\delta(\Delta)$ is continuous and strictly decreasing in Δ because F_2^δ is continuously differentiable, strictly decreasing, and strictly convex in Δ (see Assumption 1b). Hence, $D_2^c - D_2^n + \psi_2^\delta(\Delta)$ is also continuous and strictly decreasing in Δ. The rest of the derivations are the same as those in the proof of Lemma 1 except that $F_2^c(t_2^c)$ is replaced by $F_2^\delta(\Delta)$, D_2^c by $D_2^n - D_2^c$, and $\psi_2^c(t_2^c)$ by $\psi_2^\delta(\Delta)$. □

Proof of Lemma 4. Lemma 3shows that δ^* is well defined because $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) < D_2^n - D_2^c$.

- When $\delta^* = 0$, based on Lemma 3 we note that $\Pi_2(t_2^c, t_2^c) > \Pi_2(t_2^c, t_2^c + \Delta)$ for any $\Delta \in (0,\infty)$. Meanwhile,

$$
\begin{aligned}
\Pi_2(t_2^c, t_2^c) &= \lim_{\gamma\to 0}\Pi_2(t_2^c, t_2^c+\gamma)\\
&= \lim_{\gamma\to 0}\left\{\int_{t_2^c}^{t_2^c+\gamma} D_2^c\, e^{-rs}\, ds + \int_{t_2^c+\gamma}^{\infty} D_2^n\, e^{-rt_2^n} - F_2^c(t_2^c)\, e^{-rt_2^c} - F_2^\delta(\gamma)\, e^{-r(t_2^c+\gamma)}\right\}\\
&= \int_{t_2^c}^{\infty} D_2^n\, e^{-rt_2^n} - (F_2^c(t_2^c) + F_2^\delta(0))\, e^{-rt_2^c}\\
&= \int_{t_2^c}^{\infty} D_2^n\, e^{-rs}\, ds - F_2^n(t_2^c)\, e^{-rt_2^c} \text{ (based on Assumption 2)}\\
&= \Pi_2(\hbar, t_2^c).
\end{aligned} \tag{10}
$$

We have $\Pi_2(\hbar, t_2^c) = \Pi_2(t_2^c, t_2^c) > \Pi_2(t_2^c, t_2^n)$ for any $t_2^c \in [0,\infty)$ and any $t_2^n \in (t_2^c,\infty)$. Therefore, any decision to launch both generations of the product (i.e., $(t_2^c, t_2^n) \in [0,\infty) \times [t_2^c,\infty)$) is dominated by the maximizer of $\Pi_2(\hbar, t_2^n)$ over the region: $t_2^n \in [0,\infty) \cup \{\hbar\}$. This completes the proof of part (i) of the lemma.

- When $\delta^* > 0$ and $\lim_{t\to\infty}\psi_2^c(t) \geqslant D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, for any $t_2^c \in [0,\infty)$ we have $e^{-rt_2^c}(-D_2^c + \psi_2^c(t_2^c) + e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)) > 0$ because $\psi_2^c(t)$ is strictly decreasing in t for any $t \in [0,\infty)$. Consequently, for any $t_2^c \in [0,\infty)$, $(d/dt_2^c)\Pi_2(t_2^c, t_2^c+\delta^*) > 0$ and, hence, $\Pi_2(t_2^c, t_2^c+\delta^*)$ is strictly increasing in t_2^c. The continuity of $\Pi_2(t_2^c, t_2^c+\delta^*)$ further implies that $\lim_{t\to\infty}\Pi_2(t, t+\delta^*) > \Pi_2(t_2^c, t_2^c+\delta^*)$ for any $t_2^c \in [0,\infty)$.Lemma 3 shows that $\Pi_2(t_2^c, t_2^c+\delta^*) > \Pi_2(t_2^c, t_2^n)$ for $(t_2^c, t_2^n) \in [0,\infty) \times [t_2^c,\infty)$ as long as $t_2^n \neq t_2^c + \delta^*$. Meanwhile, $\Pi_2(\hbar,\hbar) = 0 = \lim_{t\to\infty}\Pi_2(t, t+\delta^*)$. Hence, any decision to launch both generations (i.e., $(t_2^c, t_2^n) \in [0,\infty)\times[t_2^c,\infty)$) is dominated by $(t_2^c, t_2^n) = (\hbar,\hbar)$. This completes the proof of part (ii) of the lemma.
- When $\delta^* > 0$ and $\lim_{t\to\infty}\psi_2^c(t) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, we further examine two possibilities: $\psi_2^c(0) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, or $\psi_2^c(0) \geqslant D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$.
If $\psi_2^c(0) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, then $-D_2^c + \psi_2^c(t_2^c) + e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*) < 0$ for any $t_2^c \in [0,\infty)$ because $\psi_2^c(t)$ is strictly decreasing in t. Hence, we have $(d/dt_2^c)\Pi_2(t_2^c, t_2^c+\delta^*) < 0$. For any $t_2^c \in (0,\infty)$ we have $\Pi_2(0,\delta^*) > \Pi_2(t_2^c, t_2^c+\delta^*) > \lim_{t\to\infty}\Pi_2(t, t+\delta^*) = \Pi_2(\hbar,\hbar)$. Meanwhile, $\tau_2^{c\delta} = 0$ when $\psi_2^c(0) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$. So, $\Pi_2(\tau_2^{c\delta}, \tau_2^{c\delta}+\delta^*) = \Pi_2(0,\delta^*) > \Pi_2(t_2^c, t_2^c+\delta^*)$ for any $t_2^c \in (0,\infty) \cup \{\hbar\}$.
If $\psi_2^c(0) \geqslant D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, then, by the definition of $\tau_2^{c\delta}$ in the lemma and the monotonicity of $\psi_2^c(t)$, we have

