On Vertical Relations and Technology Adoption Timing

Maria Alipranti Chrysovalantou Milliou Emmanuel Petrakis*

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Abstract

This paper explores how vertical relations influence the timing of new technology adoption. It shows that both the bargaining power distribution among the vertically related firms and the contract type through which vertical trading is conducted affect crucially the speed of adoption: the downstream firms can adopt later a new technology when the upstream bargaining power increases as well as when wholesale price contracts, instead of two-part tariffs, are employed. Importantly, it shows that technology adoption can take place earlier when firms obtain their inputs from external suppliers than when they produce them in-house; hence, the presence of vertical relations can accelerate the adoption of a new technology.

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*Alipranti: Düsseldorf Institute for Competition Economics (DICE), Heinrich-Heine University of Düsseldorf, e-mail: alipranti@dice.hhu.de; Milliou: Department of International and European Economic Studies, Athens University of Economics and Business, e-mail: cmilliou@aueb.gr; Petrakis (corresponding author): Department of Economics, University of Crete, Univ. Campus at Gallos, Rethymnon 74100, Greece, tel: +302831077409, e-mail: petrakis@uoc.gr. This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Thalis - Athens University of Economics and Business - "New Methods in the Analysis of Market Competition: Oligopoly, Networks and Regulation". Full responsibility for all shortcomings is ours.

1 Introduction

The speed with which new technologies are adopted and diffused constitutes a fundamental determinant of economic growth (e.g., Lucas, 1993; Krugman, 1994). However, extensive empirical observations indicate that new technologies often display both long time lags between their invention and their adoption and a slow adoption rate (e.g., Griliches, 1957; Mansfield, 1968, 1985; Jovanovic and Lach, 1997; Genesove, 1999; Asterbo, 2002).[1] In addition, they indicate that there are significant differences in the adoption timing of new technologies not only across different firms in the same market, but also across different markets (e.g., Griliches, 1957; Mansfield, 1968, 1985; Rogers, 1995).

In response to these observations, an extensive theoretical literature (see e.g., Reinganum, 1981a&b, 1983 a&b; Fudenberg and Tirole, 1985; Quirmbach, 1986; Riordan, 1992; Riordan and Salant, 1994) studying the timing of technology adoption has been developed.[2] This literature has stressed the significant impact of the strategic interactions between the potential adopters on the timing of adoption. Moreover, a number of papers within this literature have argued that the variation in the adoption timing across different markets could be due to differences in the markets' features. For instance, it could be due to the presence of network externalities (Cabral, 1990; Choi and Thum, 1998), the existence of informational externalities (Chamley and Gale, 1994), the strategic managerial delegation (Mahathi and Rupayan, 2013), and the mode and the intensity of market competition (Milliou and Petrakis, 2011).

Although the existing literature has significantly increased our understanding regarding the timing of technology adoption, it has done so focusing exclusively on one-tier markets. That is, on markets in which the production process consists of only one stage or all the production stages are fully internalized within a firm. In reality though, most markets are vertically related, i.e., most markets consist of various production stages - the stages of the so-called vertical production chain - and have distinct firms operating at the different production stages. Vertically related markets have a number of important features which are absent in one-tier markets. Their main diverse feature is the presence of trading among the vertically

[1] A typical example of delays in the adoption and the diffusion of new technologies is the basic oxygen furnace (BOF), a technological breakthrough in the steel industry that reduces the processing time and the cost of steel making. The BOF has displayed a 15 years time lag between its invention and its adoption (it was invented in 1949 but it was first adopted in 1964 by a U.S steel manufacturer), while it has taken more than 20 years for its diffusion to go from 10% to 90% (see Hoppe, 2002)

[2] For an extended survey of the theoretical literature on the timing of technology adoption see Hoppe (2002).

related firms - the upstream firms and the downstream firms. Two additional distinct features of vertically related markets are, first, the way through which trading is conducted (i.e., the contract type employed), and second, the distribution of bargaining power among the trading partners.[3] Since one-tier markets differ significantly from vertically related markets, it follows that in order to understand the timing of technology adoption in the latter, one has to take into account the role of their distinct features, i.e., to model explicitly the vertical structure and vertical trading.

In this paper, we study the timing of adoption of a new cost-reducing technology in vertically related markets. In particular, we explore how a number of features of such markets, along with the presence of vertical relations itself, affect the speed of technology adoption. We address a number of questions, such as: When is a new technology adopted in a vertically related market? How does the bargaining power distribution among the vertically related firms affect the speed of technology adoption? Whether and how the contract type employed (two-part tariffs vs. wholesale prices) affects the adoption timing? How the vertical relations influence the timing of technology adoption, i.e., how the adoption dates differ among vertically related markets and one-tier markets? Or equivalently, how do they differ among different organization structures of production, and in particular, among input outsourcing and in-house input production?

To address the above, we consider a vertically related market in which two upstream firms sell an input to two downstream firms that transform it into a final good and compete among them. The trade relations between the upstream firms and the downstream firms are exclusive and the trading among them is conducted via two-part tariff contracts or wholesale price contracts. The downstream firms are initially endowed with the same production technology. However, both of them can adopt a new cost-reducing technology. If a downstream firm adopts the new technology first, it enjoys a competitive advantage over its rival. Instead, if it adopts it second, it incurs a lower adoption cost.[4] A game with an infinite horizon is analyzed in which, at the beginning (at date $t = 0$), the downstream firms decide their technology adoption dates

[3] The contract types take many different forms. For instance, they can be simple linear contracts, such as wholesale price contracts, or they can be more complicated non-linear contracts, such as, two-part tariff contracts. For more information regarding the various contract types that are commonly used in vertically related markets see, among others, Berto Villas-Boas (2007) and Bonnet and Dubois (2010).

[4] We assume that the cost of the adoption is decreasing over time with a decelerating rate. This could be either due to economies of learning or to basic research adoption process innovation. This is a standard assumption in the literature (see e.g., Reinganum, 1981a&b; Fudenberg and Tirole, 1985).

and commit to them.[5] Then, in every period $t \geqslant 0$, first, they negotiate with their respective upstream suppliers over their contract terms, and next, they choose their output.

We find that the speed of technology adoption differs significantly across vertical related markets with different distributions of the bargaining power or different trading contract types as well as across markets characterized by the presence or the absence of vertical relations.

Importantly, we find that a new technology can be adopted earlier in a vertically related market in which trading is conducted via two-part tariff contracts than in an one-tier market. This holds for the first adoption of the technology when the upstream bargaining power is sufficiently low as well as for the second adoption when both the upstream bargaining power and the effectiveness of the new technology are sufficiently low. Stated differently, input sourcing from a (not too powerful) external supplier may lead to earlier adoptions than input sourcing from a competitive upstream market or in-house input production. Intuitively, there are two opposite forces in action: the *output effect* force and the *profits sharing effect* force. The *output effect* force refers to the fact that an increase in output, by increasing the returns of the investment in technology adoption, it reinforces the investment incentives. The output effect force is stronger in the presence of vertical relations than in their absence. This is so because in a vertically related market the output is larger than in an one-tier market because the upstream firms subsidize the downstream production, i.e., they charge wholesale prices which are below the input's marginal cost. Doing so, the upstream firms transform their downstream partners into more aggressive competitors in the final market; they increase their output and the downstream gross profits, part of which they transfer upstream through the fixed fees that are included in the two-part tariff contracts.[6] The second force, the *profits sharing effect* force, has to do with the fact that in a vertically related market, the technology adopters do not obtain the whole surplus generated in the market - they obtain only a piece of the "pie". In particular, under two-part tariffs, the downstream firms obtain only the share of the surplus that corresponds to their bargaining power. In contrast, in a one-tier market, the technology adopters get the whole "pie". Clearly, the profits sharing effect force, in contrast to the output effect force, makes earlier adoptions more attractive in an one-tier market than in a vertically

[5] In Section 6, we also examine the case in which the downstream firms cannot precommit to their adoption dates.

