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On Vertical Relations and the Timing of Technology Adoption

Maria Alipranti Chrysovalantou Milliou Emmanuel Petrakis*

October 2015

Abstract

We study the timing of new technology adoption in markets with input outsourcing, and thus with vertical relations. We find that technology adoption can take place earlier when firms engage in input outsourcing than when they produce the input in-house. Hence, the presence of vertical relations can accelerate the adoption of a new technology. We also find that particular features of a vertically related market, such as the bargaining power distribution and the contract type through which trading is conducted, can crucially affect the speed of technology adoption.

JEL Classification: L13, O31, L22, L41

Keywords: Technology adoption; vertical relations; outsourcing; two-part tariffs; wholesale price contracts; bargaining

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1 Introduction

In today's economy, many firms outsource their inputs to external input producers instead of producing them in-house. This is common in many industries, including the automotive, aircraft, computer, mobile phone, and pharmaceutical sectors.[1] As demonstrated in a number of empirical studies, a firm's organizational mode of production—the use of in-house production or outsourcing—can crucially influence, among other things, the rate at which it adopts new technologies. In particular, Dewan et al. (1998), Hitt (1999), and Forman and Gron (2011) show that the degree of vertical integration of US firms is negatively correlated to their adoption of information technology (IT). In the same vein, Girma and Lancheros (2009) show that there are complementarities between input imports, outsourcing, and the rate of technology adoption in the software services and pharmaceutical industries of India. Others, however, provide evidence to the contrary. Lane (1991), Carlsson and Jacobsson (1994), and Helper (1995) show that in-house production encourages the adoption of new technologies in the US coal industry, the Swedish engineering industry, and the US automotive industry, respectively.

The mechanisms via which the organizational mode of production affects a firm's timing of technology adoption are still unexplored. In this paper, we study these mechanisms. Our aim is to provide answers to the following questions. How does the timing of technology adoption differ among different organizational structures of production, and in particular between input outsourcing and in-house input production? What is the impact of the main features of vertical trading—the contract type used and the bargaining power distribution—on the speed of adoption?[2] How does the effectiveness of new technology influence the speed of its adoption and, more importantly, its diffusion among competing firms?

To address these questions, we use a framework in which under outsourcing two competing downstream firms produce a final product using an input that they obtain from two external upstream firms. Trading between the upstream and downstream firms is exclusive and is conducted via two-part tariff contracts or linear wholesale price contracts. The downstream firms are initially endowed with the same production technology. However, they can both

[1] For evidence regarding the extensive use of outsourcing see e.g., Shy and Stenbacka (2003).

[2] Contract types can take many different forms. They can be simple linear contracts, such as wholesale price contracts, or more complicated non-linear contracts, such as two-part tariffs. For more information regarding the contract types commonly used in vertically related markets, see Berto Villas-Boas (2007) and Bonnet and Dubois (2010).

adopt a new cost-reducing technology. If a downstream firm adopts the new technology first, it enjoys a competitive advantage over its rival. However, if it adopts the new technology second, it incurs a lower adoption cost.[3] A game with an infinite horizon is analyzed in which the downstream firms choose their technology adoption dates at the start and commit to them. In every period thereafter, they first negotiate with their respective upstream suppliers over their contract terms, and then choose their output. The same game but without negotiations over the contract terms is also played in the case of insourcing, that is, when the two downstream firms produce their input in-house.

Our analysis reveals that there are two effects under outsourcing that are absent under insourcing. In a vertically related market, a downstream firm does not obtain the whole surplus that it generates. In fact, with two-part tariffs it obtains only the share that corresponds to its bargaining power. As a consequence, when the upstream bargaining power increases, a downstream firm's incentives to undertake costly technology adoption get weaker. This is the first effect, the *profits sharing effect*. The second effect, the *terms of trade effect*, refers to the better trading terms—the lower wholesale price—that an upstream firm offers to its downstream customer when they trade via two-part tariffs and the latter adopts the new technology. This occurs because an upstream firm has incentives to increase the competitiveness of its downstream customer by charging a lower wholesale price since it can extract part of the resulting higher downstream profits through the fixed fee. When its downstream customer adopts the new technology, its efficiency and profits increase; hence, the upstream firm's incentives to offer better contract terms are reinforced.