$$
\psi_2^c(\tau_2^{c\delta})\begin{cases} > D_2^c - e^{-r\delta^*}\frac{d}{d\Delta}F_2^\delta(\delta^*) & \text{if } t_2^c < \tau_2^{c\delta};\\ = D_2^c - e^{-r\delta^*}\frac{d}{d\Delta}F_2^\delta(\delta^*) & \text{if } t_2^c = \tau_2^{c\delta};\\ < D_2^c - e^{-r\delta^*}\frac{d}{d\Delta}F_2^\delta(\delta^*) & \text{if } t_2^c > \tau_2^{c\delta}.\end{cases}
$$

Applying Eq. (5) we have $(d/dt_2^c)\Pi_2(t_2^c, t_2^c+\delta^*)$ is positive if $t_2^c < \tau_2^{c\delta}$; negative if $t_2^c > \tau_2^{c\delta}$; and zero otherwise. Note that $\Pi_2(\hbar,\hbar) = \lim_{t\to\infty}\Pi_2(t, t+\delta^*)$. Therefore, for any $(t_2^c, t_2^n) \in \{[0,\infty)\times[t_2^c,\infty)\} \cup \{(\hbar,\hbar)\}$, we have $\Pi_2(\tau_2^{c\delta}, \tau_2^{c\delta}+\delta^*) > \Pi_2(t_2^c, t_2^n)$ as long as $(t_2^c, t_2^n) \neq (\tau_2^{c\delta}, \tau_2^{c\delta}+\delta^*)$.

This completes the proof of the lemma. □

Proof of Proposition 1. We examine three cases based on the value of $D_2^n - D_2^c$.