[6] This is a well known result in the literature of vertically related markets with two-part tariff trade contracts (see e.g., Milliou and Petrakis, 2007; Milliou and Pavlou, 2013). Further a similar result has been widely observed in the strategic managerial delegation literature (see e.g., Vickers, 1985; Fershtman and Judd, 1987).

related market. When the downstream firms possess sufficiently high bargaining power in the market, the profits share that the upstream firms can extract is low; hence, the profits sharing effect force is relatively weak and it is offset by the output effect force. The potential positive impact of vertical relations on the timing of technology adoption is empirically supported by the studies of Dewan et al. (1998) and Hitt (1999) that have concluded that vertical integration, or else, insourcing, is negatively related to the adoption of a new technology.[7]

We also find that the contract type employed in vertical trading has an important impact on the speed of technology adoption. In particular, technology adoption takes place earlier under two-part tariff contracts than under wholesale price contracts when the downstream firms are sufficiently powerful. The intuition behind this result lies again on the interaction of the output effect force and the profits sharing effect force. The wholesale price contracts do not result into downstream subsidization; they result, instead, into double marginalization (i.e., the wholesale prices exceed the inputs' marginal cost). As a result, output under wholesale price contracts is smaller than under two-part tariffs contracts. This clearly implies that the output effect force, which speeds up the technology adoption, is stronger when trading is conducted via two-part tariff contracts. The profits sharing effect force, which works in exactly the opposite way, is instead stronger under wholesale price contracts. This is so because under wholesale price contracts, due to the absence of fixed fees, the downstream firms obtain a larger share of the vertical chain's profits than under two-part tariffs. When the downstream firms are sufficiently powerful, the output effect force dominates the profits sharing effect force and the new technology can be adopted earlier under two-part tariff contracts than under wholesale price contracts.

Furthermore, we find that when firms trade via wholesale price contracts, in contrast to when they trade via two-part tariff contracts, the presence of vertical relations slows down the speed of technology adoption. This arises because, as mentioned above, under wholesale price contracts the input prices exceed the upstream marginal cost (double marginalization is present). This, in turn, means that the marginal cost faced by the technology adopters is

[7] Dewan et al. (1998) have examined the investments in Information Technology (IT) made by large U.S. firms in the period 1988-1992 and showed that the firms that are less vertically integrated have a higher level of IT investment, or else, IT is negatively correlated to the level of vertical integration. In the same vein, Hitt (1999) has studied the adoption of IT among 549 large firms in the period of 1987-1994 and provided evidence that suggests that the adoption of IT increases with substantial decreases in vertical integration. We should mention though that a number of other studies (e.g., Lane, 1991; Carlsson and Jacobsson, 1994; Helper, 1995) provide evidence for the opposite, i.e., that vertical integration encourages the adoption of a new technology.

higher in a vertically related market with wholesale price contracts than in an one-tier market, and thus, that the resulting output effect force is much stronger in the latter market.

Finally, we find that the higher is the bargaining power of the upstream firms, the more the downstream firms defer the technology adoption until later where it will be less costly. The intuition for this straightforward: when the upstream bargaining power increases, the downstream firm's share of the vertical chain's profits decreases, and thus, the downstream firm has weaker incentives to undertake the costly investment in technology adoption.

Our work is clearly related to the above mentioned literature that has studied the timing of technology adoption in the presence of strategic interactions (see e.g., Reinganum, 1981a&b, 1983a&b; Fudenberg and Tirole, 1985; Quirmbach, 1986; Hendricks, 1992; Riordan, 1992; Götz, 2000; Hoppe and Lehmann-Grube, 2001; Ruiz-Aliseda and Zemsky, 2006; Milliou and Petrakis, 2011). Some papers within this literature, following the seminal work of Reinganum (1981a&b and 1983a&b), have focused on settings in which firms can precommit to their adoption dates. Others instead, following the seminal work of Fudenberg and Tirole (1985), have assumed that firms can observe and react instantaneously to their rivals' adoption plans. However, as mentioned above, all of these papers, have restricted their attention to settings in which vertical relations are absent. Our paper extends this literature by considering instead a setting in which vertical relations are present, and in particular, by providing a detailed analysis of how a number of features of vertically related markets, as well as the presence of vertical relations itself, affect the timing of technology adoption.

Our work is also related to the literature that incorporates investments in R&D in vertically related markets. A branch of this literature has examined R&D investments by the upstream firms (e.g., Peters, 1995; Stefanadis, 1997; Inderst and Wey, 2007, 2011; Fauli-Oller et al., 2011; Milliou and Pavlou, 2013). Another branch, instead, has explored the R&D investments by the downstream firms (e.g., Steurs, 1995; Banerjee and Lin, 2003; Manasakis et al., 2014). Yet, all of the aforementioned papers have analyzed firms' decisions about *how much* to invest in R&D. We complement this literature by analyzing instead firms' decisions about *when* to invest in R&D, and in particular, when to adopt an existing new technology.

Lastly, our work is related to the literature on strategic outsourcing. This literature (e.g., Nickerson and Vanden Bergh, 1999; Shy and Stenbacka, 2003; Chen et al., 2004) has explored the strategic incentives and implications of the make-or-buy decision, i.e., the choice among in-house production and outsourcing, as well as it has studied a number of alternative input sourcing strategies (e.g., Beladi and Mukherjee, 2012; Stenbacka and Tombak, 2012). In line with this literature, we consider different organization structures of production, we focus though on the impact of these structures on the timing of technology adoption.

The remainder of the paper is organized as follows. In Section 2, we describe our main model. In Section 3, we obtain the optimal adoption dates in a vertically related market. In Section 4, we examine the impact of vertical relations on the optimal adoption dates. In Section 5, we analyze the role of the vertical contracts type. In Section 6, we discuss a number of extensions of our main model. Finally, in Section 7, we conclude. All the proofs are relegated to the Appendix.

2 The Model

We consider a vertically related industry consisting of two upstream and two downstream firms denoted respectively by U_i and D_i, with $i = 1, 2$. The upstream firms produce an input at zero marginal production cost. The downstream firms, in turn, transform the input into a final good on a one-to-one basis, facing, initially, an exogenous marginal cost, c, plus the cost of obtaining the input from the upstream firms. The latter cost corresponds to the terms of a two-part tariff contract, that is, to a per unit of input wholesale price, w_i, and a fixed fee, f_i.[8] Trade relations between U_i and D_i are exclusive.[9] Demand for the final good is given by $p(Q) = a - Q$, where Q is the total quantity, i.e., $Q = q_i + q_j$, with $i, j = 1, 2$ and $i \neq j$.

Time is continuous, it is denoted by $t \geqslant 0$, and it has an infinite horizon. At date $t = 0$, a new cost-reducing technology becomes available in the market. If D_i adopts the new technology at date $t \geqslant 0$, its marginal cost reduces from $c_i = c + w_i$ to $c_i = c + w_i - \Delta$, with $0 < \Delta < c < a$, thereafter. The adoption though of the new technology is costly. In particular, the discounted cost of adoption at date t is given by $k(t)$. This cost incorporates the present value of the purchasing cost of the new technology and the adjustment cost of bringing the new technology

[8] In Section 5, we extend our analysis, and examine the case in which firms trade via linear wholesale price contracts that include only w_i.

[9] Exclusive relations can be due to the fact that the upstream firms produce inputs which are tailored for specific downstream manufacturers and there are irreversible investments that create high switching costs. Exclusive relations is a common assumption in the literature on vertical relations (see e.g., Horn and Wolinsky, 1988; Gal-Or, 1991; Lommerud et al., 2005; Milliou and Petrakis, 2007, Milliou and Pavlou, 2013). Furthermore, exclusive relations are common in many industries. For example, in the car manufacturing industry, Lorentzen and Mollgaard (2000) note that in Central and Eastern Europe 36% of the customers imposed an exclusivity condition on their suppliers. Similarly, in the aircraft industry, engine manufacturers, such as Rolls Royce and CMF International, supply exclusively aircraft manufacturers, Airbus and Boeing, respectively.

on line at date t. The current cost of the adoption at date t is $k(t)e^{rt}$, where r is the interest rate, with $0 < r < 1$. As in most of the related literature (e.g., Fudenberg and Tirole, 1985, Katz and Shapiro, 1987), we assume that the current cost of adoption is decreasing over time with a decreasing rate, i.e., $(k(t)e^{rt})' < 0$ and $(k(t)e^{rt})'' > 0$. We also assume that technology adoption cannot take place immediately due to prohibitively high costs but that it always occurs at a finite date of time, i.e., $\lim_{t\to 0} k(t) = -\lim_{t\to 0} k'(t) = \infty$ and $\lim_{t\to\infty} k'(t)e^{rt} = 0$. Finally, as standard in the literature, we assume that no other technological improvements are available or will become available in the market.

