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Technology Adoption under Asymmetric Market Structure

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Abstract

This paper examines the impact of vertical integration on the timing of adoption of a cost-reducing technology. Combining the technology adoption and vertical relations literatures in a simple duopoly model, I compare the technology adoption patterns under different vertical structures. In particular, the study of the asymmetric case, where one firm is integrated while the other one is separated, allows me to make three main contributions. First, I show that the effect of vertical integration on technology adoption by one firm is influenced significantly by the vertical structure of the other firm. Second, I consider the two main types of technology adoption games under an asymmetric set-up and broaden the understanding of the underlying mechanisms for the solving of such games. Finally, I develop an industrial policy aimed at encouraging firms to adopt the technology at the socially optimal timing.

JEL-Code: L11, L22, L51, O33

Keywords: precommitment game, preemption game, timing of technology adoption, vertical relations, vertical integration

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1 Introduction

The study of innovation and technology patterns is a fundamental area of Industrial Organization. It drives the economic performance of a firm, a market, and more globally, of an economy. These processes are the core mechanisms of some growth models, as well as important features of competition models. Indeed, the competition economist must consider how some regulations and business practices may influence innovation. Such research activities, whether it takes the form of R&D expenses or technology adoption, may allow the consumer to access a product at a better price. Hence, a practice that could have been assessed as anticompetitive according to standard price theories may be reevaluated as beneficial to the consumer if it promotes innovation. In this paper, I explore how the vertical structures of market participants affects the timing of technology adoption. In a market where a new cost-reducing technology is available, how does the vertical structure of the firms affect the adoption patterns?

Such technologies are costly to adopt for the firm, but they allow the adopter to produce its product at a lower cost, which is beneficial to the consumer as it leads to lower prices. Game theorists developed models in order to explain the adoption patterns of such a cost-reducing technology within a market. Reinganum (1981b) and Fudenberg and Tirole (1985) introduced the main two games exploited in the literature of technology adoption; namely, the precommitment game and the preemption game, respectively. Both models start with a symmetric duopoly set-up, and conclude on technology diffusion, whereby firms adopt the technology one after the other. However, the two games use different solution concepts: the precommitment one uses Nash equilibrium while the preemption one uses subgame perfection. Their results differ in terms of pay-off; while there is a first mover advantage in the precommitment game, rent-equalization occurs in the preemption game. The mechanism behind such models rely essentially on the trade-off between adopting early in order to preempt the competitor and adopting later due to the decreasing adoption cost function.

Many papers extended these models to more firms, but almost none of them explored the impact of different vertical structure on such adoption processes. Indeed, the capacity of an upstream firm to invest in a cost-reducing technology surely depends on its relationship with its downstream partner, and the degree of vertical integration definitely has an impact on the incentives to adopt such a technology. To my knowledge, Alipranti et al. (2015) appear to be the only work comparing the timing of technology adoption under input outsourcing and input insourcing, and showing that the presence of a vertical dimension may affect the speed of adoption of a new technology. Since the timing of adoption depends on the increment to profits that the adopter gets from it, integration, affecting such profitability, may accelerate the speed of adoption when the adopter could not capture enough of the gains from adoption when separated, due to the inevitable profit-sharing between upstream and downstream firm.

I exploit many of their model's features and adapt them to an asymmetric set-up. Indeed, Alipranti et al. (2015) only compared a duopoly where either both firms are separated or both are integrated, and the only adoption game they exploited is the precommitment game of Reinganum (1981b). This paper extends their work by considering the asymmetric case where only one firm is vertically integrated, and using both precommitment and preemption game. Taking the vertical structure as exogenous,[1] I evaluate the impact of a single integration on the speed of adoption, and I see how such impact differs from a situation where the competitor is already integrated to a situation where it is separated. In addition, I can tell whether the type of technology adoption game affect these results. Such an investigation matters for competition policy purposes, as the competitive assessment of an integration in this context may be reconsidered and affected by the effect of such vertical merger on the timing of adoption.

In this paper, I use a duopoly model, where two vertical structures compete in quantities. The upstream firm is the technology adopter, so my model extends easily to any producer-retailer relationship. Downstream firms compete *à-la* Cournot, and contract negotiation between upstream and downstream partners occurs according to a Nash bargaining program. The first stage of the game is the technology adoption game, which can be either the precommitment game or the preemption game. I show that integration accelerates adoption whenever the upstream bargaining power is low and the efficiency of the technology is high, which is qualitatively unaffected by the type of adoption game. I highlight two main effects of integration: a *bargaining* effect and a *strategic* effect. The *bargaining* effect stems from the profit-sharing occurring under separation between upstream and downstream partners. When its bargaining power is low, the upstream firm (*i.e.* the adopter) faces some kind of hold-up issue, as it cannot capture the full benefits from its investment in the cost-reducing technology. In such a context, integration allows the adopter to capture the full benefits from the technology adoption. The *strategic* effect comes from the best-response functions of the separated firms. When separated, firms may benefit from a strong competitive advantage by setting a below-cost wholesale price (which is then compensated by the fixed fee) which affects downstream quantities and the response of the competitor. Hence, vertical separation is jointly more profitable for the vertical structure, which is a standard result from Bonanno and Vickers (1988). The study of the asymmetric case allows me to show that these effects of integration on technology adoption substantially depends on the vertical structure of the competitor, an effect not highlighted before.

[1]In this work, I don't discuss the vertical merger decision in itself but its impact on the timing of technology adoption. In another working paper, I investigate the decision to integrate in a similar context.

Also, the exploration of the asymmetric market structure allows me to examine the impact of the type of game explored. My work is among the first ones to have explored the technology adoption games in an asymmetric set-up. Such games are highly intractable, and numerical simulations must be used, but the exploration of such games extend our knowledge on technology adoption patterns. Indeed, the previous literature on technology adoption essentially built up on the assumption of symmetry of the market, which may not fit the reality of many markets. Exploring both preemption and precommitment games in an asymmetric set-up allows me to highlight new intuitions about the solving of these two types of game and their fundamental differences. A first result is that a unique equilibrium may exist under the asymmetric set-up, whereas only multiple symmetric equilibria exist under the symmetric cases. A second result is the fact that for some parameter values, both games yield the same timing of adoption, which is never the case under a symmetric set-up.

Ultimately, I explore an industrial policy implication of this research: how can the policy-maker influence the adoption timing? In fact, in many cases, the firms are rarely choosing the socially optimal timings of adoption; the market generally adopts the technology too late according to consumers' preferences, and too early according to the preferences of the adopter's competitor. The balance of such preferences determines whether the *laissez-faire* adoptions are occurring too late or too early from society's overall perspective. Since adoption timing is determined by its profitability, I develop a taxation scheme that influences the timing of adoption without distorting price and quantities.

This work relates to several literatures. A first one is dedicated to the study of vertical relations and their link with innovation. Indeed, an important branch of vertical relations is dedicated to the non-price strategies of the different agents of a market, and how the vertical structure of this one affects R&D investments. For instance, Stefanadis (1997), Banerjee and Lin (2003), Banerjee and Lin (2003), Buehler and Schmutzler (2008), Chen and Sappington (2010), Faulí-Oller et al. (2011) and Milliou and Pavlou (2013) develop models in which innovation is an extra strategic parameter affected by vertical relations. My work contributes to this literature as it studies both the impact of vertical relations on innovative processes.

This paper relates also to the integration literature. This classical branch of Industrial Organization focuses on the impact of vertical mergers decision both in competitive and innovative terms (*e.g.* Bonanno and Vickers (1988), Salinger (1988), Hart and Tirole (1990), Stefanadis (1997), Riordan (1998), Farrell and Katz (2000), Chen (2001), Brocas (2003), Beladi and Mukherjee (2012), Allain et al. (2014) and Liu (2016)). My paper is a contribution to this literature as it studies the effect of integration in a duopoly set-up in the presence of a cost-reducing technology, in a dynamic framework.

This work is linked to the literature relative to the timing of technology adoption. These articles describe, using game theoretical tools and other economic theories, the determinants of firms' timing choice when adopting a new technology (*e.g.* Reinganum (1981b), Reinganum (1981a), Fudenberg and Tirole (1985), Quirmbach (1986), Hoppe (2000), Cabral (1990), Riordan (1992), Riordan and Salant (1994), Choi and Thum (1998), Ruiz-Aliseda and Zemsky (2006), Milliou and Petrakis (2011) and Allain et al. (2015)). My work fits in this literature as it exploits the same features as technology adoption models, but I introduce vertical structure and asymmetry issues in such a framework.

Finally, this paper relates to the empirical literature that explored the link between innovative investments and vertical structure in many industries: the coal industry (Lane (1991)); the insurance industry (Forman and Gron (2009)); the auto industry (Helper (1995)); the TV industry (Chipty (2001), D'Annunzio (2017)); and the cement industry (Hortaçsu and Syverson (2007)). My contribution is to explore the adoption timings under several vertical structures and different technology adoption games, yielding a set of predictions fitting the reality of various industries.

This paper proceeds as follows. In Section 2, the theoretical framework is introduced. I proceed then by backward induction, solving the quantity competition and the contract negotiation first, for every type of vertical structure of the market (Section 3). The solving for the timing of adoption under precommitment game is presented in Section 4, and the one under the preemption game is presented in Section 5. Finally, policy implications are discussed in Section 6.

2 The Framework

In the following section, the model is described. Much of the notation of this work is taken from Alipranti et al. (2015); our frameworks are very similar, but in this model, the cost-reducing technology is adopted by the upstream firm. While they modeled the relationship between an innovative manufacturer transforming a product from an input provider, this work generalizes the reasoning to a simple producer-retailer framework.

2.1 The Set-Up

I consider a market where there are two upstream firms, U_A and U_B, and two downstream firms, D_A and D_B, selling a homogeneous good. A given upstream firm i faces a marginal cost of production c_i (where $i \in \{A, B\}$), and downstream firms face no costs apart from the contracted two-part tariff. This contract consists of a wholesale price w_i and a fixed fee f_i, determined by a Nash bargaining process, where $\beta \in [0, 1]$ is the bargaining power of the upstream firm. Each upstream manufacturer deals with one downstream firm exclusively, *i.e.* U_A deals with D_A and U_B deals with D_B. This vertical set-up, taken from Bonanno and Vickers (1988), is more tractable than the one with interlocking relationships, and allows us to study a case where there are no foreclosure incentives (nor synergies). The demand for final good is $P(Q) = a - Q = a - q_A - q_B$, where q_i is the quantity produced by downstream firm i. The set-up is represented in Figure 1.

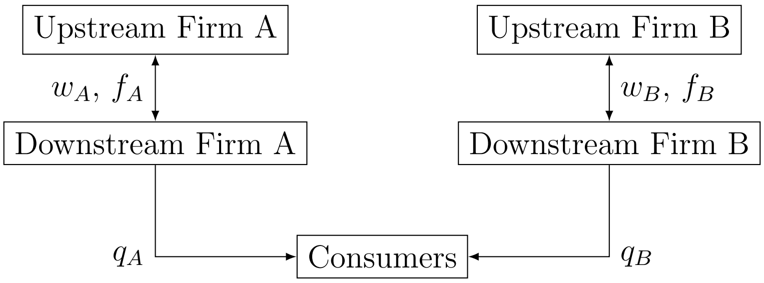


Figure 1: The Set-Up

Time t is continuous and has infinite horizon. At $t = 0$, a new cost-reducing technology is available, and when adopted, it reduces upstream marginal costs by Δ (*i.e.* marginal costs go from c to $c - \Delta$). In addition, the present value of adoption costs $k(t)$ reduces with time. The current cost of adoption $k(t)e^{rt}$ is decreasing but at a decreasing rate, where r is the interest rate.[2]

I make two other standard assumptions. In order to ensure that both vertical structures are active (*i.e.* $q_i > 0$) and that marginal costs remain positive in all cases (*i.e.* $c - \Delta > 0$), the following assumption must hold:

Assumption 1. $M \equiv a - c < \frac{a}{2}$ *and* $\delta \equiv \frac{\Delta}{M} < \frac{1}{2}$

where M is the market capacity (always positive) and δ (always positive) captures how drastic is the innovation, relative to the market capacity.

In order to ensure that adoption occurs at a finite time strictly greater than zero (*i.e.* I want to avoid the situations where adoption occurs immediately or never occurs) and that profit functions are concave, the following assumption must hold:

Assumption 2.

- $(k(t)e^{rt})' < 0$ *and* $(k(t)e^{rt})'' > 0$
- $\lim_{t \to 0} k(t) = -\lim_{t \to 0} k'(t) = +\infty$ *and* $\lim_{t \to \infty} k'(t)e^{rt} = 0$
- $r(\pi^l - \pi^0)e^{-rt} < k''(t)$

[2] These assumptions are standard in the timing of technology adoption literature, see Reinganum (1981b), Fudenberg and Tirole (1985).

2.2 The Timing of the Game

The timing of the game is as follows: at Stage 1, upstream firms U_i (firm i when integrated) decide simultaneously their adoption dates T^i. No other technologies are made available during the rest of the game and firms cannot change their adoption decision.[3] Then, at each $t \geq 0$, each upstream - downstream firm pair bargains simultaneously over the contract terms (Stage 2). Finally, D_A and D_B simultaneously set their quantities (Stage 3). Figure 2 represents the timing of this game.

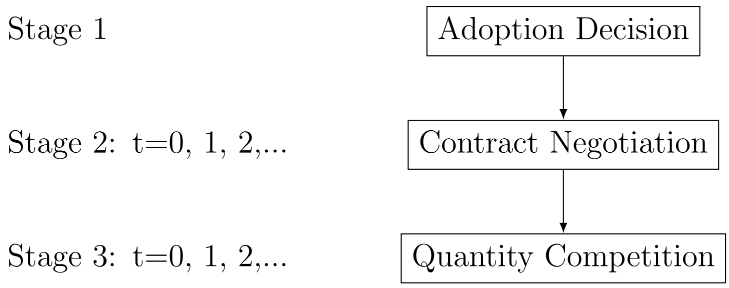


Figure 2: The Timing of the Game

Stage 1 depends on the type of adoption game. Under the precommitment game, Stage 1 occurs at time $t = 0$: firms choose their adoption timing and credibly commit to it for the rest of the game. Under the preemption game, Stage 1 occurs at every period $t > 0$ until adoption, and firms can react immediately to each other's adoption decision. One way to think of the difference between these two types of game is that information lags are infinite under precommitment whereas they are zero under the preemption game.

The vertical structure of the market is determined exogenously. It can take three forms: the vertically separated case (whereby both firms are vertically separated), the vertically integrated case (whereby both firms are vertically integrated), and the asymmetric case (whereby one firm is integrated and the other one is separated). The focus of this work is not on the vertical merger decision[4] but on the market performance in terms of technology adoption depending on its vertical structure. The link with integration will be made when comparing the timing of technology adoption between the symmetric cases and the asymmetric case. Such comparison allows me to discuss the impact of integration on adoption timings when the competitor is separated and when the competitor is integrated.

[3]These are also standard assumptions of the technology adoption literature.

[4]I explore that dimension of the problem in another working paper, as discussed in the conclusion of this paper.

3 Quantity Competition and Contract Negotiation

In this section, I solve the last two steps of the game: the quantity competition and the contract negotiation. I do this for the three different vertical structures that can arise: the vertically separated case (Subsection 3.1), the vertically integrated case (Subsection 3.2) and the asymmetric case (Subsection 3.3).

3.1 The Vertically Separated Case

In this subsection, the two last stages of the game are solved for the case where both firms are vertically separated, as depicted in Figure 1. The subscript i (where $i \in \{A, B\}$) is used throughout this subsection as this is a symmetric case: the identity of the firm does not matter.