- When $D_2^n - D_2^c \leqslant \lim_{\Delta\to\infty}\psi_2^\delta(\Delta)$, $\Pi_2(t_2^c, t_2^n) < \Pi_2(t_2^c, \hbar)$ for any $(t_2^c, t_2^n) \in [0,\infty)\times[t_2^c,\infty)$ from Lemma 3. In particular, $\Pi_2(t_2^c,\hbar) > \Pi_2(t_2^c, t_2^c) = \Pi_2(\hbar, t_2^c)$ with the last equality following from Eq. (10). Now the entrant's profit maximization is reduced to maximizing $\Pi_2(t_2^c,\hbar)$ over the region $[0,\infty)\cup\{\hbar\}$ for t_2^c. From Lemma 1 we know that $\Pi_2(t_2^c,\hbar)$ is maximized by $t_2^c = \tau_2^{c\hbar}$ if $\lim_{t\to\infty}\psi_2^c(t) < D_2^c$, and by $t_2^c = \hbar$ otherwise.
- When $\psi_2^\delta(0) \leqslant D_2^n - D_2^c$, we have $\delta^* = 0$ from Lemma 3. Applying Lemma 4, we know that any $(t_2^c, t_2^n) \in [0,\infty)\times[t_2^c,\infty)$ is dominated by the maximizer of $\Pi_2(\hbar, t_2^n)$ over the region $[0,\infty)\cup\{\hbar\}$ for t_2^n. The equality $\delta^* = 0$ also implies that $\Pi_2(t_2^c, t_2^c) > \Pi_2(t_2^c,\hbar)$ (from Lemma 3). Now, the entrant's profit maximization is reduced to maximizing $\Pi_2(\hbar, t_2^n)$ over the region $[0,\infty)\cup\{\hbar\}$ for t_2^n. From Lemma 2 we know that $\Pi_2(\hbar, t_2^n)$ is maximized by $t_2^n = \tau_2^{\hbar n}$ if $\lim_{t\to\infty}\psi_2^n(t) < D_2^n$, and by$t_2^n = \hbar$ otherwise.
- When $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) < D_2^n - D_2^c < \psi_2^\delta(0)$, we have $\delta^* > 0$ from Lemma 3. That is, $\Pi_2(t_2^c, t_2^c+\delta^*) > \Pi_2(t_2^c, t_2^c) = \Pi_2(\hbar, t_2^c)$ and $\Pi_2(t_2^c, t_2^c+\delta^*) > \Pi_2(t_2^c,\hbar)$ for any $t_2^c \in [0,\infty)$. So, the entrant's profit is maximized by either $(t_2^c, t_2^n) = (\hbar,\hbar)$ or the maximizer of $\Pi_2(t_2^c, t_2^c+\delta^*)$ over the region: $t_2^c \in [0,\infty)$. Applying Lemma 4 we conclude that the entrant's profit is maximized by $(t_2^c, t_2^n) = (\tau_2^{c\delta}, \tau_2^{c\delta}+\delta^*)$ if $\lim_{t\to\infty}\psi_2^c(t) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$, and by $(t_2^c, t_2^n) = (\hbar,\hbar)$ otherwise.

Combining the above three cases, we obtain the necessary and sufficient conditions for the entrant's optimal timing decisions.

Below we show that $\tau_2^{c\delta} \leqslant \tau_2^{c\hbar}$ is satisfied. The condition that $\lim_{t\to\infty}\psi_2^c(t) < D_2^c$ implies that $\tau_2^{c\hbar}$ is well defined (from Lemma 1). Note that $-e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$ is positive because

F_2^δ is strictly decreasing in Δ (Assumption 1b). If $\tau_2^{ch}>0$, from the definition of τ_2^{ch} in Lemma 1, we have $\psi_2^c(\tau_2^{ch}) = D_2^c < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$. Since ψ_2^c is continuous, there exists an $\varepsilon>0$ such that $\psi_2^c(\tau_2^{ch}-\varepsilon)<D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$.We also have $\psi_2^c(\tau_2^{c\delta}) = \min\{t|\psi_2^c(t)\leqslant D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)\}$ from the definition of $\tau_2^{c\delta}$ in Lemma 4. Since ψ_2^c is strictly decreasing, we know that $\tau_2^{c\delta}<\tau_2^{ch}$ if $\tau_2^{ch}>0$. Similarly, we can show that $\tau_2^{c\delta}=0$ if $\tau_2^{ch}=0$. Hence, we have $\tau_2^{c\delta}\leqslant\tau_2^{ch}$. This completes the proof of the proposition. □

Proof of Corollary 1. There are three possible entry times: $\tau_2^{c\delta}$, τ_2^{ch} and τ_2^{hn}. From Lemmas 1, 2 and 4, we know that determining these entry times is essentially comparing the following pairs: $\psi_2^c(t)$ vs D_2^c, $\psi_2^n(t)$ vs D_2^n, and $\psi_2^c(t)$ vs $D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$. Meanwhile, $\psi_2^n(t) = \psi_2^c(t) + rF_2^\delta(0)$ because $F_2^n(t) = F_2^\delta(0) + F_2^c(t)$ from Assumption 2, $\psi_2^n(t) = rF_2^n(t) - (d/dt)F_2^n(t)$ from Lemma 2, and $\psi_2^c(t) = rF_2^c(t) - (d/dt)F_2^c(t)$ from Lemma 1. The comparisons break down to $\psi_2^c(t)$ vs D_2^c, $D_2^n - rF_2^\delta(0)$, and $D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$. By replacing $F_2^c(t)$ with $F_2^c(t)-\varepsilon$, we are replacing $\psi_2^c(t)$ with $\psi_2^c(t) - r\varepsilon$. Given the decreasing trend of $\psi_2^c(t)$, we know that replacing $\psi_t^c(t)$ with $\psi_2^c(t) - r\varepsilon$ results in a smaller τ_2^{ch}, τ_2^{hn} and $\tau_2^{c\delta}$ if these times are well defined.