Firms play the following game with observable actions. At $t = 0$, each D_i decides its adoption date T_i, i.e., the date at which it will adopt the new technology. Moreover, at $t = 0$, as well as at every other period $t > 0$, first, each (U_i, D_i) pair bargains over its contract terms (w_i, f_i), and next, D_i and D_j set simultaneously their quantities after observing all contract terms.[10] We model the bargaining over the contract terms that takes place in the second stage of every period t by invoking the Nash equilibrium of simultaneous generalized Nash bargaining problems. We assume that the bargaining power of each upstream and downstream firms is respectively β and $1 - \beta$, with $0 < \beta < 1$.

The above described game is based on Reinganum's (1981a&b) *precommitment* game. The precommitment game captures the idea that a firm that would like to incorporate a technological improvement and bring it on line constructs and follows well designed long-term plans. Note that the firm's precommitment strategies are time consistent only if the cost of altering adoption plans is sufficiently high. Therefore, a firm cannot adjust its adoption timing in response to its rival's past actions. The precommitment game also captures the case of a market with infinite information lags, or else, with an open-loop information structure (see e.g., Fudenberg and Tirole, 1985).[11]

In order to guarantee that all firms are active in all the cases under consideration, we assume the following throughout:

[10] According to Rey and Vergé's (2004) terminology, we assume that contract terms are interim observable. That is, a downstream firm observes not only its contract terms but also the contract terms of its rival before the final market competition takes place. A similar assumption can be found in, among others, Horn and Wolinsky (1988), Gal-Or (1991), McAfee and Schwartz (1995), and Milliou and Petrakis (2007).

[11] In Section 6, we extend our analysis and, following Fudenberg and Tirole (1985), consider the *preemption* game too where downstream firms are able to adjust their adoption dates with respect to what has happened in the past, or else, when the cost of altering adoption plans is infinitesimal and thus, firms could immediately respond to their rivals' plans of adoption.

Assumption 1: $\delta \equiv \frac{\Delta}{A} < \frac{1}{2}$, with $A \equiv a - c$.

The parameter δ measures how drastic is the new technology. In particular, it measures how effective is the new technology in reducing the downstream firms' marginal production cost relatively to the market size. The higher is δ, the more drastic the new technology is.[12]

3 Optimal Adoption Timing

In this Section, we determine the downstream firms' optimal adoption dates, as well as we discuss their properties.

In the second stage of every period $t \geqslant 0$, each D_i chooses its output q_i, in order to maximize its per-period gross (from the adoption cost and f_i) profits:

$$\max_{q_i} \pi_{D_i}(.) = [p(Q) - c_i - w_i]q_i. \tag{1}$$

From the solution of the system of first-order conditions, we obtain the equilibrium quantities and the (gross) downstream and upstream profits in terms of the marginal costs:

$$q_i(c_i, c_j, w_i, w_j) = \frac{a - 2(c_i + w_i) + (c_j + w_j)}{3}; \tag{2}$$

$$\pi_{D_i}(c_i, c_j, w_i, w_j) = [q_i(c_i, c_j, w_i, w_j)]^2 \text{ and } \pi_{U_i}(c_i, c_j, w_i, w_j) = w_i q_i(c_i, c_j, w_i, w_j). \tag{3}$$

Observe that technology adoption by D_i as well as a reduction in w_i, decrease D_i's marginal cost, and thus, increase its quantity and decrease its rival's quantity.

In the first stage of every period $t \geqslant 0$, each (U_i, D_i) pair bargains over the contract terms (w_i, f_i), taking as given the outcome of the simultaneously run negotiations of the (U_j, D_j) pair, (w_j^T, f_j^T). In particular, w_i and f_i are chosen in order to maximize the following generalized Nash product:

$$\max_{w_i,\, f_i} [\pi_{U_i}(c_i, c_j, w_i, w_j^T) + f_i]^\beta [\pi_{D_i}(c_i, c_j, w_i, w_j^T) - f_i]^{1-\beta}. \tag{4}$$

Note that since U_i and D_i trade exclusively in the market, none of them has an outside option; hence, their disagreement payoffs are equal to zero. Maximizing (4) with respect to f_i, we

[12] In our setting, the term "drastic", in contrast to Arrow (1962) and others, does not refer to a cost-reducing innovation that allows its user to monopolize the market.

obtain:

$$f_i = \beta\pi_{D_i}(c_i, c_j, w_i, w_j^T) - (1-\beta)\pi_{U_i}(c_i, c_j, w_i, w_j^T). \tag{5}$$

Substituting (5) into (4), we observe that the generalized Nash product is proportional to the vertical chain's (i.e., U_i's and D_i's) per-period joint profits. We also observe that the per-period profits of U_i and D_i are equal to the shares of the latter that correspond to their respective bargaining powers, β and $1-\beta$. It follows that the wholesale price w_i is chosen in order to maximize U_i and D_i's per-period joint profits:

$$\max_{w_i} \; [\pi_{U_i}(c_i, c_j, w_i, w_j^T) + \pi_{D_i}(c_i, c_j, w_i, w_j^T)]. \tag{6}$$

From the solution of the system of first-order conditions, we obtain the equilibrium wholesale prices:

$$w_i^T(c_i, c_j) = \frac{-(a - 3c_i + 2c_j)}{5}. \tag{7}$$

A number of observations regarding the equilibrium wholesale prices are in order. First, they are independent of the bargaining power distribution. Second, given Assumption 1, we have $w_i^T(c_i, c_j) < 0$, i.e., the wholesale prices are always lower than the upstream suppliers' marginal cost, i.e., the upstream firms subsidize their downstream customers.[13] This occurs because a decrease in the wholesale price charged by an upstream firm shifts the reaction function of its downstream customer outwards. Given that the reaction functions are downward slopping, this outward shift leads to a lower quantity for the rival downstream firm and a higher quantity and gross profits for its downstream partner. The upstream firm gets, in turn, part of the resulting higher downstream gross profits by charging a higher fixed fee.

A further observation is that $w_1^T(c-\Delta, c) < w_i^T(c-\Delta, c-\Delta) < w_i^T(c, c) < w_2^T(c-\Delta, c) < 0$. This implies, among other things, that an upstream firm offers a larger subsidy in periods in which its downstream customer is the only adopter of the new technology. Intuitively, in such a case, the downstream customer has a competitive advantage over its rival, and thus, it enjoys a large market share and gross profits. Its upstream supplier has incentives then to further increase the competitive advantage of its downstream customer by reducing the wholesale price. This is so because, as mentioned above, it can then charge a higher fixed fee

[13]A similar result exists in the strategic delegation literature (e.g., Vickers, 1985; Fershtman and Judd, 1987) as well as in the literature on vertically related markets with two-part tariffs contracts (e.g., Milliou and Petrakis, 2007; Milliou and Pavlou, 2013).

and transfer through the latter the resulting higher gross downstream profits upstream.