In light of the above, we show that vertical relations not only affect the speed of technology adoption but also, more importantly, can accelerate it. Stated differently, a firm that engages in input outsourcing can adopt the new technology earlier than a firm that produces the input in-house. Clearly, this result is driven by the presence of the *terms of trade effect* under outsourcing that reinforces the technology adoption incentives. However, the *terms of trade effect* does not always lead to earlier adoption under outsourcing than under insourcing. When the upstream bargaining power is sufficiently high, the *profits sharing effect* is strong and dominates, resulting in earlier adoption under insourcing. Importantly, by extending our

[3] We assume that the adoption cost decreases over time at a decelerating rate. This could be because of economies of learning or basic research on innovation for the adoption process. This is a standard assumption in the literature (Reinganum, 1981a&b; Fudenberg and Tirole, 1985; Quirmbach, 1986).

analysis we demonstrate that the positive impact of outsourcing on the timing of technology adoption is reinforced when firms are unable to commit to their adoption dates at the outset and can instead respond immediately and costlessly to their rival's adoption plan.

Furthermore, we show that the contract type used in vertical trading can play a crucial role in the timing of technology adoption: adoption can occur earlier under two-part tariff contracts than under linear wholesale price contracts when the downstream firms are sufficiently powerful. The intuition behind this lies mainly on the reversal of the *terms of trade effect* under wholesale price contracts. The reversal is due to the fact that under such contracts, the only tool an upstream firm has to obtain part of the higher profits resulting from technology adoption is the wholesale price. This is also why a downstream firm obtains a relatively greater share of the surplus under wholesale price contracts than under two-part tariffs. Thus, when downstream firms are less powerful, the *profits sharing effect*, which favors wholesale price contracts, leads to earlier technology adoption under such contracts. When wholesale price contracts are used, owing to double marginalization and the reversal of the *terms of trade effect* and in contrast to what happens with two-part tariffs, vertical relations always slow down the speed of technology adoption.

Finally, we show that as expected, when the new technology is more effective it is adopted faster, but the time span between successive adoptions is longer.[4] This is because the *terms of trade effect* is stronger for the first than for the second adopter of the technology.

Our findings are consistent with the aforementioned empirical studies (e.g., Lane, 1991, Dewan et al.,1998; Forman and Gron, 2011; Helper, 1995) demonstrating that the organizational structure of production can affect the technology adoption rate. Moreover, our results suggest that the diversity in the conclusions of these studies regarding the impact of outsourcing on the timing of technology adoption could be attributed to differences in market features, such as the bargaining power of input suppliers and/or the contract types used in vertical trading. Our findings suggest, for instance, that while a new technology could be adopted earlier under outsourcing in a market with relatively weak input producers, it could be adopted earlier under insourcing in a market with powerful input producers.

There is ample evidence that there are often long time lags between the invention of new technologies and their adoption, and significant differences in the adoption timing among differ-

[4] Note that, as is standard in the literature on technology adoption, there is technology diffusion in equilibrium, that is, competing firms do not adopt the new technology simultaneously.

ent firms and different markets (Griliches, 1957; Mansfield, 1968, 1985; Rogers, 1995; Jovanovic and Lach, 1997; Genesove, 1999; Astebro, 2002).[5] In addition, the speed of the adoption of new technologies constitutes a fundamental determinant of economic growth. Given this, an extensive literature on the timing of technology adoption in the presence of strategic interactions has been developed (e.g., Reinganum, 1981a&b, 1983a&b; Fudenberg and Tirole, 1985; Quirmbach, 1986; Riordan, 1992; Hoppe and Lehmann-Grube, 2001; Ruiz-Aliseda and Zemsky, 2006; Milliou and Petrakis, 2011).[6] A number of papers within this literature have argued that variations in adoption timing across different markets could be due to differences in market features, such as network externalities (Cabral, 1990; Choi and Thum, 1998), information externalities (Chamley and Gale, 1994), strategic managerial delegation (Mahathi and Rupayan, 2013), and the mode and intensity of market competition (Milliou and Petrakis, 2011). However, the aforementioned literature has dealt exclusively with one-tier markets, that is, markets with in-house input production. Instead, we consider vertically related markets. Doing so, we offer an alternative explanation for variations in adoption timing across different markets based on the features of vertically related markets and the vertical relations themselves.