From Proposition 1, we know that as long as $\lim_{t\to\infty}\psi_2^c(t)<D_2^c$, $\lim_{t\to\infty}\psi_2^n(t)<D_2^n$, and $\lim_{t\to\infty}\psi_2^c(t)<D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$ all hold, the entrant will enter the market regardless of the value of $D_2^n - D_2^c$. Having the three inequalities hold is equivalent to having the inequality $\lim_{t\to\infty}\psi_2^c(t)<\min\{D_2^c, D_2^n - rF_2^\delta(0)\}$ hold. Replacing $F_t^c(t)$ with $F_2^c(t)-\varepsilon$ also means replacing $\lim_{t\to\infty}\psi_2^c(t)$ with $\lim_{t\to\infty}\psi_2^c(t) - r\varepsilon$. It is clear that if a pair of D_2^c and D_2^n satisfies $\lim_{t\to\infty}\psi_2^c(t)<\min\{D_2^c, D_2^n - rF_2^\delta(0)\}$, they must also satisfy $\lim_{t\to\infty}\psi_2^c(t) - r\varepsilon<\min\{D_2^c, D_2^n - rF_2^\delta(0)\}$, but not vice versa. This completes the proof of the corollary. □

Proof of Proposition 2. Since $\psi_1^n(t) = rF_1^n(t) - (d/dt)F_1^n(t)$ is continuous and strictly decreasing (from Assumption 1a), we have $\lim_{t\to\infty}\psi_1^n(t)<\psi_1^n(t_1^n)<\psi_1^n(0)$ for any $t_1^n\in(0,\infty)$.

When $\lim_{t\to\infty}\psi_1^n(t)\geqslant M^n - M^c$, $\psi_1^n(t_1^n)>M^n - M^c$ for any $t_1^n\in[0,\infty)$. That is, the first order derivative in Eq. (7) is positive for any $t_1^n\in[0,\infty)$. Therefore, we have $\Pi_1(\hbar,\hbar,\hbar) = \lim_{t\to\infty}\Pi_1(t,\hbar,\hbar)>\Pi_1(t_1^n,\hbar,\hbar)$ for any $t_1^n\in[0,\infty)$. Hence, the incumbent is better off never upgrading. This completes the proof of part (i) of the proposition.

When $\psi_1^n(0)\leqslant M^n - M^c$, we know from the first order derivative in Eq. (7) that $\Pi_1(0,\hbar,\hbar)>\Pi_1(t_1^n,\hbar,\hbar)>\lim_{t\to\infty}\Pi_1(t,\hbar,\hbar) = \Pi_1(\hbar,\hbar,\hbar)$ for any $t_1^n\in(0,\infty)$. That is, $t_1^n=0$ maximizes the incumbent's profit. Since $\tau_1^m=0$ here, we conclude that $t_1^n=\tau_1^m$ is the maximizer of the incumbent's profit.

When $\lim_{t\to\infty}\psi_1^n(t)<M^n - M^c<\psi_1^n(0)$, we know from the definition of τ_1^m that $\tau_1^m>0$. Furthermore, we know

$$\psi_1^n(t_1^n)\begin{cases} >M^n - M^c & \text{if } t_1^n<\tau_1^m; \\ =M^n - M^c & \text{if } t_1^n=\tau_1^m; \\ <M^n - M^c & \text{if } t_1^n>\tau_1^m; \end{cases} \text{ and, thus,}$$

$$\frac{d}{dt_1^n}\Pi_1(t_1^n,\hbar,\hbar)\begin{cases} >0 & \text{if } t_1^n<\tau_1^m; \\ =0 & \text{if } t_1^n=\tau_1^m; \\ <0 & \text{if } t_1^n>\tau_1^m. \end{cases}$$