A final observation is that $w_i^T(c-\Delta, c-\Delta) = -\frac{(1+\delta)(a-c)}{5}$ and $w_1^T(c-\Delta, c) = -\frac{(1+3\delta)(a-c)}{5}$ decrease with δ, while $w_2^T(c-\Delta, c) = -\frac{(1-2\delta)(a-c)}{5}$ increases with δ. In other words, the more drastic is the new technology, the lower is the wholesale price charged to the downstream firm(s) that have adopted the technology and the higher to the downstream firm that has not adopted the technology while its rival has done so. The explanation for the former is that the higher is δ, the larger is the cost-reduction that the technology adopter enjoys. The larger cost-reduction translates into a larger output for the technology adopter. The larger output, in turn, reinforces the effectiveness of a further reduction in the marginal cost through a decrease in the wholesale price. We refer to this as the *output effect* of δ.[14] Given that the decrease in the wholesale price w_i, as a result of the increase in δ, will cause a further increase in D_i's gross profits, it follows that U_i has incentives to charge a lower wholesale price to a technology adopter as δ increases. In the case instead in which a downstream firm has not adopted the technology while its rival has done so, we have the reverse output effect of δ: an increase in δ, decreases the output of the non-adopter, and thus, weakens its upstream supplier's incentives to offer a lower wholesale price.

Substituting (7) into (2), we obtain the equilibrium per-period quantities and downstream profits:

$$q_i^T(c_i, c_j) = \frac{2}{5}(a - 3c_i + 2c_j); \quad \pi_{D_i}^T(c_i, c_j) = \frac{2(1-\beta)}{25}(a - 3c_i + 2c_j)^2. \tag{8}$$

We move next to the analysis of D_i's choice of adoption date T_i at $t = 0$. Clearly, D_i will choose T_i in order to maximize the discounted sum of its infinite stream of per-period profits. We assume, without loss of generality, that D_1 is the first adopter.[15] Given this, the maximization problems that D_1 and D_2 face are:

$$\underset{T_1}{Max}\ \Pi_{D_1}(T_1,T_2) = \int_0^{T_1} \pi_{D_0} e^{-rt} dt\ + \int_{T_1}^{T_2} \pi_{D_l} e^{-rt} dt\ + \int_{T_2}^{\infty} \pi_{D_b} e^{-rt} dt - k(T_1); \tag{9}$$

$$\underset{T_2}{Max}\ \Pi_{D_2}(T_1,T_2) = \int_0^{T_1} \pi_{D_0} e^{-rt} dt\ + \int_{T_1}^{T_2} \pi_{D_f} e^{-rt} dt\ + \int_{T_2}^{\infty} \pi_{D_b} e^{-rt} dt - k(T_2), \tag{10}$$

where $\pi_{D_0} = \pi_{D_i}^T(c, c)$ and $\pi_{D_b} = \pi_{D_i}^T(c-\Delta, c-\Delta)$ denote, respectively, D_i's pre-(any) adoption

[14] Bester and Petrakis (1993) have identified a similar output effect in a different context, and in particular, in an one-tier industry with cost-reducing R&D.

[15] As will be shown next and is standard in the literature, there is technology diffusion in equilibrium.

and post-(global) adoption per-period profits. While $\pi_{D_l} = \pi^T_{D_i}(c-\Delta, c)$ denotes D_1's per-period profits when it is the only adopter - the leader, and $\pi_{D_f} = \pi^T_{D_i}(c, c-\Delta)$ denotes the per-period profits of D_2 when it is a follower, i.e., when it has not adopted the technology while its rival has. The first order conditions of (9) and (10) result into:

$$I_1 = -k'(T_1)e^{rT_1} \text{ and } I_2 = -k'(T_2)e^{rT_2}, \tag{11}$$

where $I_1 = \pi_{D_l} - \pi_{D_0}$ and $I_2 = \pi_{D_b} - \pi_{D_f}$ are, respectively, D_1's and D_2's incremental benefits from technology adoption. Observe from (11) that the optimal adoption dates, T_1^T and T_2^T, are such that each downstream firm's incremental benefits from the adoption are equal to its marginal cost of waiting. Combining this with (8), and after some manipulations, we get:

$$I_1^T = \frac{6}{25}A^2(1-\beta)\delta(2+3\delta) \text{ and } I_2^T = \frac{6}{25}A^2(1-\beta)\delta(2-\delta). \tag{12}$$

In line with the literature on technology adoption in one-tier industries, we conclude, on the basis of (12), that firms always have incentives to adopt the new cost-reducing technology, $I_i^T > 0$. We also conclude that the first adoption leads to higher incremental benefits than the second one, $I_1^T > I_2^T$. This, along with our assumptions regarding the cost of the technology adoption, implies that $T_1^T < T_2^T$, and thus, that in equilibrium there is technology diffusion. As in Quirmbach (1986) and Milliou and Petrakis (2011), the sequential adoption of the new technology here is not due to the strategic behavior of firms; instead, it is due to the diminishing pattern of the incremental benefits and the decreasing adoption cost.

Proposition 1 below informs us how the bargaining power distribution in a vertically related market affect the timing of technology adoption.

Proposition 1 *The lower the bargaining power of the upstream firms is, the earlier downstream firms adopt the new technology,* $\frac{\partial T_i^T}{\partial \beta} > 0$.

Not surprisingly, the higher is the bargaining power of the upstream firms, the later the downstream firms adopt the new technology. This holds both for the first and the second adoption. Intuitively, technology adoption tends to increase a vertical chain's per-period joint profits. We know from above that each partner in the vertical chain obtains the share of the chain's per-period joint profits that corresponds to its bargaining power. Clearly then, a higher upstream bargaining power translates into a smaller share of the vertical chain's per-period joint profits - a smaller share of the "pie" - for the downstream firm, and thus, weaker incentives for the latter to undertake the costly technology adoption investment. Stated differently, the higher is the bargaining power of its upstream supplier, the more the downstream firm defers the adoption until later where adoption will be less costly. Note also that, as expected, a more drastic technology accelerates both the first and the second adoption.[16]

4 The Impact of Vertical Relations: Outsourcing vs. Insourcing

In this Section, we examine how the presence of vertical relations affects the speed of technology adoption. In other words, we examine whether and how the optimal adoption dates differ among an one-tier market and a vertically related market as the one that we have considered so far. The comparison among these two markets corresponds to a comparison between a market with insourcing, i.e., in house production of inputs, and a market with outsourcing, i.e., sourcing of the inputs from external suppliers.

Clearly, in order to perform the above comparison, we first need to examine what happens in an one-tier industry. That is, we need to determine the optimal adoption dates of two firms that initially face marginal cost c and play the same game as the one described in Section 2, with the only difference that now stage one does not exist and $w_i = f_i = 0$ due to the in-house production of the input.[17] Obtaining the optimal adoption dates in an one-tier market and comparing them with the respective ones in a vertically related market, we reach the following conclusion.[18]

Proposition 2 *(i) The first adoption takes place earlier in a vertically related market than in an one-tier market if and only if the upstream bargaining power is sufficiently low, i.e.,* $\beta < \beta_1(\delta) \equiv \frac{4+31\delta}{27(2+3\delta)}$, *with* $\partial\beta_1(\delta)/\partial\delta > 0$.

(ii) The second adoption takes place earlier in a vertically related market than in an one-tier market if and only if the new technology is not too drastic and the upstream bargaining

[16] From (12), $\frac{\partial I_i^T}{\partial \delta} > 0$ (by Assumption 1) and thus, $\frac{\partial T_i^T}{\partial \delta} < 0$. Interestingly, I_1^T increases at an increasing rate with δ, while I_2^T increases at a decreasing rate with δ.

[17] It follows from this that an alternative interpretation of the one-tier market is a vertically related market with a perfectly competitive upstream sector or with vertically integrated firms.

[18] Given that technology adoption in an one-tier market has been analyzed by many authors before, we do not include its full analyis in our main text. Instead, we include it in Appendix A.

power is sufficiently low, i.e., $\delta < \frac{4}{27}$ *and* $\beta < \beta_2(\delta) \equiv \frac{4-27\delta}{27(2-\delta)}$*, with* $\partial\beta_2(\delta)/\partial\delta < 0$*.*

Interestingly, technology can be adopted earlier with outsourcing than with insourcing. Stated in other words, the presence of vertical relations can accelerate the adoption of the new technology. This holds for the first adoption in areas A and B of Figure 1, i.e., when the upstream bargaining power is sufficiently low. For the second adoption, it holds instead only in area A of Figure 1, that is, when both the upstream bargaining power and the effectiveness of the new technology are sufficiently low.