Our work is also related to the literature that has considered R&D investments in vertically related markets, either upstream (Stefanadis, 1997; Inderst and Wey, 2007, 2011; Fauli-Oller et al., 2011; Milliou and Pavlou, 2013) or downstream (Steurs, 1995; Banerjee and Lin, 2003; Manasakis et al., 2014). All of these papers have analyzed decisions on *how much* to invest in R&D. We complement this literature by instead analyzing decisions on *when* to invest in R&D, and in particular on when to adopt a new technology.

Finally, our work is related to strategic outsourcing literature. 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 make-or-buy decisions—the choice between in-house production and outsourcing—and alternative input sourcing strategies (e.g., Beladi and Mukherjee, 2012; Stenbacka and Tombak, 2012). In line with this literature, we consider dif-

[5]A typical example of delays in the adoption and diffusion of new technologies is the basic oxygen furnace (BOF), a technological breakthrough in the steel industry that reduces the processing time and cost of steel making. There was a 15-year time lag between BOF invention and its adoption, and it took more than 20 years for diffusion of its use from 10% to 90% (Hoppe, 2002). A more recent example comes from the manufacture of mobile chips, for which there are time lags in the adoption of next-generation (nanometer) manufacturing technologies among competing firms such as TSMC, Intel, and Samsung. However, this is not the case for all new technologies, and some (e.g., mobile phones) have rapidly diffused in the market.

[6]Hoppe (2002) provides an extensive survey of the theoretical literature on the timing of technology adoption.

ferent organizational structures of production, with a particular focus on the impact of these structures on the timing of technology adoption.

The remainder of the paper is organized as follows. Section 2 describes our model. In Section 3, we determine the optimal adoption dates in a vertically related market. Section 4 examines the impact of vertical relations on the timing of technology adoption. In Section 5, we analyze the role of the contract type. Section 6 discusses possible extensions of our model. Finally, Section 7 concludes. All proofs are relegated to the Appendix.

2 The Model

We consider a vertically related industry consisting of two upstream and two downstream firms denoted by U_i and D_i, respectively, with $i = 1, 2$. The upstream firms produce an input at zero marginal cost. The downstream firms transform the input into a final good on a one-to-one basis and face initially an exogenous marginal cost, c, plus the cost of the input. 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.[7] Trade relations between U_i and D_i are exclusive (see Figure 1).[8] Demand for the final good is given by $p(Q) = a - Q$, where $Q = q_i + q_j$ is the total quantity, with $i, j = 1, 2$ and $i \neq j$.[9]

[7] In Section 5, we examine the case in which firms trade via wholesale price contracts that include only w_i.

[8] Exclusive relations can exist because upstream firms produce inputs that are tailored for specific downstream firms and there are irreversible investments that create high switching costs. Exclusivity is a common assumption in the literature on vertical relations (e.g., Horn and Wolinsky, 1988; Gal-Or, 1991; Lommerud et al., 2005; Milliou and Petrakis, 2007). Furthermore, exclusive relations are pervasive in many markets, such as the UK beer market, the gasoline market, and the car and aircraft manufacturing markets. In particular, 36% of the car manufacturing firms in Central and Eastern Europe impose exclusivity conditions on their suppliers (Lorentzen and Mollgaard, 2000), while the engine manufacturers Rolls Royce and CMF International exclusively supply the aircraft manufacturers Airbus and Boeing, respectively. The pervasiveness of exclusive relations is also reflected in many antitrust cases that involve exclusivity agreements, such as Scholler vs. Commission - European Court T-9/95, Conwood vs. US Tobacco - 290 F3d 768 (2002), and US vs. Visa USA - 344 F3d 229 (2003).