We, therefore, conclude that $t_1^n=\tau_1^m$ is the unique maximizer of the incumbent's profit when $\lim_{t\to\infty}\psi_1^n(t)<M^n - M^c$. This completes the proof of part (ii) of the proposition. □

Proof of Lemma 5. When $\lim_{t\to\infty}\psi_1^n(t)<D_1^n - D_1^c<M^n - M^c$, τ_1^d and τ_1^m are well defined. If $\tau_1^d=0$, then $\psi_1^n(0)\leqslant D_1^n - D_1^c<M^n - M^c$. In this case, $\tau_1^m=0=\tau_1^d$. On the other hand, if $\tau_1^d>0$, then $\psi_1^n(\tau_1^d) = D_1^n - D_1^c<M^n - M^c$. Given the continuity and monotonicity of ψ_1^n, we know that there exists an $\varepsilon>0$ such that $\psi_1^n(\tau_1^d-\varepsilon)\leqslant M^n - M^c$. Therefore, $\tau_1^m = \min\{t|\psi_1^n(t)\leqslant M^n - M^c\}\leqslant\tau_1^d-\varepsilon<\tau_1^d$. This completes the proof of the lemma. □

Proof of Proposition 3. Consider scenarios where $(t_2^c,t_2^n)\neq(\hbar,\hbar)$. Namely $\tilde{t}_2$ is well defined. From $D_1^n - D_1^c<M^n - M^c$ we have $\tau_1^m\leqslant\tau_1^d$ (see Lemma 5).

- Consider the case where $M^n - M^c\leqslant\lim_{t\to\infty}\psi_1^n(t)$.

$$\frac{d}{dt_1^n}\Pi_1(t_1^n,t_2^c,t_2^n) = \begin{cases} e^{-rt_1^n}(M^c - M^n + \psi_1^n(t_1^n))>0 & \text{if } t_1^n\in[0,\tilde{t}_2); \\ e^{-rt_1^n}(D_1^c - D_1^n + \psi_1^n(t_1^n))>0 & \text{if } t_1^n\in(\tilde{t}_2,\infty). \end{cases}$$

  The above inequalities imply that $t_1^n=\tilde{t}_2$ maximizes Π_1 on $[0,\tilde{t}_2]$, and $\Pi_1(\hbar,t_2^c,t_2^n) = \lim_{t\to\infty}\Pi_1(t,t_2^c,t_2^n)>\Pi_1(t_1^n,t_2^c,t_2^n)$ for $t_1^n\in[\tilde{t}_2,\infty)$. We can then conclude that $t_1^n=\hbar$ is the unique maximizer of the incumbent's profit when $M^n - M^c\leqslant\lim_{t\to\infty}\psi_1^n(t)$. This completes the proof of part (i) of the proposition.
- Consider the case where $D_1^n - D_1^c\leqslant\lim_{t\to\infty}\psi_1^n(t)<M^n - M^c$. We use the notation $\wedge$ to denote the operation of choosing a smaller number, and the notation $\vee$ to denote the operation of choosing a larger number.

$$\frac{d}{dt_1^n}\Pi_1(t_1^n,t_2^c,t_2^n) = \begin{cases} e^{-rt_1^n}(M^c - M^n + \psi_1^n(t_1^n))>0 & \text{if } t_1^n\in[0,\tau_1^m\wedge\tilde{t}_2); \\ e^{-rt_1^n}(M^c - M^n + \psi_1^n(t_1^n))=0 & \text{if } t_1^n=\tau_1^m<\tilde{t}_2; \\ e^{-rt_1^n}(M^c - M^n + \psi_1^n(t_1^n))<0 & \text{if } t_1^n\in(\tau_1^m\wedge\tilde{t}_2,\tilde{t}_2); \\ e^{-rt_1^n}(D_1^c - D_1^n + \psi_1^n(t_1^n))>0 & \text{if } t_1^n\in(\tilde{t}_2,\infty). \end{cases}$$