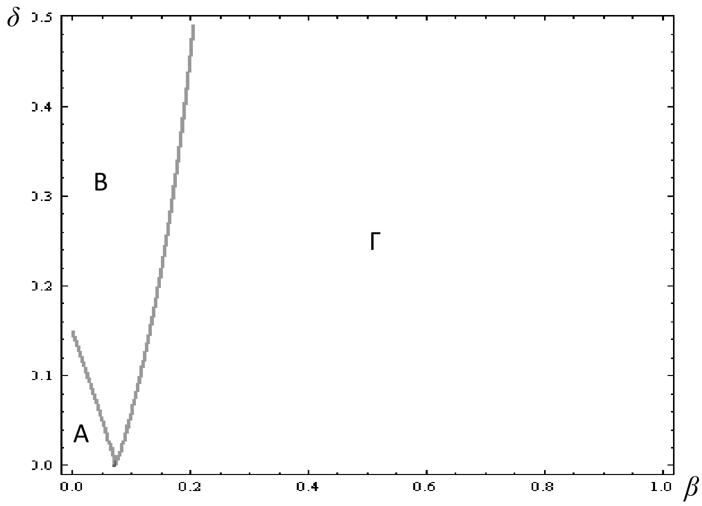

Figure 1. Comparison of the firms' incremental benefits under a two-tier industry with two-part tariff contracts and an one-tier industry.

Two main forces drive the above findings. The first force has to do with the fact that the higher is the per-period output, the stronger are the returns of the investment in technology adoption. We refer to this as the *output effect* force.[19] The output effect force works in favor of the vertically related market. This is so because, due to subsidization, the downstream firms face a lower marginal cost in a vertically related market than in an one-tier market, and thus, they produce more in the former market. The second force, the *profits sharing* force, has to do with the fact that in an one-tier market, due to the absence of the upstream firms,

[19]This is similar but not exactly the same as the output effect of δ mentioned earlier. The latter referred to an increase in the incentives to reduce the wholesale price, due to the increase in output. Here, instead, we refer to an increase in the incentives to invest in technology adoption.

downstream firms obtain the whole surplus - the whole "pie". In contrast, as we saw above, in a vertically related market, they obtain only the share of the chain's per-period joint profits that corresponds to their bargaining power - they obtain only a piece of the "pie". As a result, when technology adoption occurs and the chain's joint profits increase, a downstream firm obtains a lower share of the larger surplus with outsourcing than it would obtain with insourcing. Clearly, this force, in contrast to the output effect force, favours more the earlier technology adoption with insourcing than with outsourcing. When the upstream bargaining power is relatively low, the profits sharing force gets weaker and strengthens the incentives for earlier first technology adoption in the presence than in the absence of vertical relations. This holds for the second adoption too but only if the new technology is not too drastic. This is due to the reverse output effect of δ, mentioned earlier, that exists only in a vertically related market. In particular, a higher δ reduces D_2's (the non-adopter's) output and leads, in turn, to an increase in the wholesale price charged to D_2, which further reduces its output. The latter clearly weakens the output effect force and results into an earlier second adoption in an one tier market than in a vertically related market for high enough values of δ.

5 The Role of Contract Type: Wholesale Price Contracts vs. Two-part Tariffs

In our main model, we have assumed that the vertically related firms trade through two-part tariff contracts. Next, we examine whether our main findings also hold when firms trade, instead, through wholesale price contracts. More importantly, we examine whether and how the contract type used in vertical trading affects the timing of adoption.

When trading is conducted via wholesale price contracts, in the first stage of every period $t \geq 0$, U_i negotiates with D_i over w_i, taking as given the equilibrium wholesale price of the (U_j, D_j) pair, w_j^W. Therefore, they maximize the generalized Nash product (4) in which $f_i = 0$ in terms of w_i, after substituting w_j^T with w_j^W in it. The resulting equilibrium wholesale prices are:

$$w_i^W(c_i, c_j) = \frac{\beta[a(4+\beta) - (8-\beta)c_i + 2(2-\beta)c_j]}{16-\beta^2}. \tag{13}$$

The equilibrium wholesale prices (13) differ from the respective ones under two-part tariffs (7) in four main aspects. The first aspect is that they depend on the bargaining power distribution.

More specifically, under wholesale price contracts, the equilibrium wholesale prices increase with the bargaining power of the upstream firms. This occurs because the only tool that an upstream firm has for capturing part of the vertical chain's profits is the wholesale price - the fixed fees are not available. As a result, when an upstream firm is more powerful, it charges a higher wholesale price.

The second aspect is that under wholesale price contracts, the equilibrium wholesale prices always exceed the upstream marginal cost - downstream subsidization is no longer present. This is again related to the fact that the wholesale price is the only available instrument with which the input supplier transfers upstream part of the vertical chain's profits. Evidently, if the upstream supplier did not charge a wholesale price above its marginal cost, it would make negative profits.

The third aspect is that $0 < w_2^W(c-\Delta, c) < w_i^W(c, c) < w_i^W(c-\Delta, c-\Delta) < w_1^W(c-\Delta, c)$. This means that under wholesale price contracts, a downstream firm pays the highest, and not the lowest, wholesale price in a period in which it is the leader. As a leader enjoys a competitive advantage, and in the absence of fixed fees, its upstream supplier can only exploit its customer's competitive advantage by charging a higher wholesale price. In a similar vein, a follower in adoption with a competitive disadvantage pays the lowest price to its supplier.

The last difference between the equilibrium wholesale prices under wholesale price contracts and two-part tariff contracts is that they move in exactly the opposite direction with respect to δ: under wholesale price contracts, both $w_i^W(c-\Delta, c-\Delta)$ and $w_1^W(c-\Delta, c)$ increase with δ, while $w_2^W(c-\Delta, c)$ decreases with δ. Clearly, as upstream firms have only one instrument to transfer profits upstream, the more efficient the downstream firm's technology is, the higher is the wholesale price that the adopter(s) pay. At the same time, a sole non-adopter is charged with a lower wholesale price in order not to be marginalized in the downstream market. In this way, its upstream partner could make higher input sales and obtain some level of profits.

Substituting (13) into (3), we obtain D_i's per-period profits:

$$\pi_{D_i}^W(c_i, c_j) = \frac{4(2-\beta)^2[a(4+\beta) - (8-\beta)c_i + 2(2-\beta)c_j]^2}{9(16-\beta^2)^2}.$$

At $t = 0$, D_1 and D_2 choose their adoption dates such as to maximize their discounted sum of profits. That is, they maximize (9) and (10) after setting $\pi_{D_0} = \pi_{D_i}^W(c, c)$, $\pi_{D_l} = \pi_{D_i}^W(c-\Delta, c)$, $\pi_{D_f} = \pi_{D_i}^W(c, c-\Delta)$, $\pi_{D_b} = \pi_{D_i}^W(c-\Delta, c-\Delta)$. From the resulting first order conditions, we obtain:

$$I_1^W = \frac{4(8-\beta)(2-\beta)^2\delta A^2[2(4+\beta)+(8-\beta)\delta]}{9(16-\beta^2)^2} = -k'(T_1^W)e^{rT_1^W}; \tag{14}$$

$$I_2^W = \frac{4(8-\beta)(2-\beta)^2\delta A^2[2(4+\beta)+3\beta\delta]}{9(16-\beta^2)^2} = -k'(T_2^W)e^{rT_2^W}. \tag{15}$$

We confirm that under wholesale price contracts too, the downstream firms always have incentives to adopt the new technology ($I_i^W > 0$) and that there is technological diffusion in equilibrium ($I_1^W > I_2^W$, and thus, $T_1^W < T_2^W$). In addition, we confirm that the impact of the bargaining power distribution on the optimal adoption dates is similar to the one under two-part tariff contracts ($\frac{\partial T_i^W}{\partial \beta} > 0$). Finally, here too, as the new technology becomes more drastic, both adoptions occur earlier ($\frac{\partial T_i^W}{\partial \delta} < 0$).[20] Still, as Proposition 3 below informs us, the speed of technology adoption crucially differs among the two contract types.