[9] Although the final products are homogeneous, they can still be produced via different production technologies that in turn require different or specialized inputs. This is the case for a number of products that tend to be homogeneous, such as textiles, plastics, and paper, but are produced by some firms using traditional technologies and by others using biotechnology (Gil-Moltó et al., 2005). As we demonstrate in Section 6.2, our main results also hold when final products are differentiated as long as the degree of differentiation is not too high.

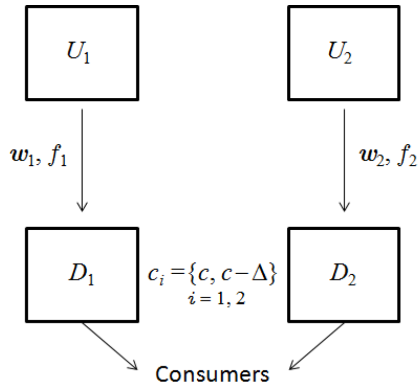

Figure 1: Market Structure

Time, denoted by $t \geqslant 0$, is continuous and has an infinite horizon. At $t = 0$, a new cost-reducing technology becomes available in the market. If D_i adopts the new technology at $t \geqslant 0$, its marginal cost decreases by Δ thereafter, with $0 < \Delta < c < a$. Thus, D_i's gross from the wholesale price marginal cost at $t \geqslant 0$ is $c_i \in \{c, c - \Delta\}$, depending on whether or not it has adopted the technology. Adoption of the new technology is costly. Following Reinganum (1981a&b) and Fudenberg and Tirole (1985) and letting $k(t)$ denote the present value of the cost of bringing the new technology on line by date t, we assume that $(k(t)e^{rt})' < 0$ and $(k(t)e^{rt})'' > 0$, where r $(0 < r < 1)$ is the interest rate. That is, the current cost of adoption, $k(t)e^{rt}$, is decreasing, but at a decreasing rate. The latter implies that the current cost of adoption falls faster than the discount rate e^{-r}. These assumptions are satisfied, for instance, by $k(t) = e^{-(r+\alpha)t}$, with $\alpha > 0$. We also assume that technology adoption cannot occur immediately because of prohibitively high costs, but that it always occurs at a finite date: $\lim_{t\to 0} k(t) = -\lim_{t\to 0} k'(t) = \infty$ and $\lim_{t\to\infty} k'(t)e^{rt} = 0$. Finally, as standard in the technology adoption 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, the date on which it will adopt the new technology. Moreover, at $t = 0$ and in every other period $t > 0$, first, each (U_i, D_i) pair bargains over the contract terms $(w_i,\ f_i)$, and then D_i and D_j simultaneously set their quantities after observing all the contract terms.[10] We model the bargaining over contract terms in the first stage of every period t by invoking

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

the Nash equilibrium of simultaneous generalized Nash bargaining problems. We assume that the bargaining power of each U_i and D_i is β and $1-\beta$, respectively, with $0<\beta<1$.

The game we have described is based on the precommitment game of Reinganum (1981a&b). 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 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.[11]

To guarantee that all firms are active and that their marginal costs are positive in all the cases considered, we assume the following throughout.

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

The parameter δ measures the effectiveness of the new technology. In particular, it measures how effective the new technology is in reducing the marginal production cost of the downstream firms relative to the market size. The higher that δ is, the more effective is the new technology.

We finally assume, without loss of generality, that if the downstream firms do not adopt the technology simultaneously, then D_1 is the first adopter and D_2 is the second adopter. Moreover, for periods in which only D_1 has adopted the technology, we refer to D_1 as the *technology leader* and to D_2 as the *technology laggard*.

3 Optimal Adoption Timing

In the second stage of every period $t \geqslant 0$, each D_i chooses its output q_i to maximize its per-period gross (from the adoption cost and f_i) profits, given by $\pi_{D_i}(.) = (p(Q) - c_i - w_i)\, q_i$. The resulting equilibrium quantities and (gross) downstream and upstream profits are

$$q_i(c_i, c_j, w_i, w_j) = \frac{a - 2(c_i + w_i) + (c_j + w_j)}{3}; \tag{1}$$

[11] In Section 6.1, we extend our analysis to a closed-loop framework and show that our results remain qualitatively intact. In particular, following Fudenberg and Tirole (1985), we consider a preemption game in which downstream firms are able to adjust their adoption dates with respect to what has happened in the past. This occurs when there are no information lags and the cost of altering adoption plans is infinitesimal, and thus firms can immediately respond to the adoption plans of their rivals.