  Therefore, $\Pi_1(\hbar,t_2^c,t_2^n) = \lim_{t\to\infty}\Pi_1(t,t_2^c,t_2^n)>\Pi_1(t_1^n,t_2^c,t_2^n)$ for $t_1^n\in[\tilde{t}_2,\infty)$. Furthermore, if $\tilde{t}_2\leqslant\tau_1^m$ then $t_1^n=\tilde{t}_2$ maximizes Π_1 on $[0,\tilde{t}_2]$. In this case, $t_1^n=\hbar$ is the overall maximizer of the incumbent's profit.
  If $\tau_1^m<\tilde{t}_2$ then $t_1^n=\tau_1^m<\tilde{t}_2$ maximizes Π_1 on $[0,\tilde{t}_2]$. In the latter case, the incumbent's profit is maximized by either $t_1^n=\tau_1^m$ or $t_1^n=\hbar$.This completes the proof of part (ii) of the proposition.
- Consider the case where $\lim_{t\to\infty}\psi_1^n(t)<D_1^n - D_1^c$.

$$\frac{d}{dt_1^n}\Pi_1(t_1^n,t_2^c,t_2^n) = \begin{cases} e^{-rt_1^n}(M^c - M^n + \psi_1^n(t_1^n))>0 & \text{if } t_1^n\in[0,\tau_1^m\wedge\tilde{t}_2); \\ e^{-rt_1^n}(M^c - M^n + \psi_1^n(t_1^n))=0 & \text{if } t_1^n=\tau_1^m<\tilde{t}_2; \\ e^{-rt_1^n}(M^c - M^n + \psi_1^n(t_1^n))<0 & \text{if } t_1^n\in(\tau_1^m\wedge\tilde{t}_2,\tilde{t}_2); \\ e^{-rt_1^n}(D_1^c - D_1^n + \psi_1^n(t_1^n))>0 & \text{if } t_1^n\in(\tilde{t}_2,\tilde{t}_2\vee\tau_1^d); \\ e^{-rt_1^n}(D_1^c - D_1^n + \psi_1^n(t_1^n))=0 & \text{if } t_1^n=\tau_1^d>\tilde{t}_2; \\ e^{-rt_1^n}(D_1^c - D_1^n + \psi_1^n(t_1^n))<0 & \text{if } t_1^n\in(\tilde{t}_2\vee\tau_1^d,\infty). \end{cases}$$

Recall that $\tau_1^m \leqslant \tau_1^d$. We examine three subcases below.
If $\tilde{t}_2 \leqslant \tau_1^m$, $t_1^n = \tilde{t}_2$ maximizes Π_1 on $[0, \tilde{t}_2]$, $t_1^n = \tau_1^d$ maximizes $[\tilde{t}_2, \infty)$ on $[\tilde{t}_2, \infty)$, and $\Pi_1(\tau_1^d, t_2^c, t_2^n) > \Pi_1(t_1^n, t_2^c, t_2^n) > \lim_{t\to\infty}\Pi_1(t, t_2^c, t_2^n) = \Pi_1(\hbar, t_2^c, t_2^n)$ for $t_1^n > \tau_1^d$. Firm 1's profit is then maximized by $t_1^n = \tau_1^d$.
If $\tau_1^d \leqslant \tilde{t}_2, t_1^n = \tau_1^m$ maximizes Π_1 on $[0, \tilde{t}_2]$, and $\Pi_2(\tilde{t}_2, t_2^c, t_2^n) > \Pi_2(t_1^n, t_2^c, t_2^n) > \lim_{t\to\infty}\Pi_1(t, t_2^c, t_2^n) = \Pi_1(\hbar, t_2^c, t_2^n)$ for any $t_1^n > \tilde{t}_2$. Firm 1's profit is then maximized by $t_1^n = \tau_1^m$.
If $\tau_1^m < \tilde{t}_2 < \tau_1^d$, $t_1^n = \tau_1^m$ maximizes Π_1 on $[0, \tilde{t}_2]$, $t_1^n = \tau_1^d$ maximizes $[\tilde{t}_2, \infty)$ on $[\tilde{t}_2, \infty)$,and $\Pi_1(\tau_1^d, t_2^c, t_2^n) > \Pi_1(t_1^n, t_2^c, t_2^n) > \lim_{t\to\infty}\Pi_1(t, t_2^c, t_2^n) = \Pi_1(\hbar, t_2^c, t_2^n)$ for $t_1^n > \tau_1^d$. In this case, either $t_1^n = \tau_1^m$ or $t_1^n = \tau_1^d$ maximizes the incumbent's profit.