During the second stage of every period t, D_i chooses q_i to maximize its gross per-period profits π^{D-}:

$$\pi_i^{D-} = (P(Q) - w_i)q_i = (a - q_i - q_j - w_i)q_i$$

where $j \in \{A, B\}$ and $j \neq i$. The subscript of the profits denote the identity of the vertical structure (A or B) and the superscript denotes the position in this vertical structure (U for upstream, D for downstream). The "-" in the superscript denotes gross profits (*i.e.* without fixed fees). Equilibrium quantity is then:

$$q_i^* = \frac{a - 2w_i + w_j}{3}$$

During the first stage of every period t, w_i and f_i (paid from downstream firm to upstream partner) are determined by maximizing the Nash bargaining problem:

$$\max_{w_i, f_i} \quad (\pi_i^{U-} + f_i)^{\beta}(\pi_i^{D-} - f_i)^{(1-\beta)} \tag{1}$$

where β is the upstream bargaining power.

Solving for f_i and plugging back into (1), one can observe that each upstream firm gets a proportion β of the sum of upstream and downstream gross profits, while the downstream firm gets a proportion $(1 - \beta)$ of same. Therefore, w_i is chosen in order to maximize the sum of the gross profits, and is equal to:

$$w_i^* = \frac{-a + 8c_i - 2c_j}{5}$$

Finally, plugging the equilibrium wholesale price into the quantity and profits equation, one gets:

$$\begin{aligned}
q_i^* &= \frac{2}{5}(a - 3c_i + 2c_j) \\
\pi_i^{U*} &= \beta(\pi_i^{U-} + \pi_i^{D-}) = \frac{2\beta}{25}(a - 3c_i + 2c_j)^2 \\
\pi_i^{D*} &= (1-\beta)(\pi_i^{U-} + \pi_i^{D-}) = \frac{2(1-\beta)}{25}(a - 3c_i + 2c_j)^2
\end{aligned} \tag{2}$$

3.2 The Vertically Integrated Case

This subsection presents the solving of the case in which both vertical structures are integrated. This set-up is represented in Figure 3.

Figure 3: The Vertically Integrated Case

Hence, vertical structures A and B behave as in a horizontal set-up, without contract negotiation. The per-period profits are then:

$$\pi_i = (P(Q) - c_i)q_i = (a - q_i - q_j - c_i)q_i$$

The profits maximizing quantity is:

$$q_i^* = \frac{a - 2c_i + c_j}{3} \tag{3}$$

Maximized profits are:

$$\pi_i^* = \frac{1}{9}(a - 2c_i + c_j)^2 \tag{4}$$

3.3 The Asymmetric Case

The case (henceforth "the asymmetric case") in which one firm is integrated and the other one is separated is now investigated. I am going to call firm AI the vertically integrated one, and firm AS the vertically separated one, as represented in Figure 4.[5] Thus, the resolution follows the same steps as Subsection 3.1 for firm AS. However, for firm AI, there is no contract negotiation, as in Subsection 3.2.

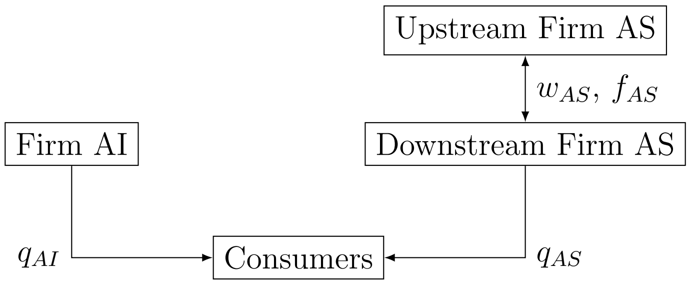


Figure 4: The Asymmetric Case

Let's write the downstream per-period profits:

$$\pi_{AI} = (P(Q) - c_{AI})q_{AI} = (a - q_{AI} - q_{AS} - c_{AI})q_{AI}$$
$$\pi_{AS}^{D} = (P(Q) - w_{AS})q_{AS} = (a - q_{AS} - q_{AI} - w_{AS})q_{AS}$$

Maximizing the previous equations with respect to q_{AI} and q_{AS} yields:

$$q_{AI} = \frac{a - 2c_{AI} + w_{AS}}{3}$$
$$q_{AS} = \frac{a - 2w_{AS} + c_{AI}}{3}$$

w_{AS} and f_{AS} are determined by the Nash bargaining problem:

$$\max_{w_{AS}, f_{AS}} \quad (\pi_{AS}^{U-} + f_{AS})^{\beta}(\pi_{AS}^{D-} - f_{AS})^{(1-\beta)}$$

Solving for f_{AS}, then for w_{AS} one gets:

$$\begin{aligned} w_{AS}^{*} &= \frac{-a - c_{AI} + 6c_{AS}}{4} \\ q_{AS}^{*} &= \frac{a + c_{AI} - 2c_{AS}}{2} \\ q_{AI}^{*} &= \frac{a - 3c_{AI} + 2c_{AS}}{4} \end{aligned} \tag{5}$$

[5] "AI" stands for asymmetrically integrated, and "AS" for asymmetrically separated. Each vertical structure A or B can be AS or AI.

The optimal profits are then:

$$\begin{aligned} \pi_{AS}^{U*} &= \frac{\beta}{8}(a + c_{AI} - 2c_{AS})^2 \\ \pi_{AI}^{*} &= \frac{1}{16}(a - 3c_{AI} + 2c_{AS})^2 \end{aligned} \tag{6}$$

4 The Precommitment Game

In this section, I solve the first stage of the game under the precommitment game assumptions. As in Reinganum (1981b), only equilibria in pure strategies are considered. I solve and determine the timings of adoption under the different market set-ups in the three following subsections and I compare them in Subsection 4.4.

4.1 The Vertically Separated Case

Since the situation is symmetric, subscripts denote the technology position (no longer the identity of the vertical structure): the subscript 1 denotes the technology leader (*i.e.* the first adopter) and the subscript 2 denotes the technology follower (*i.e.* the second adopter). The technology leader maximizes the discounted sum of its infinite stream of per-period profits with respect to its time of adoption T_1, and the technology follower maximizes its equivalent with respect to T_2:

$$\begin{aligned} \max_{T_1} \quad \Pi_1^U(T_1, T_2) &= \int_0^{T_1} \pi^{U_0} e^{-rt} dt + \int_{T_1}^{T_2} \pi^{U_l} e^{-rt} dt + \int_{T_2}^{\infty} \pi^{U_b} e^{-rt} dt - k(T_1) \\ \max_{T_2} \quad \Pi_2^U(T_1, T_2) &= \int_0^{T_1} \pi^{U_0} e^{-rt} dt + \int_{T_1}^{T_2} \pi^{U_f} e^{-rt} dt + \int_{T_2}^{\infty} \pi^{U_b} e^{-rt} dt - k(T_2) \end{aligned}$$

where $\pi^{U_0} = \pi_i^{U*}(c, c)$, $\pi^{U_l} = \pi_i^{U*}(c - \Delta, c)$, $\pi^{U_b} = \pi_i^{U*}(c - \Delta, c - \Delta)$ and $\pi^{U_f} = \pi_i^{U*}(c, c - \Delta)$.[6] Hereinafter, the superscript VS denotes the optimality conditions under the vertically separated case. Denoting:

$$\begin{aligned} I_1^{VS} &\equiv \pi_{U_l} - \pi_{U_0} = \frac{6}{25}\beta M^2 \delta(2 + 3\delta) \\ I_2^{VS} &\equiv \pi_{U_b} - \pi_{U_f} = \frac{6}{25}\beta M^2 \delta(2 - \delta) \end{aligned} \tag{7}$$

[6] I write here the per-periods profits $\pi_i(c_i, c_j)$ as a function of the firm's own costs c_i and the other's ones c_j. "0" denotes the situation when no one has adopted, "l" when the firm is the technology leader, "b" when both have adopted and "f" when the firm is the technology follower.

First order conditions are:

$$
\begin{aligned}
I_1^{VS} &= -k'(T_1^{VS})e^{rT_1^{VS}} \\
I_2^{VS} &= -k'(T_2^{VS})e^{rT_2^{VS}}
\end{aligned}
\tag{8}
$$

From these conditions, one can observe that technology diffusion (*i.e.* non-simultaneous technology adoption) happens under both pure strategy equilibria. Indeed, since $I_1^{VS} > I_2^{VS}$ and since $-k'(t)e^{rt}$ is decreasing (see proof in Appendix A.1), $T_1^{VS} < T_2^{VS}$. Also, a first mover advantage is occurring here as first exposed by Reinganum (1981b).[7]

4.2 The Vertically Integrated Case

Similar to before, one must solve:

$$
\begin{aligned}
\max_{T_1} \quad \Pi_1(T_1, T_2) &= \int_0^{T_1} \pi^0 e^{-rt} dt + \int_{T_1}^{T_2} \pi^l e^{-rt} dt + \int_{T_2}^{\infty} \pi^b e^{-rt} dt - k(T_1) \\
\max_{T_2} \quad \Pi_2(T_1, T_2) &= \int_0^{T_1} \pi^0 e^{-rt} dt + \int_{T_1}^{T_2} \pi^f e^{-rt} dt + \int_{T_2}^{\infty} \pi^b e^{-rt} dt - k(T_2)
\end{aligned}
$$

where $\pi^0 = \pi_i^*(c, c)$, $\pi^l = \pi_i^*(c - \Delta, c)$, $\pi^b = \pi_i^*(c - \Delta, c - \Delta)$ and $\pi^f = \pi_i^*(c, c - \Delta)$. The superscript VI denotes the optimality conditions under the vertically integrated case. Denoting:

$$
\begin{aligned}
I_1^{VI} &\equiv \pi_l - \pi_0 = \frac{4}{9} M^2 \delta(1 + \delta) \\
I_2^{VI} &\equiv \pi_b - \pi_f = \frac{4}{9} M^2
\end{aligned}
\tag{9}
$$

First order conditions are:

$$
\begin{aligned}
I_1^{VI} &= -k'(T_1^{VI})e^{rT_1^{VI}} \\
I_2^{VI} &= -k'(T_2^{VI})e^{rT_2^{VI}}
\end{aligned}
\tag{10}
$$

Again here, technology diffusion happens under both pure strategy equilibria ($I_1^{VI} > I_2^{VI}$). One can also observe the first mover advantage.[8]

4.3 The Asymmetric Case

In the asymmetric case, two situations may occur. In pure strategies, either firm AI or firm AS is the technology leader. Hence, I solve the precommitment game under these two possible situations.

[7] It is easy to show that $\Pi_1^U(T_1^{VS}, T_2^{VS}) > \Pi_1^U(T_2^{VS}, T_2^{VS}) = \Pi_2^U(T_2^{VS}, T_2^{VS}) \geq \Pi_2^U(T_1^{VS}, T_2^{VS})$.

[8] It is easy to show that $\Pi_1(T_1^{VI}, T_2^{VI}) > \Pi_1(T_2^{VI}, T_2^{VI}) = \Pi_2(T_2^{VI}, T_2^{VI}) \geq \Pi_2(T_1^{VI}, T_2^{VI})$.

Let's consider first the case where firm AI (the vertically integrated firm) is leading. Using the same notations as in the previous sections, firms maximize:

$$\max_{T_1} \quad \Pi_{AI}(T_1, T_2) = \int_0^{T_1} \pi_{AI}^0 e^{-rt} dt + \int_{T_1}^{T_2} \pi_{AI}^l e^{-rt} dt + \int_{T_2}^{\infty} \pi_{AI}^b e^{-rt} dt - k(T_1)$$
$$\max_{T_2} \quad \Pi_{AS}^U(T_1, T_2) = \int_0^{T_1} \pi_{AS}^{U_0} e^{-rt} dt + \int_{T_1}^{T_2} \pi_{AS}^{U_f} e^{-rt} dt + \int_{T_2}^{\infty} \pi_{AS}^{U_b} e^{-rt} dt - k(T_2)$$

where $\pi_{AI}^0 = \pi_{AI}^*(c,c)$, $\pi_{AI}^l = \pi_{AI}^*(c-\Delta, c)$, $\pi_{AI}^b = \pi_{AI}^*(c-\Delta, c-\Delta)$, and $\pi_{AS}^{U_0} = \pi_{AS}^{U*}(c,c)$, $\pi_{AS}^{U_f} = \pi_{AS}^{U*}(c, c-\Delta)$, $\pi_{AS}^{U_b} = \pi_{AS}^{U*}(c-\Delta, c-\Delta)$. For the ease of exposition, the optimal conditions are denoted by a subscript indicating the technology position ($i.e.$ 1, 2) and a superscript indicating the identity of the firm ($i.e.$ AI, AS). Denoting:

$$\begin{aligned} I_1^{AI} &\equiv \pi_{AI}^l - \pi_{AI}^0 = \frac{3}{16} M^2 \delta(2 + 3\delta) \\ I_2^{AS} &\equiv \pi_{AS}^{U_b} - \pi_{AS}^{U_f} = \frac{1}{2}\beta M^2 \delta \end{aligned} \tag{11}$$

First order conditions are:

$$\begin{aligned} I_1^{AI} &= -k'(T_1^{AI}) e^{rT_1^{AI}} \\ I_2^{AS} &= -k'(T_2^{AS}) e^{rT_2^{AS}} \end{aligned} \tag{12}$$

For such an equilibrium to exist, I need $T_1^{AI} < T_2^{AS}$. This is true for a certain range of parameter values:

$$\begin{aligned} & T_1^{AI} < T_2^{AS} \\ \Leftrightarrow \quad & I_1^{AI} > I_2^{AS} \\ \Leftrightarrow \quad & \beta < \beta_1^* \equiv \frac{3}{8}(2 + 3\delta) \end{aligned} \tag{13}$$

The case where the vertically separated firm leads is now considered. Using the same notation as before, firms maximize:

$$\max_{T_1} \quad \Pi_{AS}^U(T_1, T_2) = \int_0^{T_1} \pi_{AS}^{U_0} e^{-rt} dt + \int_{T_1}^{T_2} \pi_{AS}^{U_l} e^{-rt} dt + \int_{T_2}^{\infty} \pi_{AS}^{U_b} e^{-rt} dt - k(T_1)$$
$$\max_{T_2} \quad \Pi_{AI}(T_1, T_2) = \int_0^{T_1} \pi_{AI}^0 e^{-rt} dt + \int_{T_1}^{T_2} \pi_{AI}^f e^{-rt} dt + \int_{T_2}^{\infty} \pi_{AI}^b e^{-rt} dt - k(T_2)$$

where $\pi_{AS}^{U_0} = \pi_{AS}^{U*}(c,c)$, $\pi_{AS}^{U_l} = \pi_{AS}^{U*}(c-\Delta, c)$, $\pi_{AS}^{U_b} = \pi_{AS}^{U*}(c-\Delta, c-\Delta)$, and $\pi_{AI}^0 = \pi_{AI}^*(c,c)$,

$\pi^f_{AI} = \pi^*_{AI}(c, c-\Delta)$, $\pi^b_{AI} = \pi^*_{AI}(c-\Delta, c-\Delta)$. Denoting:

$$\begin{aligned} I_1^{AS} &\equiv \pi^{U_l}_{AS} - \pi^{U_0}_{AS} = \frac{1}{2}\beta M^2\delta(1+\delta) \\ I_2^{AI} &\equiv \pi^b_{AI} - \pi^f_{AI} = \frac{3}{16}M^2\delta(2-\delta) \end{aligned} \tag{14}$$

First order conditions are:

$$\begin{aligned} I_1^{AS} &= -k'(T_1^{AS})e^{rT_1^{AS}} \\ I_2^{AI} &= -k'(T_2^{AI})e^{rT_2^{AI}} \end{aligned} \tag{15}$$

Such an equilibrium exists if and only if:

$$\begin{aligned} & & T_1^{AS} &< T_2^{AI} \\ \Leftrightarrow & & I_1^{AS} &> I_2^{AI} \\ \Leftrightarrow & & \beta > \beta_2^* &\equiv \frac{3(2-\delta)}{8(1+\delta)} \end{aligned} \tag{16}$$

Therefore, according to the values of β and δ, several types of equilibria may exist. Figure 5 displays the threshold values associated with equilibrium existence conditions (13) and (16). One can state the following proposition.