Proposition 3 *(i) The first adoption takes place earlier under two-part tariff contracts than under wholesale price contracts if and only if the upstream bargaining power is sufficiently low.*

(ii) The second adoption takes place earlier under two-part tariff contracts than under wholesale price contracts if and only if the new technology is not too drastic and the upstream bargaining power is sufficiently low.

The contact type affects crucially the adoption dates. In particular, technology adoption can take place earlier with two-part tariff contracts than with wholesale price contracts. This holds for the first adoption as long as the downstream firms are powerful enough (areas A and B of Figure 2). It also holds for the second adoption but only if both the downstream firms are powerful enough and the new technology is not too drastic (area A of Figure 2). The intuition draws again on the interaction of the output effect force and the profits sharing force. The output effect force is stronger under two-part tariff contracts than under wholesale price contracts. This is due to the fact that the input prices are lower under the former than under the latter contracts. The lower input prices under two-part tariffs translate into lower downstream marginal cost, and thus, into higher output. The stronger output effect under two-part tariffs increases the likelihood that technology will be adopted faster there than under

[20]Note however that, in contrast to the two-part tariff contracts case, under wholesale price contracts the incremental benefits of *both* the first and the second adopter increase at an increasing rate with δ.

wholesale price contracts. Conversely to the output effect force, the profits sharing force works in favor of faster adoption under wholesale price contracts. In particular, under wholesale price contracts, due to the lack of the fixed fees, the downstream firms get a larger piece of the "pie" than the one corresponding to their bargaining power, and thus, than the one that they get under two-part tariff contracts. As a result, when a vertical chain's per-period profits increase because of technology adoption, a downstream firm obtains a larger share of the bigger profits than it would obtain under two-part tariff contracts, and thus, it has stronger incentives to invest in technology adoption. The more powerful the upstream firms are, the more the profits sharing effect works in favor of wholesale prices and it can then offset the output effect force and lead to earlier first adoption under wholesale price contracts. It can also lead to earlier second adoption but only if the new technology is not too drastic. This is due to the output effect of δ that, as we saw above, is reverse under two part tariff contracts as compared with wholesale price contracts.[21]

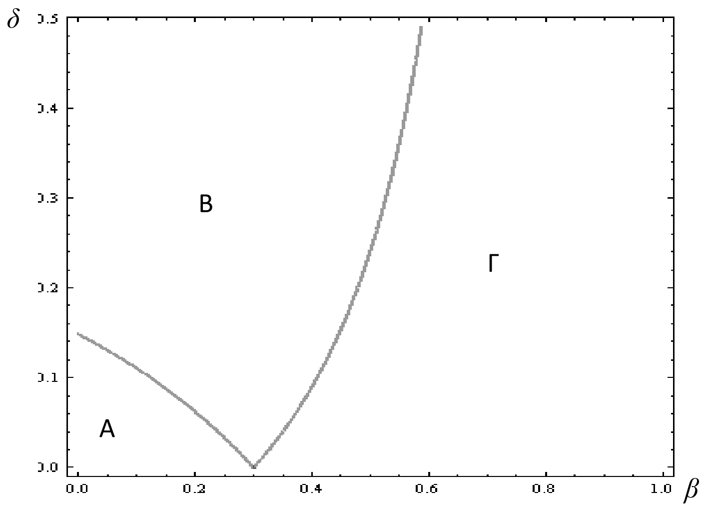

Figure 2. Comparison of the firms' incremental benefits under two-part tariff contracts and wholesale price contracts.

[21] In particular, a higher δ reduces the non-adopter D_2's output and leads, in turn, to an increase (decrease) in the wholesale price charged to D_2 under two part-tariff (wholesale price) contracts, which further reduces (ameliorates reduction) of the D_2´s output. The latter clearly weakens (strengthens) the output effect force under two-part tariff (wholesale price) contracts. As a consequence, the second adoption occurs earlier under wholesale price than under two-part tariff contracts for high enough values of δ.

One might wonder whether vertical relations can also accelerate the adoption when trading in a vertically related market is conducted via wholesale price contracts. Comparing the optimal adoption dates in a vertically related market with wholesale price contracts with the respective ones in an one-tier market, we find that the former are always later. This differs from our respective finding in a vertically related market with two-part tariff contracts. Therefore, the contract type affects crucially the impact of vertical relations on the adoption timing. The explanation for the different result under wholesale price contracts has mainly to do with the fact that under wholesale price contracts, the input prices exceed the upstream marginal cost (double marginalization is present). This means that while the marginal cost in a vertically related market with two-part tariffs is lower than that in an one-tier market, the opposite holds in a vertically related market with wholesale price contracts. In particular, since $w_i^W > 0$, we have $c + w_i^W > c$. In turn, this means that the output is lower in a vertically related market with wholesale price contracts than in an one-tier market, and thus, that the output effect force which reinforces the incentives for earlier technology adoption is weaker in the former market than in an one-tier market.

6 Extensions

In this Section, we extend our model in various dimensions in order to examine the robustness of our main results, as well as in order to explore the role of some of our assumptions.

6.1 Preemption Game

We examine first what happens when the downstream firms cannot precommit to their adoption dates at $t = 0$. In particular, we analyze the so-called preemption game in which the downstream firms can respond immediately to their rivals' adoption decisions.

It is well known (see e.g., Fudenberg and Tirole, 1985) that in the preemption game, contrary to the precommitment game, symmetric firms in equilibrium receive the same payoffs. This is so since if one of the firms plans to adopt first at date t, it will obtain a higher payoff than the firm that will adopt second. The second adopter is aware of this, and thus, it has incentives to preempt and adopt the new technology just before t. Faced with preemption, the first adopter will adopt the new technology at a date at which the second adopter is indifferent between adopting just before or much after. In other words, the threat of preemption ensures that in equilibrium symmetric firms obtain the same payoffs and the early mover's potential advantage disappears. Because of this, there is always technology diffusion in the equilibrium of the preemption game too, where once one of the firms has adopted the new technology the second adopter's decision can be transformed to a one-player decision problem.

In particular, in a vertically related market with two-part tariff contracts, the second adopter decides its adoption date τ_2^T in order to maximize its profits $\Pi_{D_2}^T(\tau_1^T, \tau_2^T)$, given by equation (10) where τ_2^T takes the place of T_2. Solving the maximization problem of the second adopter, we end up with the same first order condition as the one in the precommitment game. Hence, the optimal adoption date of the second adopter is identical with the one of the precommitment game, $\tau_2^T = T_2^T$. Turning to the first adoption, since the firms' discounted profits are the same in equilibrium, i.e., $\Pi_{D_1}^T(\tau_1^T, T_2^T) = \Pi_{D_2}^T(\tau_1^T, T_2^T)$, we get from (9) that:

$$\pi_{D_l}^T - \pi_{D_f}^T = \frac{r[k(\tau_1^T) - k(T_2^T)]}{e^{-r\tau_1^T} - e^{-rT_2^T}} \tag{16}$$

Hence, the optimal adoption date of the first adopter depends on the difference between the per-period equilibrium profits of the leader and the follower. As in Katz and Shapiro (1987), we refer to the latter as the first adopter's preemptive incentives. In the vertically related market with two-part tariff contracts, preemptive incentives are given by:

$$L^T = \pi_{D_l}^T - \pi_{D_f}^T = \frac{2}{5}A^2(1-\beta)\delta(2+\delta) \tag{17}$$

Clearly, the preemptive incentives are increasing in δ and decreasing in β. Moreover, if we compare the preemptive incentives in a vertically related market and an one-tier market (see Appendix for the relevant expression), we conclude that the former are higher than the latter if and only if $\beta < \frac{1}{6}$. This is so, since when the downstream firms are relatively powerful in the market, they extract a higher share of the per-period vertical chain's joint profits. This coupled with the fact that the leader is more heavily subsidized than the follower under two-part tariff contracts, and thus the difference between the leader's and follower's profits is higher in a vertically related than in an one-tier market, makes the preemptive incentives in a vertically related market stronger as long as β is small enough.