This completes the proof of the proposition. □

Proof of Corollary 2. When the entrant's arrival is certain (i.e., $\tilde{t}_2$ is well defined), the entrant's decisions affect the incumbent's profit through $\tilde{t}_2$. We, therefore, express the incumbent's profit as a function of t_1^n and $\tilde{t}_2$.

On Region (II), $(t_1^n)^{opt}$ is either τ_1^m or τ_1^d. We need to show that the difference, $\Pi_1(\tau_1^m, \tilde{t}_2) - \Pi_1(\tau_1^d, \tilde{t}_2)$, increases with $\tilde{t}_2$. We have $\tau_1^m < \tilde{t}_2 < \tau_1^d$ on Region (II). So,

$$\Pi_1(\tau_1^m, \tilde{t}_2) = \int_0^{\tau_1^m} M^c\, e^{-rs}\, ds + \int_{\tau_1^m}^{\tilde{t}_2} M^n\, e^{-rs}\, ds + \int_{\tilde{t}_2}^{\infty} D_1^n\, e^{-rs}\, ds - F_1^n(\tau_1^m)\, e^{-r\tau_1^m}$$

and

$$\Pi_1(\tau_1^d, \tilde{t}_2) = \int_0^{\tilde{t}_2} M^c\, e^{-rs}\, ds + \int_{\tilde{t}_2}^{\tau_1^d} D_1^c\, e^{-rs}\, ds + \int_{\tau_1^d}^{\infty} D_1^n\, e^{-rs}\, ds - F_1^n(\tau_1^d)\, e^{-r\tau_1^d}.$$

Consequently,

$$\begin{aligned}\Pi_1(\tau_1^m, \tilde{t}_2) - \Pi_1(\tau_1^d, \tilde{t}_2) &= \int_{\tau_1^m}^{\tilde{t}_2} (M^n - M^c)\, e^{-rs}\, ds + \int_{\tilde{t}_2}^{\tau_1^d} (D_1^n - D_1^c)\, e^{-rs}\, ds + x(\tau_1^m, \tau_1^d)\\ &= \frac{1}{r}\, e^{-r\tilde{t}_2}[D_1^n - D_1^c - (M^n - M^c)] + y(\tau_1^m, \tau_1^d),\end{aligned}$$

where both $x(\tau_1^m, \tau_1^d)$ and $y(\tau_1^m, \tau_1^d)$ are functions independent of $\tilde{t}_2$. Since $D_1^n - D_1^c < M^n - M^c$, we know that the larger $\tilde{t}_2$ is, the larger $\Pi_1(\tau_1^m, \tilde{t}_2) - \Pi_1(\tau_1^d, \tilde{t}_2)$ is, the more the incumbent prefers the upgrade time τ_1^m.

Similarly, on Region (III) we can show that $\Pi_1(\tau_1^m, \tilde{t}_2) - \Pi_1(\hbar, \tilde{t}_2)$ increases with $\tilde{t}_2$. Since $(t_1^n)^{opt}$ is either τ_1^m or $\hbar$ on Region (III), the proof of the corollary is completed. □

Proof of Proposition 4. There are two cases in which the entrant launches the next generation product: $(t_2^c, t_2^n)^{opt} = (\hbar, \tau_2^{\hbar n})$ or $(t_2^c, t_2^n)^{opt} = (\tau_2^{c\delta}, \tau_2^{c\delta} + \delta^*)$.

If $(t_2^c, t_2^n)^{opt} = (\hbar, \tau_2^{\hbar n})$ then $\psi_2^\delta(0) \leqslant D_2^n - D_2^c$ and $\lim_{t\to\infty}\psi_2^n(t) < D_2^n$ from Proposition 1. So, we have $\psi_1^n(0) \leqslant \psi_2^\delta(0) \leqslant D_2^n - D_2^c = D_1^n - D_1^c < M^n - M^c$.

By the definition of τ_1^m and τ_1^d, we know that $\tau_1^m = \tau_1^d = 0$ and $(t_1^n)^{opt} = 0$ in this case. Therefore, the entrant's launch time of the next generation product $\tau_2^{\hbar n}$ cannot be earlier than the incumbent's launch time of the same generation product.