Proposition 1. *In the asymmetric case, the equilibria in pure strategies are as follows:*

1. *when $\beta < \beta_2^*(\delta)$, there is a unique equilibrium in which the vertically integrated firm is the technology leader.*

2. *when $\beta > \beta_1^*(\delta)$, there is a unique equilibrium in which the vertically separated firm is the technology leader.*

3. *when $\beta_2^*(\delta) < \beta < \beta_1^*(\delta)$, there are two equilibria: one in which the vertically integrated firm is the technology leader, one in which the vertically separated firm is the technology leader.*

Intuitively, the condition of existence of these equilibria relies on the fact that the incentives to adopt first must be higher than those of adopting second.

For instance, let's consider the case where firm AS leads. From equation (15), one can see that the timing of first adoption relies on the increment to profits from first adoption, whereas the timing of second adoption relies on the increment to profits from second adoption. For the equilibrium to exist (*i.e.* for first timing to be earlier than second timing), the first must be larger than the second. However, for the parameter values in the area below $\beta_2^*(\delta)$, the increment to benefits of the technology leader (the vertically separated firm) is lower than the one of the technology follower (the vertically integrated

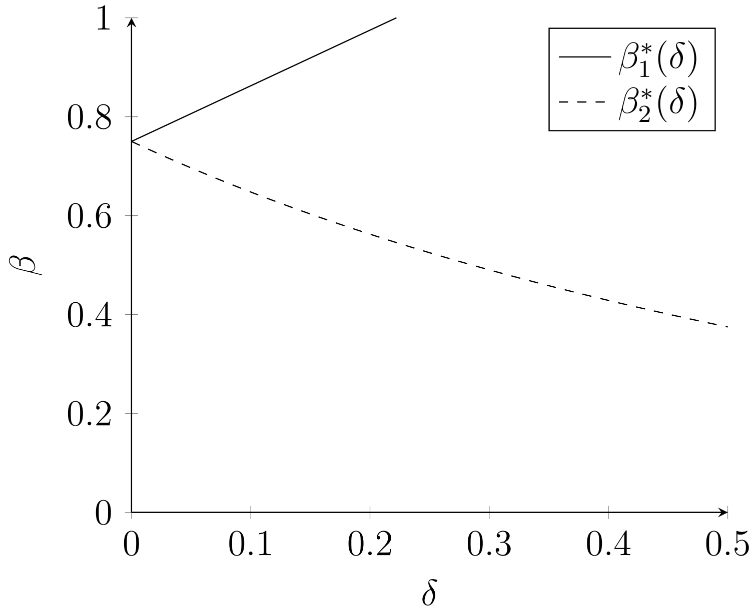


Figure 5: Equilibria under Precommitment: the Asymmetric Case

Note: For the values of β and δ below the plain line, the equilibrium in which the vertically integrated firm is the leader exists. For the values of β and δ above the dashed line, the equilibrium in which the vertically separated firm is the leader exists.

firm). When the upstream bargaining power β is low, the upstream firm AS does not capture much of the benefits from the technology adoption, since the upstream firm's per-period profits is a share β of total profits. While a low upstream bargaining power considerably reduces the incentives to adopt early for the vertically separated firm, the incentives to adopt the technology for the integrated firm are unaffected by it. This is what I call a *bargaining* effect: vertical separation implies profit-sharing between upstream and downstream partners, which does not occur under vertical integration.

Let's consider now the case where firm AI leads. From equation (12), one can see that here too, for the equilibrium to exist, the increment in terms of revenues from first adoption must be higher than the one from second adoption. However, for the parameters values in the area above $\beta_1^*(\delta)$, the increment to profits from technology adoption is higher for second adopter (*i.e.* the vertically separated firm) than for the first one: a high β implies that the innovator in the vertically separated case captures most of the gains from technology adoption, whereas a low δ implies that the innovator in the vertically integrated case has low gains from technology adoption. The effect at stake here is what I call a *strategic* effect, since it is related to the competitor's best response function. When separated, an upstream firm can give an important competitive advantage to its downstream partner using below-cost wholesale price, and then capturing a share of profits using the fixed fee.[9] Hence, per-period total profits are higher for firm AS, and upstream firm AS has incentives to adopt very early whenever β is high. As δ increases, however, the

[9]This is a result demonstrated by Bonanno and Vickers (1988).

aforementioned competitive advantage of vertical separation vanishes, since the leader's advantage (*i.e.* the vertically integrated firm) increases: this is why $\beta_1^*(\delta)$ is upward slopping.

I discuss further now the fact that $\beta_1^*(\delta)$ is upward slopping and $\beta_2^*(\delta)$ is downward slopping. For $\beta_1^*(\delta)$, this is due to the fact that, when δ increases, the speed of adoption generally increases faster for firm AI when it is the leader than for firm AS when it is the follower ($i.e. \frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_2^{AS}}{\partial \delta}$). For $\beta_2^*(\delta)$, this is due to the fact that, when δ increases, the speed of adoption generally increases slower for firm AI when it is the follower than for firm AS when it is the leader ($i.e.$ $\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_1^{AS}}{\partial \delta}$). In fact, often,[10] the impact of the effectiveness of the technology is stronger (weaker) on the timing of first (second) adoption for the vertically integrated firm than for the separated one ($i.e. \frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_1^{AS}}{\partial \delta}$ and $\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_2^{AS}}{\partial \delta}$). Indeed, this is a result of the aforementioned *strategic* effect: the gains from being the technology leader, and the losses from being the technology follower, are particularly intense when competing with a vertically separated firm.

This is an important intuition revealed by the study of the asymmetric case. This complements the work of Alipranti et al. (2015) by pointing out that what matters in a firm's decision to adopt is not only its own vertical structure but also the competitor's vertical strcuture. Indeed, the gain from being the leader (or the loss from being the follower) is very strong when facing a separated competitor, since the cost-reduction of the adopter affects not only the quantity competition but also the contract negotiation. The upstream firm will react to the adoption by changing the level of his wholesale price, which in turn will change the strategy of the downstream firm. This sort of amplification effect makes the firm's decision to adopt very sensitive to the efficiency of the technology, δ.

Therefore, the existence of equilibria in the asymmetric case is determined by two effects: an *strategic* and a *bargaining* effect. Whenever the *strategic* effect is relatively strong, the equilibrium where AI leads does not exist, and whenever the *bargaining* effect is relatively strong, the equilibrium where AS leads does not exist. To discuss the impact of an integration on the speed of adoption, I need to compare the timings of adoption under the three different cases previously studied, which is done in Subsection 4.4.

4.4 The Timing of Adoption: a Comparison

In this subsection, I compare the timing of adoption of the new technology under the three different market set-ups previously examined. Using the first order conditions of the various aforementioned cases, I obtain a set of threshold values and a ranking of the

[10] By often, I mean for many parameters values. An extended discussion and demonstration of this claim is presented in Appendix A.2.

timing of technology adoption according to the market structure. This allows a further discussion of the two main effects of the vertical structure on the timing of adoption, namely the *strategic* and the *bargaining* effect.

4.4.1 The Vertically Separated Case versus the Asymmetric Case

First, let's compare the vertically separated case and the asymmetric case. In fact, starting from a situation where both firms are separated, this corresponds to examining the impact of the first integration on the timings of adoption: firm AS remains separated while firm AI becomes integrated. Therefore, the timing of first and second adoption must be compared for both existing pure strategy equilibria under the asymmetric case, yielding the following four relations:

$$\begin{aligned} T_1^{AI} < T_1^{VS} &\Leftrightarrow 0 \leq \beta < \beta_3^* \equiv \frac{25}{32} \quad and \quad 0 < \delta \leq 1/2 \\ T_2^{AS} < T_2^{VS} &\Leftrightarrow 0 < \beta \leq 1 \quad and \quad 0 < \delta \leq 1/2 \end{aligned} \tag{17}$$

$$\begin{aligned} T_1^{AS} < T_1^{VS} &\Leftrightarrow 0 < \beta \leq 1 \quad and \quad 0 < \delta < \delta_1^* \equiv \frac{1}{11} \\ T_2^{AI} < T_2^{VS} &\Leftrightarrow 0 \leq \beta < \beta_3^* \equiv \frac{25}{32} \quad and \quad 0 < \delta \leq 1/2 \end{aligned} \tag{18}$$

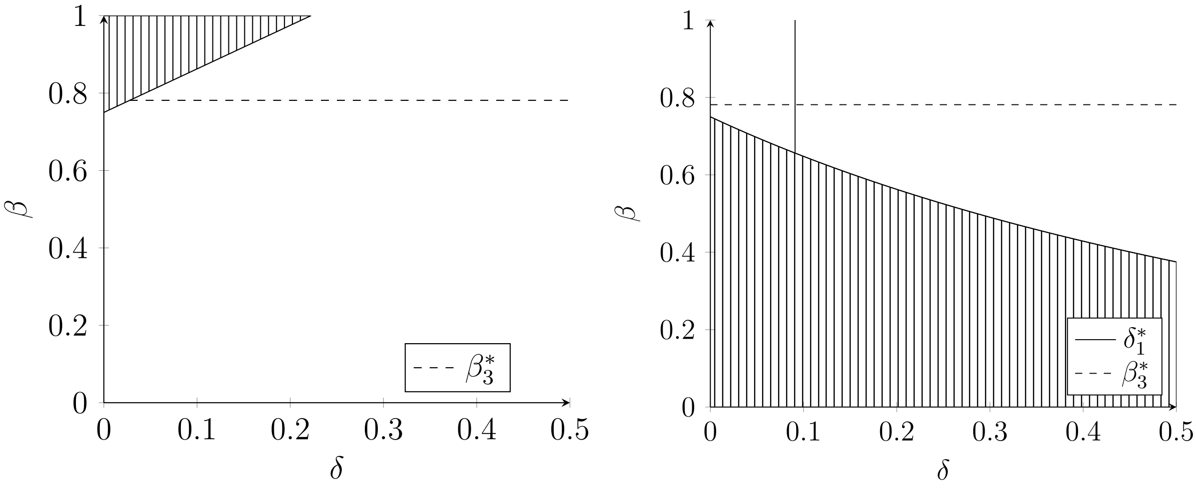
The range of parameter values for which a certain set-up yields an earlier adoption than another one can then be delimited for both equilibria and both adoptions. In Figure 6, the striped area delimits the zone where the equilibria do not exist and the lines corresponds to the threshold values described in equations (17) and (18). I also state Corollary 1.

Corollary 1. *Under the precommitment game, when the competitor is separated and:*

- *when the integrated firm is the technology leader in the asymmetric case, integration always accelerates second adoption and accelerates the first one when* $\beta < \beta_3^*$.
- *when the integrated firm is the technology follower in the asymmetric case, integration accelerates first adoption when* $\delta < \delta_1^*$ *and accelerates the second one when* $\beta < \beta_3^*$.

In the first case (when AI leads), integration necessarily accelerates the second adoption. This is a due to the *strategic* effect: when competing with a vertically integrated firm, a vertically separated firm (being the technology follower) has more incentives to adopt the technology earlier than the case in which it competes with a vertically separated firm. Indeed, the loss from being the technology follower is more intense in this second situation than in the asymmetric case.

When AI leads, integration accelerates first adoption for all parameters values under



(a) AI leads

(b) AS leads

Figure 6: Comparison of Precommiment Timing: VS v. Asymmetric Case

Note: The stripped area corresponds to the parameter values for which the appropriate equilibrium in the asymmetric case does not exist. (a) For the values of β and δ below the dotted line, integration accelerates first adoption. For all values of β and δ, integration accelerates second adoption. (b) For the values of β and δ to the left of the plain line, integration accelerates first adoption. For the values of β and δ below the dotted line, integration accelerates second adoption.

the dotted line, which is below $\beta_3^* \approx 0.78$. This is due to the *bargaining* effect: once vertically integrated, the innovator no longer has to share the increment to profits from the innovation. However, when the bargaining power of the vertically separated firm is high, the vertically separated firm gets a higher increment to profits from first adoption than if it was integrated. Then, for $\beta < \beta_3^*$, first integration accelerates both adoptions.

For the equilibrium where AS leads, integration makes first adoption occur earlier in the area to the left of the plain line, that is below $\delta_1^* \approx 0.09$. As suggested by equation (18), the impact of integration on first timing depends on δ only. This is due to the same *strategic* effect aforementioned: for low values of δ, the increment in terms of revenue from first adoption is higher for the vertically separated firm when competing with a vertically integrated firm. Intuitively, the advantage from being the technology leader is more important when competing with a vertically separated firm, but only when the effectiveness of the technology is sufficiently large. Also, when AS leads, integration accelerates second adoption if and only if $\beta < \beta_3^*$. Here too, the *bargaining* effect is relevant: for low upstream bargaining power values, the increment to profits, and then the incentives to adopt second faster, are higher after first integration.

4.4.2 The Asymmetric Case versus the Vertically Integrated Case

Second, let's compare the asymmetric case to the vertically integrated case. This corresponds to estimating the impact of second integration on timings of adoption: firm *AI* is already integrated, and firm AS gets integrated. Here as well, the two pure strategy equilibria have to be considered, yielding the following set of four equations:

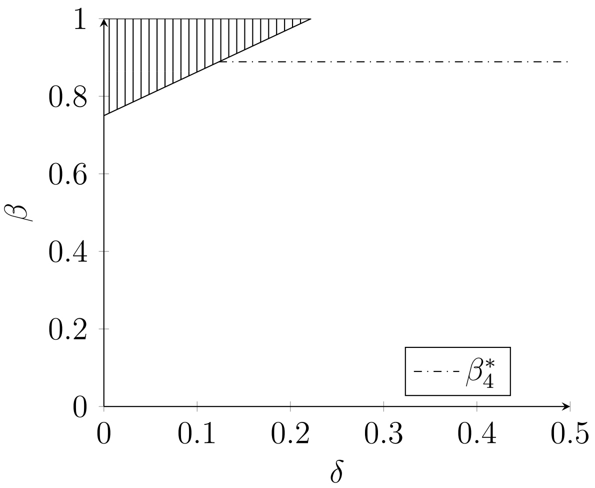
$$\begin{aligned} T_1^{VI} < T_1^{AI} &\Leftrightarrow \quad 0 \leq \beta \leq 1 \quad and \quad 0 < \delta \leq 1/2 \\ T_2^{VI} < T_2^{AS} &\Leftrightarrow \quad 0 \leq \beta < \beta_4^* \equiv \frac{8}{9} \quad and \quad 0 < \delta \leq 1/2 \end{aligned} \tag{19}$$

$$\begin{aligned} T_1^{VI} < T_1^{AS} &\Leftrightarrow \quad 0 \leq \beta < \beta_4^* \equiv \frac{8}{9} \quad and \quad 0 < \delta \leq 1/2 \\ T_2^{VI} < T_2^{AI} &\Leftrightarrow \quad 0 \leq \beta \leq 1 \quad and \quad 0 < \delta \leq 1/2 \end{aligned} \tag{20}$$

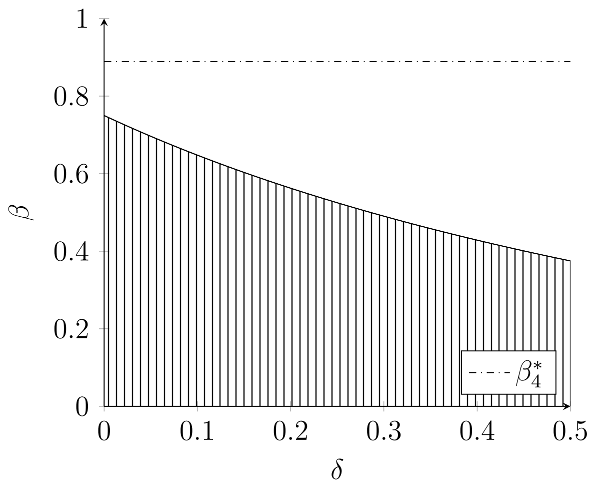
In Figure 7, the stripped area delimits the zone where the equilibria do not exist and the lines corresponds to the threshold values described in equations (19) and (20). I also state Corollary 2.