The comparison of the optimal adoption dates in a vertically related market with the respective ones in an one-tier market cannot be performed analytically; hence, we resort to numerical simulations. The simulations confirm our results included in Proposition 2. In the preemption game too, the first adoption takes place earlier in a vertically related market with two-part tariff contracts than in an one-tier industry, i.e., $\tau_1^T < \tau_1^I$, if and only if the downstream bargaining power is sufficiently high. As we already know, the same holds for the second adoption, i.e., $\tau_2^T < \tau_2^I$, if and only if the downstream bargaining power is sufficiently high and the new technology is not too drastic. These findings are illustrated in Tables 1 and 2 for different values of δ and β. For example, we observe that when $\delta = 0.1$ (see Table 1), $\tau_1^T < \tau_1^I$ if $\beta < 0.3$ and $\tau_2^T < \tau_2^I$ (i.e., $T_2^T < T_2^I$) if $\beta < 0.03$. We also observe that for higher values of δ (see e.g., $\delta = 0.3$ in Table 2), we can never have $\tau_2^T < \tau_2^I$.

β	τ_1^T	τ_1^I	T_1^T	T_1^I	T_2^T	T_2^I
.01	.179729	.193982	.226063	.231632	.235616	.236397
.015	.179982	.193982	.226317	.231632	.235869	.236397
.02	.180236	.193982	.226571	.231632	.236124	.236397
.03	.180749	.193982	.227084	.231632	.236637	.236397
.05	.181791	.193982	.228126	.231632	.237678	.236397
.1	.184494	.193982	.230829	.231632	.240382	.236397
.2	.190383	.193982	.236718	.231632	.246271	.236397
.3	.197060	.193982	.243395	.231632	.252947	.236397
.6	.225041	.193982	.271375	.231632	.252947	.236397
.9	.294356	.193982	.340690	.231632	.350243	.236397
.99	.409485	.193982	.455819	.231632	.465372	.236397

Table 1: Optimal adoption dates in a vertically related market and in an one-tier market when the new technology is not too drastic ($\delta = .1, \alpha = 20, r = .1$)

β	τ_1^T	τ_1^I	T_1^T	T_1^I	T_2^T	T_2^I
.01	.113654	.131167	.159543	.168348	.186247	.181466
.015	.113908	.131167	.159796	.168348	.186500	.181466
.02	.114162	.131167	.159796	.168348	.186754	.181466
.03	.114675	.131167	.160563	.168348	.187267	.181466
.05	.115717	.131167	.161605	.168348	.188309	.181466
.1	.118420	.131167	.164308	.168348	.191012	.181466
.2	.124309	.131167	.170197	.168348	.196901	.181466
.3	.130986	.131167	.176874	.168348	.203578	.181466
.6	.158967	.131167	.204855	.168348	.231559	.181466
.9	.228281	.131167	.274169	.168348	.300874	.181466
.99	.343410	.131167	.389299	.168348	.416003	.181466

Table 2: Optimal adoption dates in a vertically related market and in an one-tier market when the new technology is relatively drastic ($\delta = .3, \alpha = 20, r = .1$)

More importantly, we observe from the above Tables that in the preemptive game the range of β for which the first technology adoption takes place earlier in the vertically related market than in the one-tier market is larger in comparison to the precommitment game. For instance, we observe that when $\delta = 0.1$ (see Table 1), $\tau_1^T < \tau_1^I$ if $\beta < 0.3$ and $T_1^T < T_1^I$ if $\beta < 0.2$.

6.2 Product Differentiation

In our main model, we have assumed that firms produce a homogenous good. We now extend our model and consider the case in which firms' products are differentiated. In particular, we consider the case in which each D_i faces the following (inverse) demand function: $p_i(q_i, q_j) = a - q_i - \gamma q_j$, where γ, with $0 \leq \gamma < 1$, denotes the degree of the product substitutability; namely, the higher is γ, the closer substitutes the final products are. Keeping the rest of the specifications of our model fixed, we find that the equilibrium wholesale prices are negatively related to product substitutability. This means that the closer substitutes the products are, the more extensive is the subsidization in a vertically related market with two-part tariff contracts. This is so because when products are closer substitutes, downstream competition is fiercer and the incentives to strengthen the position of the downstream firm in the vertical chain via a lower wholesale price, or else to make the downstream firm more aggressive, are stronger. The latter implies that the fiercer downstream competition leads to a lower marginal cost in the vertically related market with two-part tariffs and hence, to a stronger output effect force then. In light of this, it is not surprising that we find that the first adoption takes place earlier in a vertically related market than in an one-tier market if the bargaining power of the downstream firms is sufficiently high and the products are relatively close substitutes. This holds also for the second adoption with the only difference, as in our main model results, that the new technology should be not too drastic. Thus, as far as the products are close substitutes, we reconfirm the results of our main model regarding the differences in the speed of the adoption between a vertically related market with two-part tariff contracts and an one-tier industry. However, if the products are not close substitutes, the output effect force is weak and the profits sharing force dominates. This means that, ceteris paribus, both the first and the second adoption take place earlier in the one-tier industry.

6.3 Price Competition

In our main model, we assumed that the downstream firms compete in quantities. We examine now what would happen if instead they compete in prices and produce differentiated goods.[22] Each firm D_i faces the following demand function, $q_i(p_i, p_j) = \frac{a(1-\gamma)-p_1+\gamma p_2}{1-\gamma^2}$, with $\gamma < \frac{1}{2}[\sqrt{9+2\delta+\delta^2}-(1+\delta)]$. Under this setting, we find that the upstream suppliers do not subsidize the downstream firms via the wholesale prices. This is so because the upstream suppliers do not longer want their downstream partners to behave aggressively because prices, in contrast to quantities, are strategic complements. However, we find that when the downstream firms are powerful enough, the fixed fees are negative - they take the form of "slotting allowances" that are paid from the upstream suppliers to their downstream customers. Given that in this case the wholesale prices always exceed the upstream marginal cost, the final output production in an one-tier market is always higher than that of a vertically related market. This fact tends to decrease the speed of adoption in a vertically related market relatively to the respective one in an one-tier market, since the new technology will be applied to a lower volume of production in the former market. On the contrary, the slotting allowances that the

[22] Clearly, with homogeneous products and price competition, the downstream firms would make zero gross profits, and thus, they would not have technology adoption incentives.

downstream firms obtain when they possess high bargaining power, along with the fact that these slotting allowances are positively related to the adoption of the new technology (i.e., they increase when a downstream firm adopts the technology), tend to enhance the speed of the adoption in a vertically related market relatively to the respective one in an one-tier market. Summing up, we find that in line with our main results, even under Bertrand competition, the first adoption takes place earlier in a vertically related market with two-part tariff contracts than in an one-tier industry, if the downstream firms are powerful enough and the final market competition is fierce enough. Regarding the second adoption the same result holds as far as the new technology is not too drastic. Clearly, under these circumstances, the *slotting allowances* effect is strong enough and dominates the negative output effect force.

7 Concluding Remarks

We have examined the timing of technology adoption in vertically related markets. In particular, we have studied how a number of important features of vertically related markets, such as the distribution of bargaining power and the contract type employed in vertical trading, along with the presence of vertical relations itself affects the adoption timing.

We have shown that the higher is the downstream bargaining power in the market, the earlier the new technology is adopted. Moreover, we have shown that the speed of technology adoption differs between vertically related markets with two-part tariff contracts and with wholesale price contracts. More specifically, due to the fact that under wholesale price contracts, double marginalization arises in equilibrium, the new technology can be adopted earlier when two-part tariff contracts, instead of wholesale price contracts, are employed as long as the downstream firms are sufficiently powerful.

Importantly, we have shown that when the final product manufacturers outsource input production, they might adopt earlier a new technology than when they produce the input inhouse. In other words, we have concluded that the presence of vertical relations and trading might speed up technology adoption. This holds when vertical trading is conducted through two-part tariff contracts and the upstream bargaining power is sufficiently low. Under these circumstances, the downstream production is subsidized by the upstream firms and the downstream firms gain a large share of the profits that are generated by technology adoption.