If$(t_2^c, t_2^n)^{opt} = (\tau_2^{c\delta}, \tau_2^{c\delta} + \delta^*)$ then $\lim_{\Delta\to\infty}\psi_2^\delta(\Delta) < D_2^n - D_2^c < \psi_2^\delta(0)$ and $\lim_{t\to\infty}\psi_2^c(t) < D_2^c - e^{-r\delta^*}(d/d\Delta)F_2^\delta(\delta^*)$ from Proposition 1. So, we have $\psi_1^n(\delta^*) \leqslant \psi_2^\delta(\delta^*) = D_2^n - D_2^c = D_1^n - D_1^c < M^n - M^c$.

By the definition of τ_1^m and τ_1^d, we know that $\tau_1^m \leqslant \tau_1^d = \delta^*$ and the incumbent's optimal launch time of the next generation product is either τ_1^m or τ_1^d. So, the entrant's launch time of the next generation product: $\tau_2^{c\delta} + \delta^*$ cannot be earlier than the incumbent's launch time of the same generation product. This completes the proof of the proposition. □

References

Bohlmann, J., Golder, P., Mitra, D., 2002. Deconstructing the pioneer's advantage: examining vintage effects and consumer valuations of quality and variety. Management Science 48, 1175–1195.

Boulding, W., Christen, M., 2003. Sustainable pioneering advantage? Profit implications of market entry order. Marketing Science 22, 371–392.

Chung, K., Tsou, C., 1998. Analysis and algorithm for the optimal investment times of new manufacturing technologies in a duopoly. European Journal of Operational Research 109, 632–645.

Doraszelski, U., 2004. Innovations, improvements, and the optimal adoption of new technologies. Journal of Economic Dynamics & Control 28, 1461–1480.

Farzin, Y., Huisman, K., Kort, P., 1998. Optimal timing of technology adoption. Journal of Economic Dynamics & Control 22, 779–799.

Filippini, L., 1999. Leapfrogging in a vertical product differentiation model. International Journal of the Economics of Business 6, 245–256.

Fudenberg, D., Tirole, J., 1985. Preemption and rent equalization in the adoption of new technology. Review of Economic Studies LII, 383–401.

Hammonds, K., 1990. How a $4 razor ends up costing $300 million. Business Week January 29, 62–63.

Hoppe, H., 2002. The timing of new technology adoption: theoretical models and empirical evidence. The Manchester School 70, 56–76.

Huisman, K., Kort, P., 2003. Strategic investment in technological innovations. European Journal of Operational Research 144, 209–223.

Jensen, R., 1982. Adoption and diffusion of an innovation of uncertain profitability. Journal of Economic Theory 27, 182–193.

Jensen, R., 1988. Information cost and innovation adoption policies. Management Science 34, 230–239.

Kyle, M., 2006. The role of firm characteristics in pharmaceutical product launches. The Rand Journal of Economics 37, 602–618.

Lieberman, M., Montgomery, D., 1998. First-mover (dis)advantages: retrospective and link with the resource-based view. Strategic Management Journal 19, 1111–1125.

Lin, P., Saggi, K., 2002. Timing of entry under externalities. Journal of Economics 75, 211–225.

Mamer, J., McCardle, K., 1987. Uncertainty, competition, and the adoption of new technology. Management Science 33, 161–177.

McCardle, K., 1985. Information acquisition and the adoption of new technology. Management Science 31, 1372–1389.

Moorthy, K., Png, I., 1992. Market segmentation, cannibalization, and the timing of product introductions. Management Science 38, 345–359.

Narasimhan, C., Zhang, Z., 2000. Market entry strategy under firm heterogeneity and asymmetric payoffs. Marketing Science 19, 313–327.

Ofek, E., Sarvary, M., 2003. R&D, marketing, and the success of next-generation products. Marketing Science 22, 355–370.

Rahman, A., Loulou, R., 2001. Technology acquisition with technological progress: effects of expectations, rivalry and uncertainty. European Journal of Operational Research 129, 159–185.

Reinganum, J., 1981. On the diffusion of new technology: a game theoretic approach. Review of Economic Studies 48, 395–405.

Souza, G., 2004. Product introduction decisions in a duopoly. European Journal of Operational Research 152, 745–757.