Corollary 2. *Under the precommitment game, when the competitor is integrated and:*

- *when the integrated firm is the technology leader in the asymmetric case, integration always accelerates first adoption and accelerates the second one when* $\beta < \beta_4^*$.
- *when the integrated firm is the technology follower in the asymmetric case, integration always accelerates second adoption and accelerates the first one when* $\beta < \beta_4^*$.



(a) AI leads



(b) AS leads

Figure 7: Comparison of Precommitment Timing: Asymmetric Case v. VI

Note: The stripped area corresponds to the parameter values for which the appropriate equilibrium in the asymmetric case does not exist. (a) For the values of β and δ below the dotted line, integration accelerates second adoption. For all values of β and δ, integration accelerates first adoption. (b) For the values of β and δ below the dotted line, integration accelerates first adoption. For all values of β and δ, integration accelerates second adoption.

When AI leads, integration always accelerates first adoption. This is the *strategic* effect: the increment to profits from first adoption is higher for a vertically integrated firm when facing another integrated firm than when competing with a vertically separated firm.

Indeed, the gain from being the leader are mitigated when the competitor is separated. Under this equilibrium, integration accelerates second adoption when the upstream bargaining power is below $\beta_4^* \approx 0.89$. This is the *bargaining* effect: when β is very high, the innovator (the upstream firm) earns most of the gains from second technology adoption, and the incentives to adopt are therefore higher.

When AS leads, integration accelerates the first adoption for $\beta < \beta_4^*$, due to the *bargaining* effect mentioned before. Under this equilibrium, second adoption always occurs earlier after integration: the *strategic* effect previously described prevails here.

In sum, the exploration of the asymmetric set-up under the precommitment game allowed highlighting two main insights. The first one concerns the resolution of the precommitment game in itself: while the existence of two symmetric pure strategy Nash equilibria is systematic in the symmetric cases, the precommitment game may have a single pure strategy Nash equilibrium depending on the incentives to adopt of each player. The second insight relates to the effect of integration on timings of adoption. Such effect depends crucially on the vertical structure of the competitor (*i.e.* whether it is integrated or not) and on the technology position of the integrating firm. Whenever the *bargaining* effect is strong enough (*i.e.* when the upstream bargaining power is low), integration unambiguously accelerates adoption. Whenever the *strategic* effect is strong enough (*i.e.* when β and δ are high), integration may slow down adoption. The next section investigates the preemption game in an asymmetric set-up and allows to prove whether these insights are specific to the type of game exploited.

5 The Preemption Game

I explore now the impact of the vertical structure on the outcomes of the preemption game as first described by Fudenberg and Tirole (1985). Contrary to the precommitment game where firms commit at $t = 0$ to their adoption timing, firms can adjust their adoption decision at any time in the game. Technically, there is no information lag in the preemption (while there are infinite ones in the precommitment game): firms immediately know about the other's decisions. Hence, I am using the concept of subgame perfection.

An intuitive way to think about such a game is described by Riordan (1992). One can think of the preemption game as a discrete sequential game where firms take turn in deciding whether to adopt the technology or not, and where the time gap between every node of the extensive form of the game (*i.e.* between every step of the sequential game) tends to zero. Time is then continuous, and firms are taking decisions simultaneously, but to solve the game, it is helpful to think of it as a sequential game.

5.1 The Symmetric Case

The intuition behind the derivation of the adoption timing is better explained with a graph, under the symmetric case. The second adoption occurs at the same timing as in the precommitment game: taking the technology follower position as given, there is no profitable deviation from T_2^{pc}.[11] In Figure 8, the payoffs of the technology leader and the technology follower are represented as a function of the first adoption timing, T_1. The payoff of the technology leader is concave in T_1, with its maximum at T_1^{pc}, the precommitment timing. In the rest of this section, the superscripts *pc* and *pe* denote the precommitment timing and the preemption timing respectively. The payoff of the technology follower is linearly increasing in T_1: indeed, the later the first adoption, the shorter the period during which the technology follower suffers from the competitor's exclusive adoption.

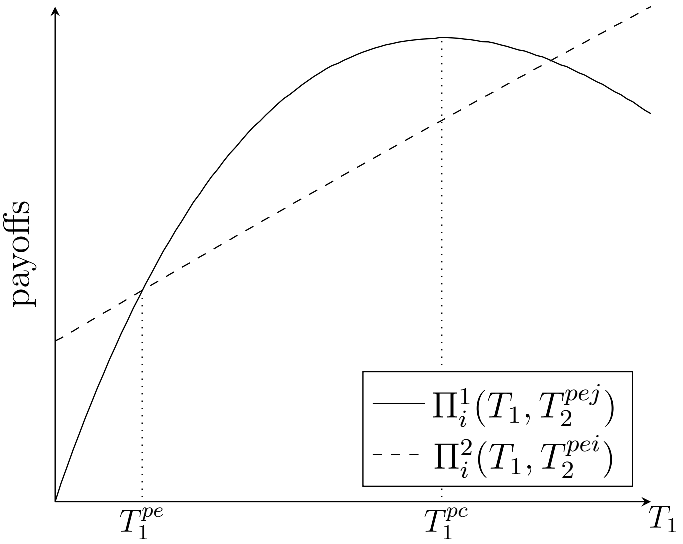


Figure 8: Preemption in the Symmetric Case

Note: The plain curve and the dashed line represents respectively the profits of the technology leader and the profits of the technology follower, as a function of the timing of the first adoption. The technology leader's profits reach a maximum at T_1^{pc}, the precommitment timing, and are equal to the follower's ones at T_1^{pe}, the preemption timing.

In the symmetric case, i and j are the same.[12] Hence, per-period payoffs and second adoption timing are the same. Let's assume that a first firm decides to adopt at T_1^{pc}: one can see that it is a profitable deviation for the follower to adopt at $T_1^{pc} - \epsilon$ for ϵ very small (i.e. $\Pi^2(T_1^{pc}, T_2^{pe}) < \Pi^1(T_1^{pc} - \epsilon, T_2^{pe})$). Knowing this, the first adopter will choose $T_1^{pc} - \epsilon$, but again, adopting at $T_1^{pc} - \epsilon - \epsilon$ is a profitable deviation. This keeps happening until T_1^{pe}, where the payoffs of the technology leader are equal to the ones of the follower, that is when there is no longer any profitable deviation. Hence, rent-equalization occurs, and

[11] This is a standard result from the technology adoption literature.

[12] The notation i and j is kept for later exposition of the asymmetric case.

there are two subgame perfect equilibria: one where firm i adopts at T_1^{pe} and firm j at T_2^{pe}, and one where j adopts at T_1^{pe} and i at T_2^{pe}.[13]

Henceforth, T_1^{pe} is obtained by solving $\Pi^1(T_1, T_2^{pe}) = \Pi^2(T_1, T_2^{pe})$. Such solving yields, in the symmetric set-up, the following condition:

$$\pi^l - \pi^f = r\frac{k(T_1^{pe}) - k(T_2^{pe})}{e^{-rT_1^{pe}} - e^{-rT_2^{pe}}} \tag{21}$$

Such condition does not have a closed-form solution, even after giving a specific form to the adoption cost function. Hence, the comparison of timings under the different set-up necessitates running simulations.

5.2 The Asymmetric Case

To my knowledge, no works have explored the solving of the preemption game in an asymmetric set-up. Such an attempt has three main difficulties. The first one stems from the fact that pure strategy precommitment equilibria do not exist for all parameter values, which implies that the payoffs as a leader and as a follower may not have the same shape as in Figure 8. The second difficulty comes from the fact that T_1^{pe} and T_2^{pe} are not the same for firm i and firm j. The final difficulty is the impossibility of obtaining a closed-form solution for T_1^{pe}, nor even a condition similar to equation (21). In the following section, I denote T_1^{pei} the solution[14] to the equation:

$$\Pi_i^1(T_1, T_2^{pej}) = \Pi_i^2(T_1, T_2^{pei}) \tag{22}$$

The full description of the different possible situations that may arise during the solving of such a game is described in Appendix A.3. For the sake of readability, I describe the intuitions behind the solving of such a game, and explore the results using numerical simulations. I describe first the best response function of the firms in Lemma 1.

Lemma 1. *Firm i's adoption decision depends on its willingness to be the technology leader and its capacity to preempt its competitor:*

- *If firm i has an incentive to be the technology leader and:*
  - *If $T_1^{pei} < T_1^{pej}$, then firm i adopts first at T_1^{pej}.*
  - *If $T_1^{pci} < T_1^{pej}$, then firm i adopts first at T_1^{pci}.*

[13] I am not considering the continuum of equilibria where firms adopt at the same time after T_2, explored by Fudenberg and Tirole (1985).

[14] Actually, I am talking only about the solution before T_1^{pci}, as $\Pi_i^1(T_1, T_2^{pej})$ and $\Pi_i^2(T_1, T_2^{pei})$ intersect twice (see Figure 8).

– *If $T_1^{pei} > T_1^{pej}$, then firm i adopts second at T_2^{pei}.*

- *If firm i has an incentive to be the technology follower, firm i adopts second at T_2^{pei}.*

Let's cover these different situations and describe the reasoning behind the results. When the firm has some gains from being the technology leader, it may or may not be able to preempt its competitor. In this case, T_1^{pe} measures the capacity to preempt: it represents the earliest timing at which it is profitable to preempt the competitor. If $T_1^{pei} < T_1^{pej}$, it means that Firm j can preempt Firm i up to T_1^{pej}, which is earlier than T_1^{pci} but still later than T_1^{pei}. As one can see from Figure 8, Firm i would like to adopt as close as possible to T_1^{pci}, but if it does, it will be preempted by Firm j. Hence, the latest Firm i can adopt without being preempted is T_1^{pej}, the competitor's preemption timing of adoption.[15] If $T_1^{pci} < T_1^{pej}$, this means that Firm j capacity to preempt is so weak that it cannot profitably adopt before the precommitment timing of Firm i. In that case, Firm i adopts at T_1^{pci}. However, as soon as Firm i knows it does not have the capacity to preempt its competitor (*i.e.* $T_1^{pei} > T_1^{pej}$), it decides to adopt second at T_2^i. A last case that may occur is that Firm i may prefer in all cases to be the technology follower: this may happen whenever its incentives to adopt are extremely low compared to the one of the competitor (this possibility is discussed in Proposition 1). In that case, Firm i naturally chooses to adopt second.

Using the best response function described in Lemma 1, I can now find the equilibria of the game under a specific parametrization. First of all, I need to use a specific adoption cost function. A classical function exploited in several papers (introduced by Fudenberg and Tirole (1985)) is $k(t) = e^{-(\alpha+r)t}$, where $\alpha > 0$ is the rate at which the current costs of adoption are falling. Taking an interest rate of 3% ($r = 0.03$), a market capacity equal to one ($M = 1$), and $\alpha = 0.8$, I obtain the set of equilibria depending on those parameter values in Figure 9.[16]

From this Figure 9, I state the following proposition:

Proposition 2. *Under the specific parametrization where $r = 0.03$, $M = 1$ and $\alpha = 0.8$, the technology adoption equilibria under the preemption game in the asymmetric set-up are as follow:*

- *when $\beta < \tilde{\beta}_1$, Firm AI is the technology leader and adopts at the precommitment timing, T_1^{pcAI}.*
- *when $\tilde{\beta}_1 < \beta < \tilde{\beta}_2$, Firm AI is the technology leader and adopts at the preemption timing of Firm AS, T_1^{peAS}.*

[15] Technically, Firm i is adopting at $T_1^{pej} - \epsilon$, so that j has not incentive to preempt. I am just taking ϵ infinitely small.

[16] Market capacity is set to one for simplicity, the interest rate to the reasonable rate of three percent, and the choice of α is guided by the readability of Figure 9. Appendix A.4.1 explores other parameterizations.

- *when $\tilde{\beta}_2 < \beta < \tilde{\beta}_3$, Firm AS is the technology leader and adopts at the preemption timing of Firm AI, T_1^{peAI}.*
- *when $\beta > \tilde{\beta}_3$, Firm AS is the technology leader and adopts at the precommitment timing, T_1^{pcAS}.*

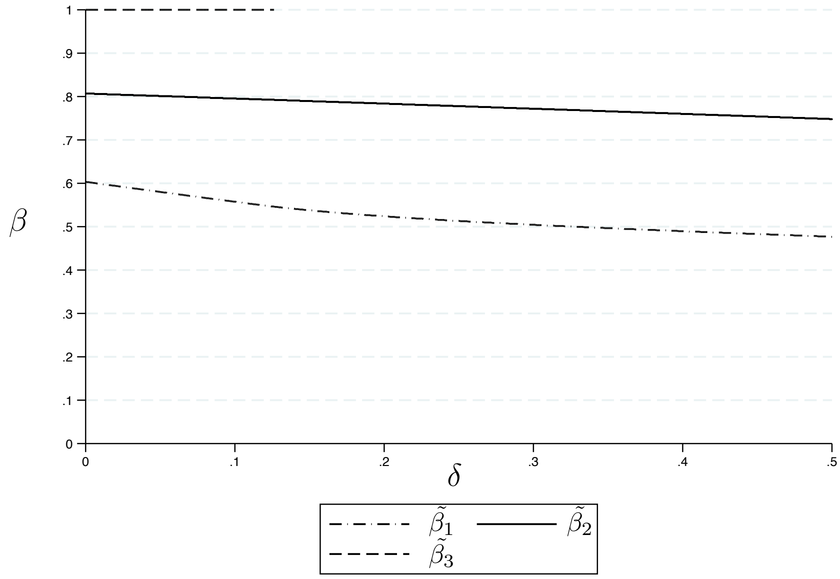


Figure 9: Equilibria under Preemption - the Asymmetric Case

Note: In this graph, the parametrization is the following one: $M = 1$, $r = 0.03$ and $\alpha = 0.8$. The three thresholds delimits the four types of equilibria: the one where AI is the technology leader and adopts at the precommitment timing, the one where AI is the technology leader and adopts at the preemption timing, the one where AS is the technology leader and adopts at the preemption timing and the one where AS is the technology leader and adopts at the precommitment timing.

Some novel intuitions stem from Proposition 2. First of all, the preemption timing as described by Fudenberg and Tirole (1985) is not necessarily the timing chosen by firms in a preemption game under an asymmetric set-up; in some cases, the firm still adopts at the precommitment timing. This is due to the fact that adoption is not only influenced by its profitability for the adopter but also by the profitability of the adoption for the competitor. Indeed, as outlined by Lemma 1, two elements influence the capacity to adopt early or not: the firm's capacity to preempt its competitor and the competitor's capacity to preempt. The first element affects whether the firm has the potential to be the technology leader or not. For low upstream bargaining power (*i.e.* low β), AS prefers being the technology follower, as it does not have enough incentives to be the leader (due to the *bargaining* effect). This is in line with the results of the precommitment game: the more a firm is able to capture benefits from the adoption, the earlier it will adopt the technology.