We should mention that most of our results extend to the case in which firms cannot precommit to their adoption dates as well as to the case in which downstream firms compete in prices. Still, we recognize that our paper constitutes just a first step in the direction of understanding the relationship between vertical relations and the timing of technology adoption. In a following step, one could explore how alternative structures of the upstream and/or the downstream market could influence the speed of adoption. For instance, one could examine what would happen in a market in which there is upstream monopoly or in which vertical relations are non-exclusive. Similarly, one could explore the timing of technology adoption by the upstream firms. These extensions are left for future research.

8 Appendix A: One-tier industry

We present here briefly the analysis of the firms' timing of adoption in an one-tier industry. Solving each firm's maximization problem in the last stage given by (1) after setting $w_i = 0$, we obtain the equilibrium quantities and the (gross) profits:

$$q_i^I(c_i, c_j) = \frac{1}{3}(\alpha - 2c_i + c_j);\ \pi_i^I(c_i, c_j) = [q_i^I(c_i, c_j)]^2.$$

Precommitment game: Turning to the firms' optimal adoption dates at $t = 0$, firms 1 and 2 choose, respectively, T_1 and T_2 such as to maximize their discounted sum of profits. Setting $\pi_{D_0} = \pi_i^I(c, c)$, $\pi_{D_l} = \pi_i^I(c-\Delta, c)$, $\pi_{D_f} = \pi_i^I(c, c-\Delta)$ and $\pi_{D_b} = \pi_i^I(c-\Delta, c-\Delta)$ into (9) and (10), and taking the first order conditions, we end up with (11), from which the incremental benefits of firm 1 and firm 2 are:

$$I_1^I = \frac{4}{9}A^2\delta(1+\delta) \text{ and } I_2^I = \frac{4}{9}A^2\delta.$$

Clearly, in an one-tier industry firms always have incentives to adopt the new cost reducing technology, $I_i^I > 0$. In addition, the first adoption leads to higher incremental benefits than the second one, $I_1^I > I_2^I$, and therefore in equilibrium there is technological diffusion, $T_1^I < T_2^I$. Further, we observe that the firms incremental benefits are increasing in δ, $\frac{\partial I_i^I}{\partial \delta} > 0$; hence, firms will adopt the new technology earlier as δ increases ($\frac{\partial T_i^I}{\partial \delta} < 0$). Note also that the incremental benefits of the first adopter increase at an increasing rate with δ, while those of the second adopter increase at a constant rate with δ.

Preemption game: The second adopter chooses its adoption date τ_2^I such as to maximize its profits $\Pi_2^I(\tau_1^I, \tau_2^I)$, given by equation (10) after setting $T_2 = \tau_2^I$. Solving the maximization problem of the second adopter we end up with the same first order condition as in the pre-commitment game: hence, $\tau_2^I = T_2^I$. Regarding the first adoption, since the firms' discounted profits should be the same in equilibrium, i.e., $\Pi_1^I(\tau_1^I, T_2^I) = \Pi_2^I(\tau_1^I, T_2^I)$, we have from (9) that:

$$\pi_l^I - \pi_f^I = \frac{r[k(\tau_1^I) - k(T_2^I)]}{e^{-r\tau_1^I} - e^{-rT_2^I}}$$

Hence, the preemptive incentives in the one tier industry are:

$$L^I = \pi_l^I - \pi_f^I = \frac{1}{3}A^2\delta(2+\delta)$$

Note that the preemptive incentives are increasing in δ in this case too. Taking the difference of the preemptive incentives in the one-tier industry given above and in the vertically related market given in (17), we have:

$$L^T - L^I = \frac{1}{15}(1-6\beta)\delta(2+\delta)$$

Clearly then, preemptive incentives are stronger in a vertically related market with two part tariff contracts than in an one-tier market if and only if $\beta < \frac{1}{6}$.

9 Appendix B

Proof of Proposition 1

By inspection of (12), we see that $\frac{\partial I_i^T}{\partial \beta} < 0$; hence $\frac{\partial T_i^T}{\partial \beta} > 0$. ■

Proof of Proposition 2

Taking the difference between the firms' incremental benefits in a vertically related market with two-part tariff contracts and those in an one-tier industry, we have:

$$I_1^T - I_1^I = \frac{2}{225}\delta[4 + 31\delta - 27\beta(2+3\delta)] \text{ and } I_2^T - I_2^I = \frac{2}{225}\delta[4 - 27\beta(2-\delta) - 27\delta]$$

(i) Setting $I_1^T - I_1^I = 0$ and solving for β we find $\beta_1(\delta) = \frac{4+31\delta}{27(2+3\delta)}$, with $\frac{\partial \beta_1}{\partial \delta} > 0$. It follows that $I_1^T - I_1^I > 0$, and thus, $T_1^T < T_1^I$ if $\beta < \beta_1(\delta)$; otherwise, $T_1^T > T_1^I$.

(ii) Setting $I_2^T - I_2^I = 0$ and solving for β we find $\beta_2(\delta) = \frac{4-27\delta}{27(2-\delta)}$, with $\beta_2(\delta) > 0$ only if $\delta < \frac{4}{27}$; moreover, $\frac{\partial \beta_2}{\partial \delta} < 0$. It follows that $I_2^T - I_2^I > 0$, and thus, $T_2^T < T_2^I$ if $\delta < \frac{4}{27}$ and $\beta < \beta_2(\delta)$; otherwise, $T_2^T > T_2^I$. ■

Proof of Proposition 3

Taking the difference of the incremental benefits in a vertically related market with two-part tariff contracts and those with wholesale price contracts we have:

$$I_1^T - I_1^W = \frac{2(1+\beta)\delta\Omega}{225(16-\beta^2)^2} \text{ and } I_2^T - I_2^W = \frac{2(1+\beta)\delta\Phi}{225(16-\beta^2)^2},$$

where $\Omega \equiv 16\beta^3(13+7\delta) + 120\beta^2(6+29\delta) + 256(4+31\delta) - 27\beta^4(2+3\delta) - 192\beta(19+66\delta)$ and $\Phi \equiv 256(4-27\delta) - 27\beta^4(2-\delta) + 16\beta^3(13+6\delta) + 120\beta^2(6-23\delta) - 192\beta(19-47\delta)$.

(i) Setting $I_1^W - I_1^T = 0$ and solving for δ we find $\delta_3(\beta) = \frac{2(4+\beta)[\beta(488-\beta(212-27\beta))-128]}{7936-\beta[12672-\beta(3480+\beta(112-81\beta))]}$. Note that $0 \le \delta_3(\beta) \le 0.5$ for $0.30 \le \beta \le 0.59$ and that in this range $\frac{\partial \delta_3}{\partial \beta} > 0$. Define $\beta_3(\delta) = \delta_3^{-1}(\beta)$ for $\delta \in [0, 0.5]$. It follows that $I_1^T - I_1^W > 0$, and thus, $T_1^T < T_1^W$ if $\beta < \beta_3(\delta)$; otherwise $T_1^T > T_1^W$.

(ii) Similarly, setting $I_2^W - I_2^T = 0$ and solving for δ we find $\delta_4(\beta) = \frac{2(4+\beta)[\beta(488-\beta(212-27\beta))-128]}{3[\beta(3008-\beta(920-\beta(32+9\beta)))-2304]}$. Note that $\delta_4(0) = \frac{4}{27}$, $\delta_4(0.3) = 0$ and that $\frac{\partial \delta_4}{\partial \beta} < 0$ for $\beta \in [0, 0.3]$. Define $\beta_4(\delta) = \delta_4^{-1}(\beta)$ for $\delta \in [0, \frac{4}{27}]$. It follows that $I_2^T - I_2^W > 0$, and thus, $T_2^T < T_2^W$ if $\delta < \frac{4}{27}$ and $\beta < \beta_4(\delta)$; otherwise $T_2^T > T_2^W$. ■

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