Also, the study of the asymmetric case under preemption highlights the importance of the competitor's capacity to preempt on a firm's decision to adopt. If the competitor have very strong incentives to preempt, it is a better strategy for the firm to adopt second. On the contrary, if the competitor has very low incentives to preempt, the firm can afford to adopt at the precommitment timing without fear to be preempted. Ultimately, if the competitor have some incentives to preempt (but not enough to force the firm to adopt second), the competitor will be able to adopt as late as the competitor is able to preempt: the less the competitor can preempt, the closer to the precommitment timing the firm will be able to adopt.

Finally, a novel result highlighted by the study of the asymmetric case is the existence of unique subgame perfect equilibria under such a set-up. In the symmetric cases, in the precommitment game as in the preemption game, two symmetric equilibria exist: one where firm A is the leader and one where firm B is the leader. In the asymmetric case, I know with certainty that AI is the technology leader for parameter values below $\tilde{\beta}_2$, and AS is the technology leader for those above $\tilde{\beta}_2$. Also, another novel finding is that, for $\beta < \tilde{\beta}_1$ and $\beta > \tilde{\beta}_3$, the timings and order of adoption are the same under the precommitment game and the preemption game. Therefore, under asymmetry, these two games have the same predictions for a certain range of parameter values.

In sum, the study of the preemption game under an asymmetric set-up highlights how the capacity of the competitor to preempt drives how early adoption will occur.[17]

5.3 The Timing of Adoption under Preemption: a Comparison

Using the same parametrization, I am able to compare the adoption timing under the two symmetric cases versus the asymmetric case, for the preemption game. The preemption game highlights the same *strategic* and *bargaining* effects, but they are embodied in a single effect that drives the speed of adoption: the *preemption* effect. This effect determines which firm will adopt first and how fast it will adopt in the asymmetric case.

5.3.1 The Vertically Separated Case versus the Asymmetric Case

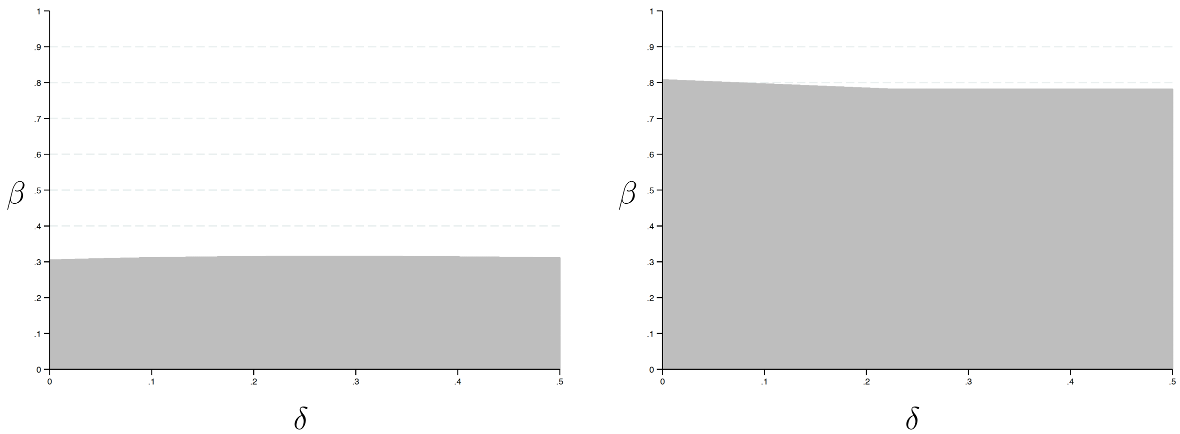
Let's consider the effect of the integration of a firm when the competitor is separated, represented in Figure 10. From these graphs, I state Corollary 3.

Corollary 3. *Under the specific parametrization where $r = 0.03$, $M = 1$ and $\alpha = 0.8$, under the preemption game and when the competitor is separated:*

- *integration accelerates first adoption when the integrated firm have strong incentives to adopt first at the precommitment timing in the asymmetric case (i.e. for low values of β).*

[17]The previous intuitions are qualitatively unaffected by changes in the parametrization, as shown in Appendix A.4.

- *integration accelerates second adoption when the separated firm is the technology follower in the asymmetric case (i.e. whenever β is not high).*



(a) First Adoption (b) Second Adoption

Figure 10: Comparison of Preemption Timing: VS v. Asymmetric Case

Note: In this graph, the parametrization is the following one: $M = 1$, $r = 0.03$ and $\alpha = 0.8$. The grey area corresponds to the parameters values for which the adoption is occurring earlier after the integration.

One can see that the conclusion about the impact of integration when the competitor is separated is different though quite similar to the precommitment game. In particular, the case of the first integration is more complex due to what I call the *preemption* effect. Indeed, for low upstream bargaining power, Firm AI knows it cannot be preempted and will adopt at its precommitment timing, whereas if it remained separated, it would have adopted at the vertically separated preemption timing, which is late for such low values of β (due to the *bargaining* effect). For the rest of the parameter values, the preemption incentive is much stronger under the vertically separated case than under the asymmetric case, due to the *strategic* effect. Hence, the area of parameters for which integration accelerates first adoption is smaller under the preemption game than under the precommitment game, because preemption always occurs under the symmetric set-up, which is not necessarily the case in the asymmetric one.

The conclusions for the second adoption are very similar to the precommitment game: as long as the separated firm is the follower in the asymmetric case (*i.e.* when β is high), the second adoption occurs faster after integration. For some parameter values, the integrated firm adopts second, but as described in the precommitment case, the *bargaining* effect is relevant, and integration accelerates second adoption whenever the upstream bargaining power is not too high.

5.3.2 The Asymmetric Case versus the Vertically Integrated Case

I numerically estimate the effect of integration on the timing of technology adoption under the preemption game, but since the result is unambiguous (*i.e.* true for all parameter values), I skip the graphical exposition and directly state Corollary 4.

Corollary 4. *Under the specific parametrization where* $r = 0.03$*,* $M = 1$ *and* $\alpha = 0.8$*, under the preemption game and when the competitor is integrated, integration always accelerates both adoptions.*

The conclusions about the impact of integration on the timing of adoption is much simpler than under the precommitment game. Integration necessarily accelerates the first integration. When AI is the technology leader in the asymmetric case (*i.e.* for low values of β), the *strategic* and the *preemption* effect are at stake: an integrated firm has more incentives to adopt when the competitor is integrated, especially because its preemptive threat is stronger. When AS is the technology leader in the asymmetric case (*i.e.* for high values of β), even though the *bargaining* effect is at stake, it is counterbalanced by the *preemption* effect: the poor preemptive threat of AI makes AS adopt closer to its precommitment timing, which is later than the preemption timing of the vertically integrated case.

Integration always accelerate second adoption when the competitor is already integrated. Indeed, in the precommitment game, the only situation where second adoption occurs faster in the asymmetric case was when β was high, and AS was adopting second. Here, when β is high, AS is always the technology leader. Hence, second adoption always occur faster under the vertically integrated case.

The type of game driving the technology adoption decision crucially affect the impact of the vertical structure of market on the timing of adoption. Especially when considering the integration of firm facing an integrated competitor, the conclusion about the effect of such merger on innovative activities strongly differs from the precommitment game to the preemption game.[18] The following section, which examines some policy implications, also highlights some fundamental differences between precommitment and preemption games.

6 Policy Implications: the Socially Optimal Timing

An industrial policy aims at optimizing the performance of an industry by giving it the right incentives to produce optimally. The optimality standard in this section is social welfare: an outcome is optimal if it maximizes the sum of profits and consumers' surplus. I design here a policy intervention at the adoption decision stage (taking the vertical

[18] This result, as shown in Appendix A.4.2, does not qualitatively depend on the parametrization.

structure of the market as exogenous): how and in which direction should the timing of adoption decision be influenced?

First of all, the socially optimal timing of adoption must be defined. This involves writing down the infinite stream of per-period social welfare, and maximizing it with respect to timing of adoption. Under the Cournot type of competition I used in this paper, consumer surplus is simply defined by the squared total output divided by two.[19] Such problem takes the following form:

$$\max_{T_1,T_2} SW_i = \int_0^{T_1} (\frac{(q_i^0+q_j^0)^2}{2} + \pi_i^0 + \pi_j^0) e^{-rt} dt + \int_{T_1}^{T_2} (\frac{(q_i^l+q_j^f)^2}{2} + \pi_i^l + \pi_j^f) e^{-rt} dt \\ + \int_{T_2}^{\infty} (\frac{(q_i^b+q_j^b)^2}{2} + \pi_i^b + \pi_j^b) e^{-rt} dt - k(T_1) - k(T_2) \tag{23}$$

where i is the identity of the technology leader, j the one of the follower, and where the superscript has the same meaning as before. Both i and j can be replaced by VS or VI in the vertically separated and integrated cases, as the identity of the firm does not matter in the symmetric case. Also, in this case, the per-period profits are the total ones (*i.e.* upstream plus downstream profits).

Maximizing (23) with respect to T_1 and T_2, I obtain the first order conditions defining the socially optimal timings, per vertical set-up: I_1^{VSsw}, I_2^{VSsw}, I_1^{VIsw}, I_2^{VIsw}, I_1^{AIsw}, I_2^{ASsw}, I_1^{ASsw} and I_2^{AIsw}.[20]

6.1 Industrial Policy under the Precommitment Game

I compare now these first order conditions to the *laissez-faire* ones under the precommitment game. This allows me to indicate whether a given adoption is occurring "too fast" or "too late", depending on the market structure. Under the precommitment game, I obtain the following relationships:

$$\begin{aligned} T_1^{VS} > T_1^{VSsw} \quad &\Leftrightarrow \quad 0 \le \beta \le 1 \quad and \quad 0 < \delta \le 1/2 \\ T_2^{VS} > T_2^{VSsw} \quad &\Leftrightarrow \quad 0 \le \beta < \beta_5^* \equiv \frac{2(3-4\delta)}{3(2-\delta)} \quad and \quad 0 < \delta \le 1/2 \end{aligned}$$

$$\begin{aligned} T_1^{VI} > T_1^{VIsw} \quad &\Leftrightarrow \quad 0 \le \beta \le 1 \quad and \quad 0 < \delta \le 1/2 \\ T_2^{VI} < T_2^{VIsw} \quad &\Leftrightarrow \quad 0 \le \beta \le 1 \quad and \quad 0 < \delta \le 1/2 \end{aligned}$$

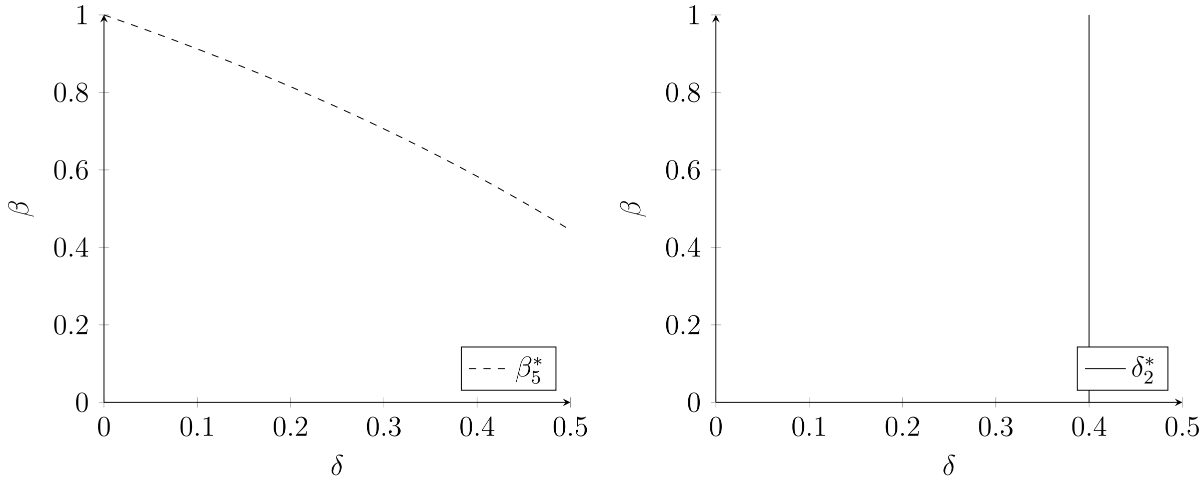
[19]This is a standard Cournot result. To see this, one can compute $\int_0^Q (a-t)dt - (a-Q)Q$.

[20]Notation is the same than before, where the subscript SW is added to indicate social optimality.

$$T_1^{AI} < T_1^{AI_{SW}} \Leftrightarrow 0 \leq \beta \leq 1 \quad and \quad 0 < \delta < \delta_2^* \equiv 2/5$$
$$T_2^{AS} > T_2^{AS_{SW}} \Leftrightarrow 0 \leq \beta \leq 1 \quad and \quad 0 < \delta \leq 1/2$$

$$T_1^{AS} > T_1^{AS_{SW}} \Leftrightarrow 0 \leq \beta \leq 1 \quad and \quad 0 < \delta \leq 1/2$$
$$T_2^{AI} < T_2^{AI_{SW}} \Leftrightarrow 0 \leq \beta \leq 1 \quad and \quad 0 < \delta \leq 1/2$$

I represent the threshold values for the vertically separated case and the asymmetric case where AI leads in Figure 11. Then, I state Proposition 3.



(a) The Vertically Separated Case (b) The Asymmetric Case: *AI* leads

Figure 11: The Optimal Timings of Adoption under Precommitment

Note: (a) For the values of β and δ below the dashed curve, second adoption under the vertically separated case occurs too late. (b) For the values of β and δ to the right of the plain line, first adoption occurs too late in the asymmetric case where the integrated firm leads.

Proposition 3. *Under the precommitment game, defining optimality as maximizing social welfare, one can state the following:*

- *When both firms are separated, first adoption always occurs too late, and second adoption occurs too late (early) when $\beta < \beta_5^*$ ($\beta > \beta_5^*$).*
- *When both firms are integrated, first adoption always occurs too late, and second adoption always occurs too early.*
- *When the integrated firm leads in the asymmetric case, first adoption occurs too late (early) when $\delta > \delta_2^*$ ($\delta < \delta_2^*$), and second adoption always occurs too late.*
- *When the separated firm leads in the asymmetric case, first adoption always occurs too late, and second adoption always occurs too early.*

The intuition is as follow. In Section 4, the timing of adoption depended only on the pay-off of the adopter. Here, the optimal timing of adoption takes into account three other elements: the pay-off of the downstream firm when the firm is separated, the pay-off of the competitor, and the consumers' surplus. The weight of these different agents in social welfare will determine whether the stand-alone incentives to adopt the technology are too important or not sufficient. In general, the consumers will prefer earlier adoption,[21] whereas the competitor will prefer later adoption; depending on how important these preferences are, the *laissez-faire* adoption may occur too late or too early.

Now I have defined whether adoptions should happen later or earlier, which policy instrument should be used in order to incentivize firms to adopt at the right time? The taxation (or subsidization) schedule should be such that no price or quantity distortion is observed. Ideally, the only variable affected should be the timing of technology adoption. Hence, a lump-sum per-period tax, imposed to the leader from the first adoption on, and another one imposed to the follower from the second adoption on, fits such requirements. Technically, it is necessary to impose a tax on the technology leader only during the period between the two adoptions. The reason why I still imposed the tax after the second adoption is that, from a social policy point of view, it seems hard to defend a taxation scheme imposed on one firm depending on the actions of its competitor. However, the reader should keep in mind that taxation for the leader do not need to be imposed after second adoption.

Mathematically, the tax Tax_1^i and Tax_2^i are imposed such that the problem of the firms becomes:

$$\max_{T_1} \Pi_1^i(T_1, T_2) = \int_0^{T_1} \pi_i^0 e^{-rt} dt + \int_{T_1}^{T_2} (\pi_i^l - Tax_1^i) e^{-rt} dt + \int_{T_2}^{\infty} (\pi_i^b - Tax_1^i) e^{-rt} dt - k(T_1)$$

$$\max_{T_2} \Pi_2^i(T_1, T_2) = \int_0^{T_1} \pi_i^0 e^{-rt} dt + \int_{T_1}^{T_2} \pi_i^f e^{-rt} dt + \int_{T_2}^{\infty} (\pi_i^f - Tax_2^i) e^{-rt} dt - k(T_2)$$

where $i \in \{VS, VI, AI, AS\}$, like before. Solving this maximization program, it is easy to show that, in order to obtain the socially optimal first order conditions, one should just set:

$$Tax_1^i = I_1^i - I_1^{isw} \quad Tax_2^i = I_2^i - I_2^{isw}$$

Whenever Tax_1^i and Tax_2^i are negative, they become subsidies. Indeed, they take positive values when the firms should adopt later, and negative values when they should adopt earlier. Thus, I state Corollary 5.

Corollary 5. *The market will naturally select the optimal timing of technology adoption if a tax $Tax_1^i = I_1^i - I_1^{isw}$ is imposed on the technology leader from T_1^i on, and if a tax $Tax_2^i = I_2^i - I_2$ is imposed on the technology follower from T_2^i on.*

Such taxation schedule does not distort price, quantities or contracts; it solely affects the

[21] Indeed, they would like simultaneous immediate adoption, since it triggers the highest output.

timing of technology adoption. However, it may also affect the existence of equilibria in the asymmetric case: when AI leads, $T_1^{AIsw} < T_2^{ASsw}$ only if $\delta > \delta_3^* \equiv 10/31 \approx 0.32$. For parameter values below δ_3^*, the incentives to adopt for the separated firm (the follower in this case) are higher than the ones of the integrated firm (the leader). This is due to the consumers' preference for high quantity, and then for the case where the separated firm, which produces more, has adopted the technology. Therefore, under such taxation schedule, the asymmetric equilibrium where the integrated firm leads does not exist for parameter values below δ_3^*. For values below this threshold, the taxation scheme dissuades the integrated firm to be the leader in the asymmetric case, and the equilibrium where AS is the technology leader is unique. Henceforth, in the asymmetric case, the taxation scheme unambiguously increases welfare whenever AS is the leader and when AI is the leader for parameter values above δ_3^*.

6.2 Industrial Policy under the Preemption Game

The optimal timing of adoption under the preemption game is the same as under the precommitment game. Also, since the timing of second adoption is the same under both types of game (*i.e.* $T_2^{pei} = T_2^{pci}$), the conclusions and taxation scheme developed before for the second adoption are also valid under the preemption game.

However, the lack of analytical solution for the timing of first adoption prevents us from drawing general optimality conclusions. Still, I can run simulations and numerically compare the preemption timings of adoption with the optimal one. Figure 12 depicts the parameter values for which first adoption occurs too late. When the optimality conclusions are unambiguous (*i.e.* true for all parameter values), graphical representation is skipped.

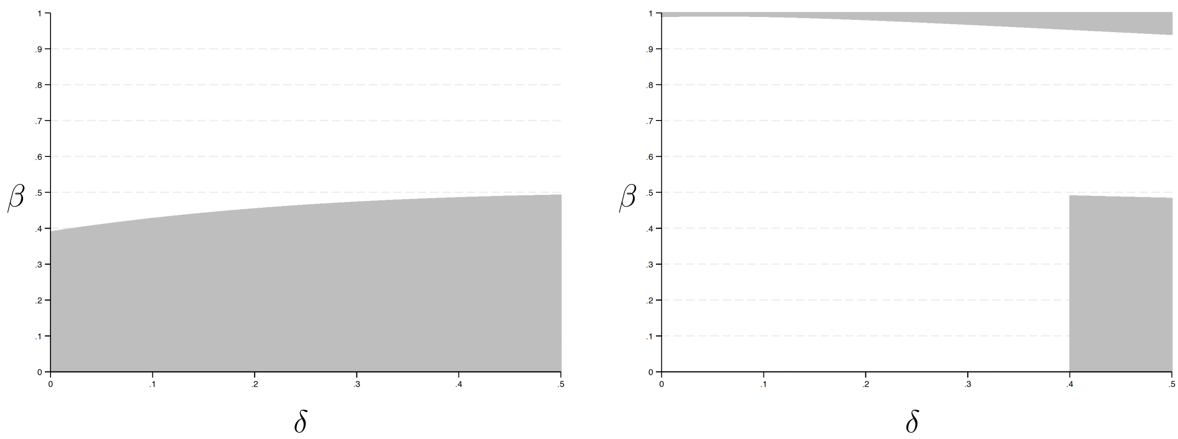
From Figure 12, I state Proposition 4.

Proposition 4. *Under the preemption game and for the parametrization $M = 1$, $r = 0.03$ and $\alpha = 0.8$, defining optimality as maximizing social welfare, one can state the following:*

- *When both firms are separated, first adoption occurs too late (early) for low (high) values of upstream bargaining power .*
- *When both firms are integrated, first adoption always occurs too early.*
- *Under the asymmetric case, first adoption occurs too late when:*
  - *the integrated firm adopts first at the precommitment timing and the effectiveness of the technology is high,*
  - *the separated firm adopts first and the upstream bargaining power is very high.*

  Otherwise, first adoption occurs too early.

The conclusions about the optimal timing of second adoption under the precommitment game are also valid under the preemption game.



(a) The Vertically Separated Case (b) The Asymmetric Case

Figure 12: The Optimal Timings of Adoption under Preemption

Note: In this graph, the parametrization is the following one: $M = 1$, $r = 0.03$ and $\alpha = 0.8$. The grey areas correspond to the parameters values for which the first adoption is occurring too late according to social welfare criterion. For the parameters values in the blank areas, first adoption is occurring too fast under the preemption game.

The optimality conclusions about first adoption are considerably different. Under the precommitment game, firms were always adopting too late under the vertically integrated case, whereas here, they are always adopting too early. This is due to the *preemption* effect, that forces the leader to adopt much earlier than he would like to, and even the competitor would like it to adopt later.

For the vertically separated case, first adoption was always occurring too late under the precommitment game, whereas it is the case under the preemption game only for low upstream bargaining power. This is related to the *bargaining* effect: when β is low, the preemption incentive is very low, and adoption does not occur fast enough. On the contrary, as soon as β gets bigger, the *preemption* effect gets stronger and adoption occurs too fast according to both firms' taste.

Finally, in the asymmetric case, when the integrated firm leads and adopts at the precommitment timing under the preemption game, it adopts too late for the same parameters range than the precommitment game, that is for high technology effectiveness (*i.e.* $\delta > \delta_2^*$). When the separated firm leads, it adopts too late only for very high upstream bargaining power values, whereas it was adopting too late for all parameters values under the precommitment game. This is due to the fact that the preemptive pressure from the competitor is too low when β is high, allowing AS to adopt closer (or at) to its precommitment timing. For the other parameter values, the *preemption* effect is relevant and make the firms adopt earlier than they would like to. The previous results are robust to parametrization changes, as shown in Appendix A.4.3.

In terms of taxation policy, it remains the same as in the precommitment one for the second adoption. However, due to the lack of analytical solution, it is impossible to design a general taxation policy for the timing of first adoption under the preemption game. Nevertheless, for the symmetric case, condition (21) allows us to figure out which type of taxation would be efficient. It would still consist of a lump-sum tax imposed on the technology leader from its adoption until the next one (in order to affect π^l in the left-hand side of the equation). Indeed, since T_1^{pei} is determined through the equalization of the leader's rent and the follower's one, imposing such tax (subsidy) would make the first adoption occur later (earlier). Graphically, this would make the leader's profit curve (*i.e.* the concave one) shift down (or up) towards the follower's profits curve (*i.e.* the linearly increasing one) in Figure 8. Concerning the asymmetric case, imposing a taxation and trying to influence the timing of adoption would change the equilibria and the technology positions of the players in the preemption game. Hence, a taxation scheme would distort the price and quantities through the change of the technology positions, which would affect the welfare benefit from such a policy.

7 Conclusion

Vertical structure is an important driver of economic performance. In particular, it affects the capacity to innovate and to undertake costly research investments. In my model, I show how the vertical structure of a market affect the patterns of adoption of a cost-reducing technology. In particular, I focus on the resolution of the technology adoption game under an asymmetric set-up, whereby one firm is integrated while the other one is separated. The study of the asymmetric case reveals the two main drivers of technology adoption: a *bargaining* and *strategic* effect. The first one relates to the capacity of the adopter to capture the benefits from adoption depending on its vertical structure, whereas the second one relates to the fact that this capacity also depends on the vertical structure of the competitor. These effects can be differentiated thanks to the study of the asymmetric case.

This work improves the understanding of the effect of integration on the technology adoption patterns. The investigation of the asymmetric market structure allows comparing the effect of a vertical integration on technology adoption when the competitor is separated to the situation when the competitor is integrated. Indeed, the impact of integration on the timing of technology adoption differs significantly depending on the competitor's vertical structure. Especially when considering the preemption game, integration unambiguously accelerates adoptions when the competitor is integrated, whereas it is not necessarily the case when it is is separated.

Finally, this research develops some policy implications. While it is an important information for competition authorities to know the effect of a vertical integration on innovation, the industrial policy-maker can use a taxation scheme to make the market adopt the technology at the socially optimal time. There are substantial differences between the two types of adoption game on that question. While firms tend to adopt too late under the precommitment game, they tend to adopt too early under the preemption game, due to a *preemption* effect that accelerates adoptions. Also, while a taxation scheme can be easily designed under precommitment and symmetry, it is much harder to impose a taxation system without distorting quantities under preemption and under asymmetric set-up in general.

In addition, this paper contributes to the technology adoption literature by solving adoption games in an asymmetric set-up. New features of this type of games is revealed by asymmetry. First, unique pure strategy equilibria may be obtained under the precommitment game, and unique subgame perfect equilibria are obtained under the preemption game. Also, the timings of adoption under the preemption game may be identical to the ones of the precommitment game in an asymmetric set-up.

Overall, this work aims to highlight two main features. First, vertical structure is a key driver of the speed of technology adoption, and this must be taken into account when considering the impact of a vertical integration on a market performance. Second, the nature of the technology adoption game considerably affect the predictions of adoption patterns and their welfare impact. These results pave the way to what I think being two important future research. A first one shall investigate empirically which type of game predicts best the adoption patterns within an industry. A second one shall endogenize the integration decision of firms, in order to estimate the impact of innovation on merger decisions on the one hand, and whether such integration should be forbidden or not on the other hand. I explore that research path in my second working paper and show that the presence of cost-reducing technology affects the integration choices of firm, yielding under some conditions the situation of asymmetric integration, whereby one firm chooses to integrate its downstream partner while the competitor remain separated. I ultimately discuss whether such integrations should be prevented by competition authorities, and argue that the *laissez-faire* outcomes are most of the time the socially preferred ones.

A Appendix

A.1 Proof: $-k'(t)e^{rt}$ is decreasing

In order to prove that $-k'(t)e^{rt}$ is decreasing with t, one must show that:

$$\begin{aligned} & (-k'(t)e^{rt})' < 0 \\ \Leftrightarrow \quad & -(k''(t)e^{rt} + rk'(t)e^{rt}) < 0 \\ \Leftrightarrow \quad & k''(t) + rk'(t) > 0 \end{aligned} \tag{24}$$

By Assumption 2, $(k(t)e^{rt})' < 0$ and $(k(t)e^{rt})'' > 0$. Therefore:

$$\begin{aligned} & (k(t)e^{rt})' < 0 \\ \Leftrightarrow \quad & k'(t)e^{rt} + rk(t)e^{rt} < 0 \\ \Leftrightarrow \quad & k'(t) + rk(t) < 0 \end{aligned} \tag{25}$$

and

$$\begin{aligned} & (k(t)e^{rt})'' > 0 \\ \Leftrightarrow \quad & re^{rt}(k'(t) + rk(t)) + e^{rt}(k''(t) + rk'(t)) > 0 \end{aligned} \tag{26}$$

Since the first term of this last equation is negative according to (25), then the second term is necessarily positive. In other words, if both (25) and (26) hold, then (24) holds for all t.

A.2 Discussion: the impact of δ on the timing of adoption

This Appendix subsection discusses the various effects of δ, the effectiveness of the technology, on the timings of adoption in the asymmetric case. The idea of this subsection is to show that for most parameters values, the impact of the innovation effectiveness on the leader's (follower's) increment to profits due to adoption is stronger (weaker) when this firm is competing with a vertically separated firm.

First of all, the partial derivatives of first order conditions with respect to δ are computed:

$$\begin{array}{ll} \dfrac{\partial I_1^{AI}}{\partial \delta} = \dfrac{3}{8}M^2(1+3\delta) & \dfrac{\partial I_2^{AI}}{\partial \delta} = \dfrac{3}{8}M^2(1-\delta) \\ \dfrac{\partial I_1^{AS}}{\partial \delta} = \dfrac{1}{2}M^2\beta(1+2\delta) & \dfrac{\partial I_2^{AS}}{\partial \delta} = \dfrac{1}{2}M^2\beta \end{array}$$

These derivatives are all positive,[22] meaning that an increase in technology's effectiveness necessarily accelerates adoption. This result is obvious for first adoption, which relies on the difference between per-period profits as a leader and those when no one has adopted. The former increases with δ whereas the latter is unaffected by it: therefore, the first order condition increases with δ. However, the result is less obvious for second adoption, which relies on the difference between per-period profits when both have adopted and those as a follower. The former increases with δ while the latter decreases with it. The first (positive) effect is visibly stronger than the second (negative) one.

In order to explain why β_1^* is upward slopping and why β_2^* is downward slopping in Figure 5, I show that for most parameters values $\frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_2^{AS}}{\partial \delta}$ and $\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_1^{AS}}{\partial \delta}$. Indeed, it is easy to show that:

$$\frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_2^{AS}}{\partial \delta} \quad \Leftrightarrow \beta < \beta_1^{'} \equiv \frac{3}{4}(1+3\delta)$$
$$\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_1^{AS}}{\partial \delta} \quad \Leftrightarrow \beta > \beta_2^{'} \equiv \frac{3}{4}\frac{1-\delta}{1+2\delta}$$

Graphically, one can see in Figure 13 that the area between the two lines covers a very important share of possible parameters values.

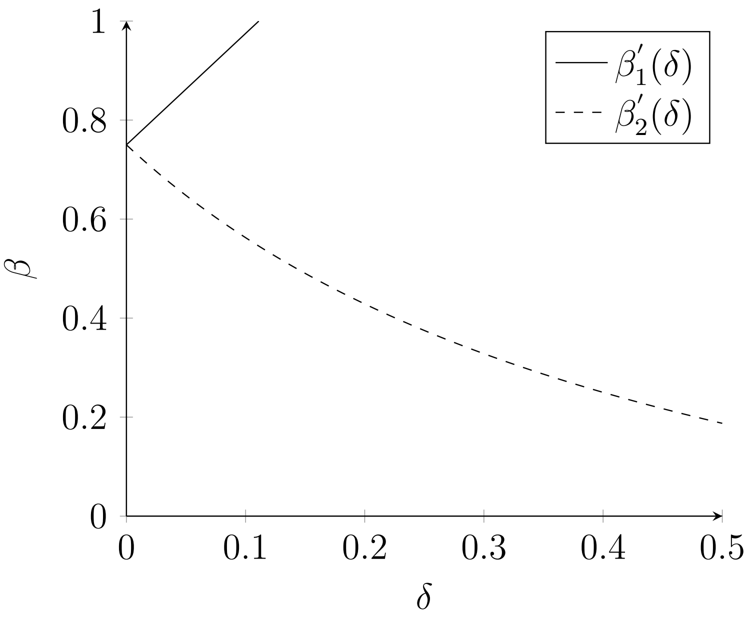


Figure 13: $\frac{\partial I_1^{AI}}{\partial \delta}$ vs $\frac{\partial I_2^{AS}}{\partial \delta}$, $\frac{\partial I_2^{AI}}{\partial \delta}$ vs $\frac{\partial I_1^{AS}}{\partial \delta}$

Note: For the values of β and δ below the plaine line, $\frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_2^{AS}}{\partial \delta}$. For the values of β and δ above the dashed line, $\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_1^{AS}}{\partial \delta}$.

Finally, in order to support the claim that generally, the vertically integrated per-period profits, and then timings, are more significantly affected by the effectiveness of the tech-

[22] Since $\delta \in [0, 0.5]$ and $\beta \in [0, 1]$.

nology than the ones of the vertically separated firms, I show that for most parameters values $\frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_1^{AS}}{\partial \delta}$ and $\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_2^{AS}}{\partial \delta}$. Indeed, it is easy to show that:

$$\frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_1^{AS}}{\partial \delta} \quad \Leftrightarrow \beta < \beta_1^{''} \equiv \frac{3}{4}\frac{1+3\delta}{1+2\delta}$$
$$\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_2^{AS}}{\partial \delta} \quad \Leftrightarrow \beta > \beta_2^{''} \equiv \frac{3}{4}(1-\delta)$$

Graphically, one can see in Figure 14 that the area between the two lines covers an important share of possible parameters values.

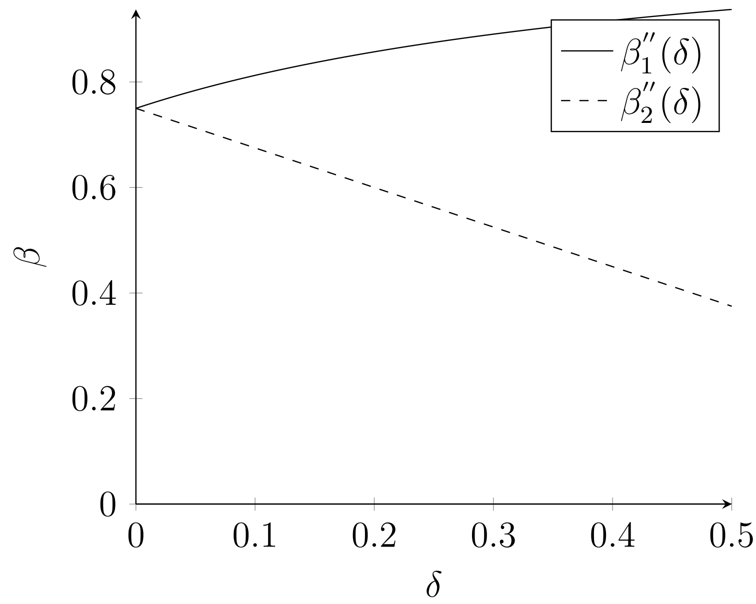


Figure 14: $\frac{\partial I_1^{AI}}{\partial \delta}$ vs $\frac{\partial I_1^{AS}}{\partial \delta}$, $\frac{\partial I_2^{AI}}{\partial \delta}$ vs $\frac{\partial I_2^{AS}}{\partial \delta}$

Note: For the values of β and δ below the plain line, $\frac{\partial I_1^{AI}}{\partial \delta} > \frac{\partial I_1^{AS}}{\partial \delta}$. For the values of β and δ above the dashed line, $\frac{\partial I_2^{AI}}{\partial \delta} < \frac{\partial I_2^{AS}}{\partial \delta}$.

A.3 Solving: Preemption game under asymmetry

This appendix presents the solving of the preemption game under the asymmetric set-up. To my knowledge, this type of solving has never been covered by the literature. I explain the solving by presenting graphically the various situations that may occur. The payoffs of the firm when it is the leader and when it is the follower may have different shapes in the asymmetric case, as the payoffs and the timings of adoption of the competitor are not symmetric anymore. Figure 15 represents the classical case: case 1. I call Firm i the firm I am considering, and Firm j the competitor. The superscripts pc and pe denote the precommitment and the preemption timings respectively.

In Case 1 (depicted in Figure 15), several situations may arise, depending on the tim-

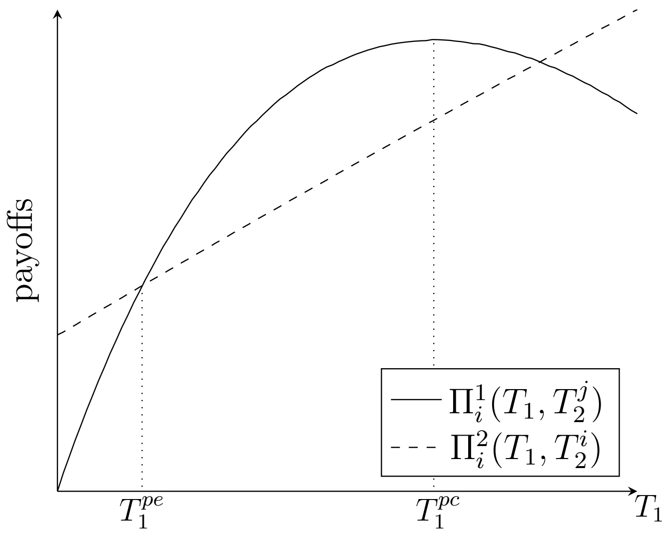


Figure 15: Preemption in the Asymmetric Case - Case 1

Note: The plain line and the dashed line represents respectively the profits of the technology leader and the profits of the technology follower, as a function of the timing of the first adoption. The technology leader's profits reach a maximum at T_1^{pc}, the precommitment timing, and are equal to the follower's ones at T_1^{pe}, the preemption timing.

ings of the competitor. If the competitor have very low incentives to preempt (*i.e.* $T_1^{pej} > T_1^{pci}$), and cannot even preempt the precommitment timing of Firm i, Firm i will choose its precommitment timing. If the competitor have some incentives to preempt (*i.e.* $T_1^{pei} < T_1^{pej} < T_1^{pci}$) but Firm i has stronger preemption incentives, Firm i adopts at the preemption timing of Firm j (T_1^{pej}). Indeed, the closest Firm i adopts to T_1^{pci}, the more profitable it is. Hence, it adopts as close as possible to the preemption timing of its competitor. When the competitor has stronger incentives to preempt (*i.e.* $T_1^{pej} < T_1^{pei}$), Firm i adopts second at T_2^{pci}. Knowing it does not have the possibility to preempt its competitor, Firm i prefers adopting second.

Since the payoffs and the timing of second adoption are identical for both firms, other cases may arise. Case 0 is represented in Figure 16. Case 0 and Case 1 are very similar and share the same reasoning. The only difference is that in Case 0, Firm i has such strong incentives to preempt that it can profitably preempt at time $t = 0$. Hence, it cannot be preempted.

Case 2, depicted in Figure 17, is a specific case where Firm i has no incentives to preempt, and always prefer to be the technology follower. This situation arises in areas where the profitability of first adoption is extremely low and the precommitment equilibrium where Firm i leads does not exist. In Case 2, Firm i always adopt second at T_2^{pci}.

A final case, Case 3, depicted in Figure 18, can be thought as an intermediary case between Case 1 and Case 2. The profitability of first adoption is so low that adopting at the precommitment timing brings less profits than adopting second, but for a certain

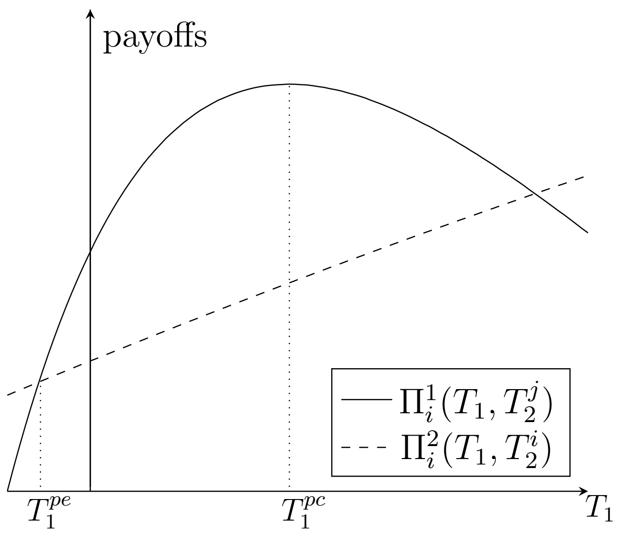


Figure 16: Preemption in the Asymmetric Case - Case 0

Note: The plain line and the dashed line represents respectively the profits of the technology leader and the profits of the technology follower, as a function of the timing of the first adoption. The technology leader's profits reach a maximum at T_1^{pc}, the precommitment timing, and are equal to the follower's ones at T_1^{pe}, the preemption timing.

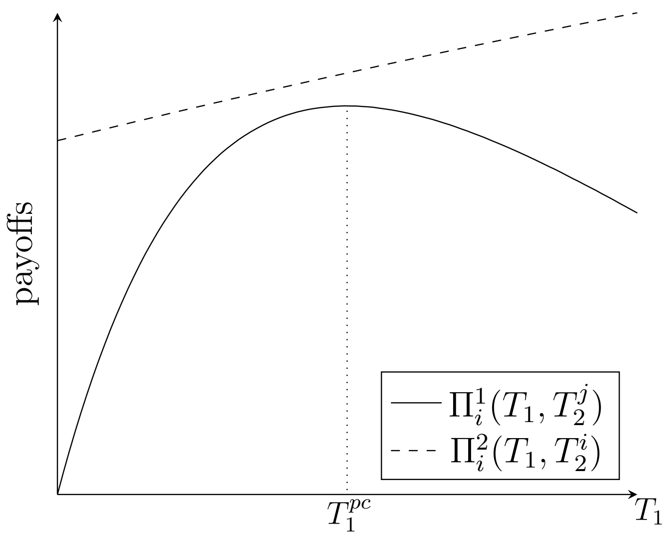


Figure 17: Preemption in the Asymmetric Case - Case 2

Note: The plain line and the dashed line represents respectively the profits of the technology leader and the profits of the technology follower, as a function of the timing of the first adoption. The technology leader's profits reach a maximum at T_1^{pc}, the precommitment timing. In this specific case, the leader's profits are constantly lower than the follower's ones.

range of timing, preemption is still profitable. t^* is the latest timing for which preemption is profitable. If $T_1^{pcj} > t^*$, Firm i adopts second at T_2^{pci}. Even if it could preempt the competitor, this would bring profits to lower levels than adopting second and let the competitor adopt at its precommitment timing. If $T_1^{pcj} < t^*$, preemption becomes profitable, and Firm i adopts at T_1^{pej} if it can preempt its competitor (*i.e.* $T_1^{pei} < T_1^{pej}$), or at T_2^{pci} if it cannot (*i.e.* $T_1^{pei} > T_1^{pej}$). The last case that could arise is the one where $T_1^{pei} < 0$ and Firm i prefers being the follower at T_1^{pci}. This is a mix of Case 0 and Case 3,

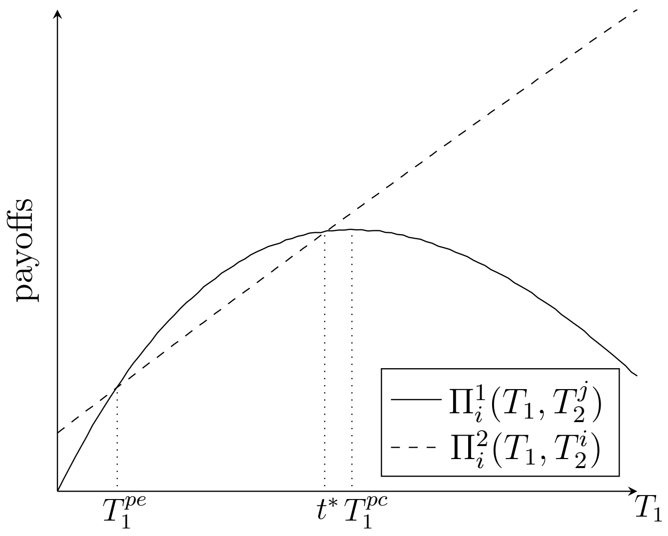


Figure 18: Preemption Figure in the Asymmetric Case - Case 3

Note: The plain line and the dashed line represents respectively the profits of the technology leader and the profits of the technology follower, as a function of the timing of the first adoption. The technology leader's profits reach a maximum at T_1^{pc}, the precommitment timing, and are equal to the follower's ones at T_1^{pe}, the preemption timing. In this specific case, the leader's profits are lower than the follower's ones at T_1^{pc}.

so I call it Case 30. I do not develop the graphical exposition and the reasoning because this case does not arise in the parameterizations of this work, and also because it consists in simply blending the response functions described above for Case 3 and Case 0.

To solve the game, it is simply sufficient to program the different response functions under the different cases for both Firm AS and AI, and compute the timings of adoption for every parameter combination of β and δ. This is how Figure 9 is obtained.

Two problematic situations may occur. The first one would be that both firms would like to adopt second. This situation would occur if both firms were in Case 2. This never happens because it is a situation that arises when the precommitment equilibrium does not exist, and there is always at least one existing equilibrium in the precommitment game. The second situation that could be problematic would be that both firms want to adopt at time $t = 0$. This corresponds to the case where both firms are in Case 0. This can occur for some parameters values where both firms have strong incentives to adopt, but this happens only if the speed of decrease of the adoption cost is not convex enough (*i.e.* when α is very low). Hence, I chose parameterizations where this situation does not arise.[23] The following Figures 19 and 20 show the different cases faced by Firm AS and AI depending on the parameter values, and Table 1 is a matrix showing the cases faced by both firms and the number of points falling in every combination of case AS and case AI. I estimated a million combinations of β and δ in total.

[23]The reader can think of this choice as an extra assumption to avoid the situation where firms want to adopt immediately, similar to the one I made in the precommitment game section.

Case AI / Case AS	Case 0	Case 1	Case 2	Case 3
Case 0	0	6,016	107,222	2,042
Case 1	9,904	337,689	388,667	59,844
Case 2	0	1,391	0	0
Case 3	968	86,257	0	0

Table 1: Cases Matrix - Preemption Game

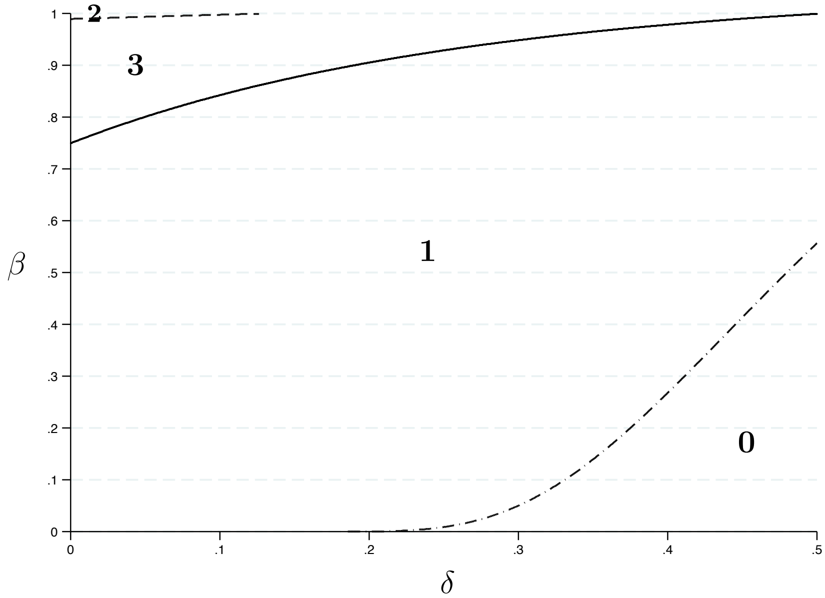


Figure 19: Preemption Cases - Firm AI

Note: In this graph, the parametrization is the following one: $M = 1$, $r = 0.03$ and $\alpha = 0.8$. The numbers indicate the parameter values for which firm AI faces the case 0, 1, 2 or 3.

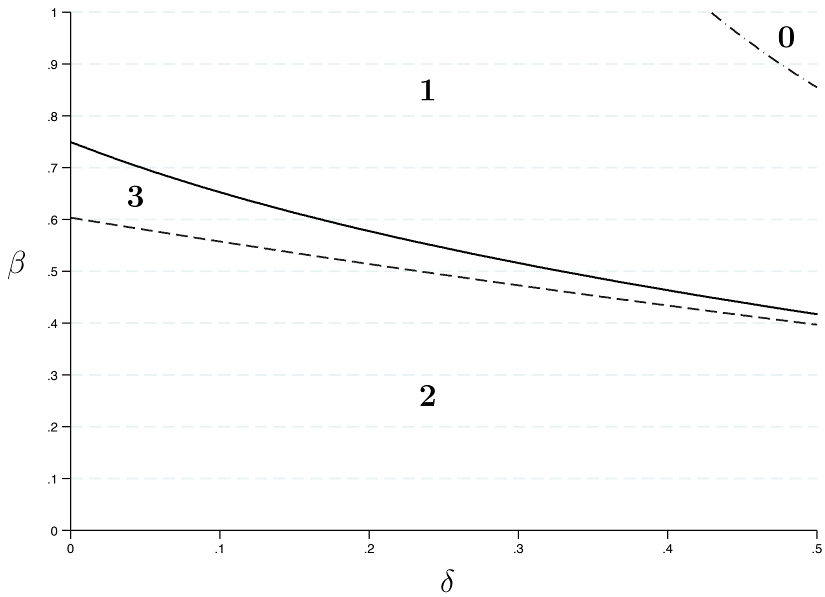


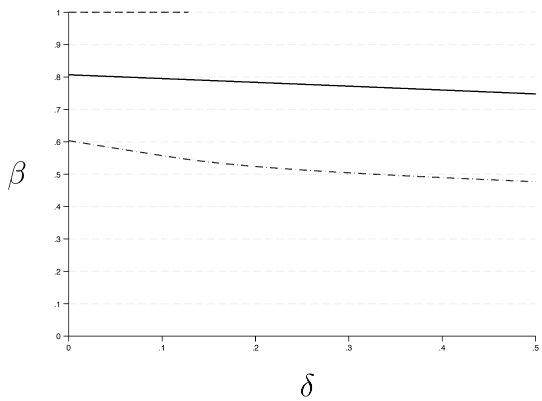
Figure 20: Preemption Cases - Firm AS

Note: In this graph, the parametrization is the following one: $M = 1$, $r = 0.03$ and $\alpha = 0.8$. The numbers indicate the parameter values for which firm AS faces the case 0, 1, 2 or 3.

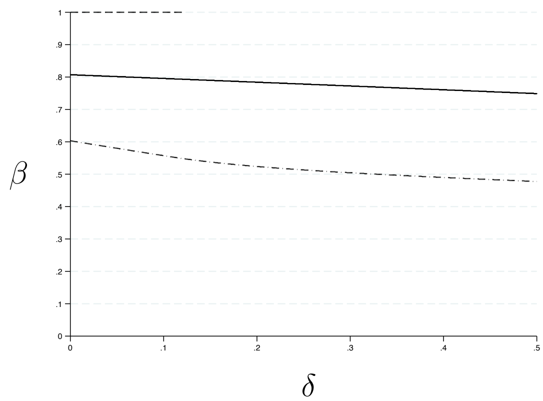
A.4 Solving: Alternative parameterizations

This last appendix section present alternative parametrizations for all the results from the preemption game analysis. Here as well, when the interpretation is unambiguous (*i.e.* true for all parameter values), graphical exposition is skipped. This is the case for two results: regardless of the paramterization, integration always accelerates both adoptions when the competitor is integrated, and first adoption always occurs too early in the vertically integrated case.

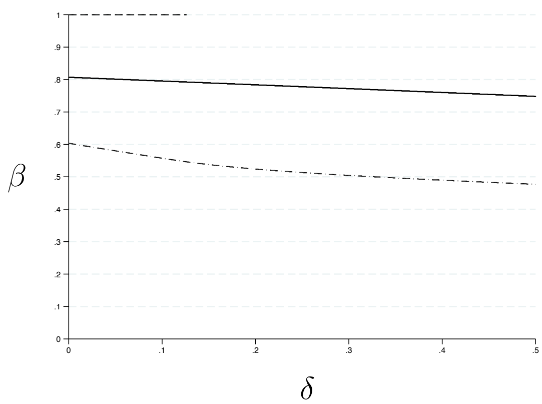
A.4.1 Adoption Equilibria - Preemption Game



(a) $M = 1$, $\alpha = 1$ and $r = 0.03$



(b) $M = 1$, $\alpha = 0.8$ and $r = 0.05$

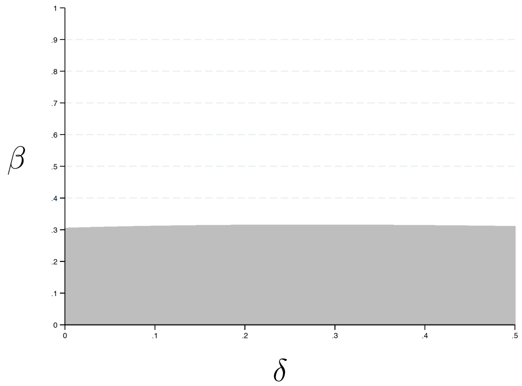


(c) $M = 0.5$, $\alpha = 0.8$ and $r = 0.03$

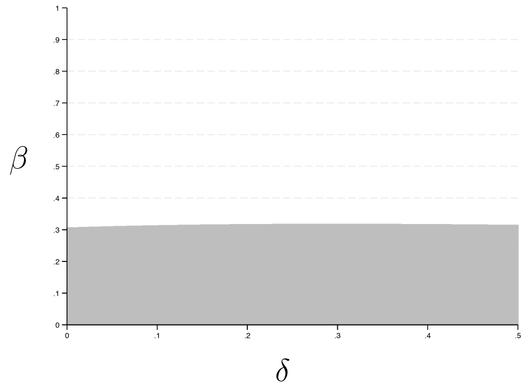
Figure 21: Comparison of Preemption Timing: First Adoption

Note: These graphs are replications of Figure 9 under different parametrizations.

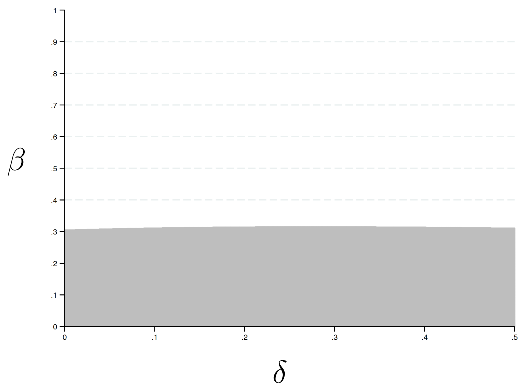
A.4.2 Comparison of Preemption Timing: VS v. Asymmetric Case



(a) $M = 1$, $\alpha = 1$ and $r = 0.03$



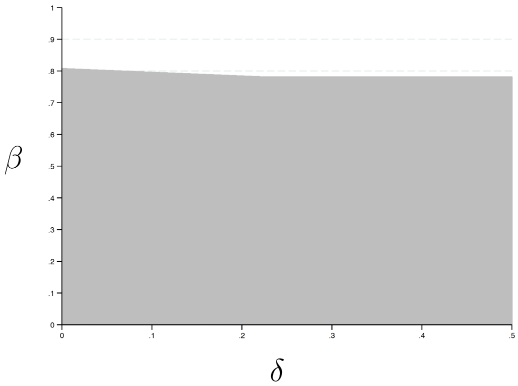
(b) $M = 1$, $\alpha = 0.8$ and $r = 0.05$



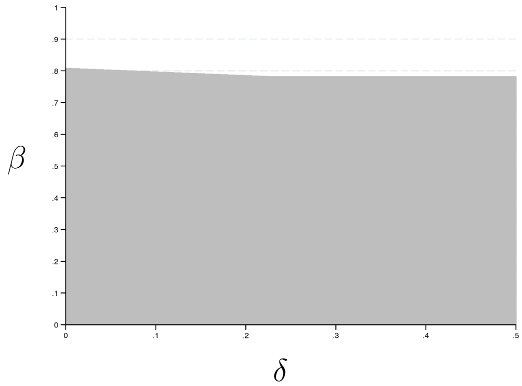
(c) $M = 0.5$, $\alpha = 0.8$ and $r = 0.03$

Figure 22: Comparison of Preemption Timing: First Adoption

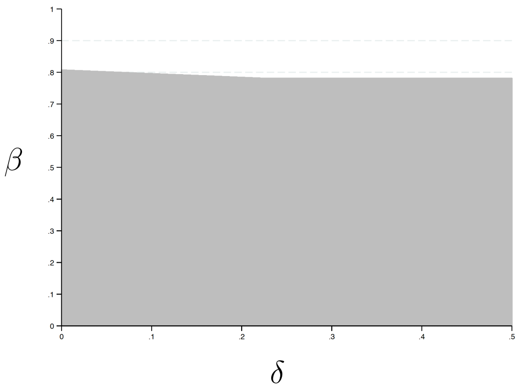
Note: These graphs are replications of Figure 10 (a) under different parametrizations.



(a) $M = 1$, $\alpha = 1$ and $r = 0.03$



(b) $M = 1$, $\alpha = 0.8$ and $r = 0.05$

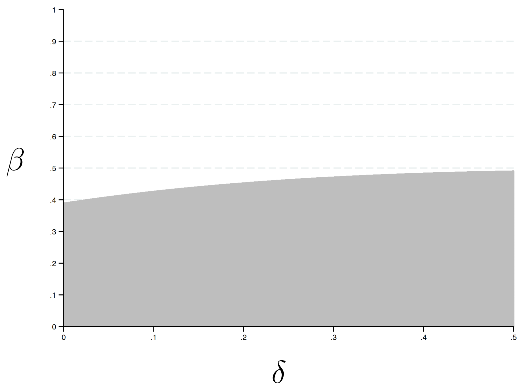


(c) $M = 0.5$, $\alpha = 0.8$ and $r = 0.03$

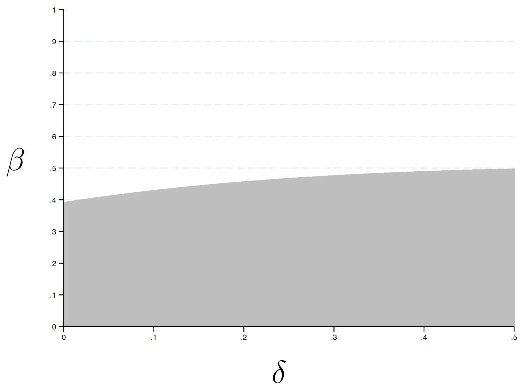
Figure 23: Comparison of Preemption Timing: Second Adoption

Note: These graphs are replications of Figure 10 (b) under different parametrizations.

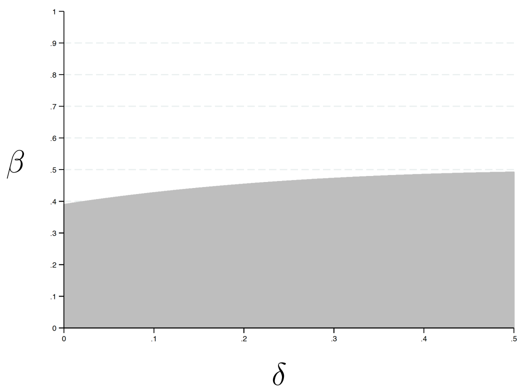
A.4.3 The Optimal Timings of First Adoption: The Preemption Game



(a) $M = 1$, $\alpha = 1$ and $r = 0.03$



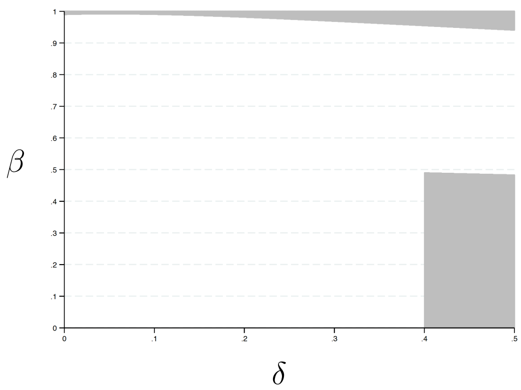
(b) $M = 1$, $\alpha = 0.8$ and $r = 0.05$



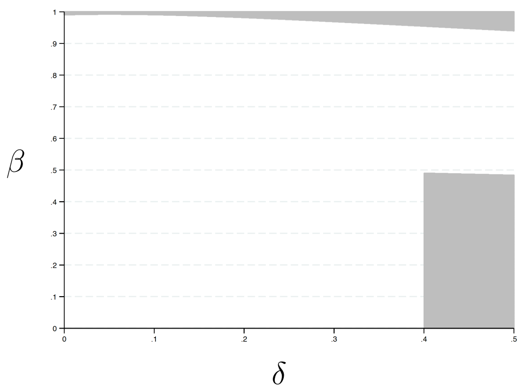
(c) $M = 0.5$, $\alpha = 0.8$ and $r = 0.03$

Figure 24: The Optimal Timings of First Adoption: The Vertically Separated Case

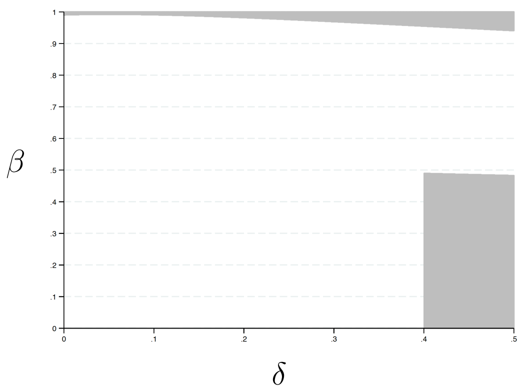
Note: These graphs are replications of Figure 12 (a) under different parametrizations.



(a) $M = 1$, $\alpha = 1$ and $r = 0.03$



(b) $M = 1$, $\alpha = 0.8$ and $r = 0.05$



(c) $M = 0.5$, $\alpha = 0.8$ and $r = 0.03$

Figure 25: The Optimal Timings of First Adoption: The Asymmetric Case

Note: These graphs are replications of Figure 12 (b) under different parametrizations.

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