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

In the first stage of every period $t \geqslant 0$, each (U_i, D_i) pair, taking as given the outcome of the simultaneous negotiations of the (U_j, D_j) pair, (w_j^T, f_j^T), solves the following maximization problem

$$\max_{w_i,\, f_i} [\pi_{U_i}(c_i, c_j, w_i, w_j^T) + f_i]^\beta [\pi_{D_i}(c_i, c_j, w_i, w_j^T) - f_i]^{1-\beta}. \quad (3)$$

Maximizing (3) with respect to f_i, we obtain $f_i = \beta\pi_{D_i}(c_i, c_j, w_i, w_j^T) - (1-\beta)\pi_{U_i}(c_i, c_j, w_i, w_j^T)$. Substituting f_i into (3), we note that the generalized Nash product is proportional to the per-period joint profits of (U_i, D_i) and that U_i and D_i obtain a share of these profits corresponding to their respective bargaining power, β and $1 - \beta$. It follows that w_i is chosen to maximize their per-period joint profits: $\pi_{U_i}(c_i, c_j, w_i, w_j^T) + \pi_{D_i}(c_i, c_j, w_i, w_j^T)$. The resulting equilibrium wholesale prices are

$$w_i^T(c_i, c_j) = \frac{-(a - 3c_i + 2c_j)}{5}. \quad (4)$$

A number of observations can be made regarding the equilibrium wholesale prices. First, the wholesale prices are independent of the bargaining power distribution. Second, they are always lower than the upstream marginal cost, that is, the upstream firms subsidize their downstream customers.[12] This occurs because a decrease in w_i shifts the reaction function of D_i outwards. Given that the reaction functions are downward-sloping, this shift leads to a lower output for rival D_j and a higher output and gross profits for D_i. In turn, U_i receives part of the resulting higher gross profits obtained by its downstream customer by charging a higher fixed fee.

The above observations have already been noted in the literature on vertically related markets (e.g., Milliou and Petrakis, 2007). A novel observation we make here is that the wholesale price charged to D_i decreases, and thus the subsidization increases, when D_i adopts the new technology. This clearly implies that when D_i adopts the technology, the cost reduction that it enjoys is greater than Δ. In particular, the *effective* cost reduction caused by technology adoption is $\Delta + w_i^T(c, c) - w_1^T(c - \Delta, c) > \Delta$ for the technology leader, and $\Delta + w_2^T(c - \Delta, c) - w_i^T(c - \Delta, c - \Delta) > \Delta$ for the second adopter. From now on, we refer to the impact on the adopter's effective cost caused by a change in the terms of vertical trading as the *terms of trade effect*. Clearly, the *terms of trade effect* is positive for the adopters. But what drives

[12] A similar result has been reported in the strategic delegation literature (Vickers, 1985; Fershtman and Judd, 1987) and in the literature on vertically related markets with two-part tariff contracts (Milliou and Petrakis, 2007; Milliou and Pavlou, 2013).

the *terms of trade effect*? Technology adoption increases the effectiveness of the downstream adopter, and thus its output. This increase in output intensifies the incentives of its upstream supplier to enhance the efficiency of its downstream customer to further increase its output. This is because, as mentioned above, it can then charge a higher fixed fee and transfer part of the resulting higher gross downstream profits upstream.

We should note that the *terms of trade effect* is stronger in periods in which D_1 is the technology leader than in periods in which both firms have adopted the technology: $w_1^T(c-\Delta, c) < w_i^T(c-\Delta, c-\Delta) < w_i^T(c, c)$. Moreover, the *terms of trade effect* does not favor the technology laggard. In particular, D_2 is charged a higher wholesale price when its rival adopts the technology: $w_2^T(c-\Delta, c) > w_i^T(c, c)$. The intuition behind this is straightforward in light of the above: when D_1 adopts the technology, it obtains a cost advantage relative to D_2; hence, the output of D_1 increases while that of D_2 decreases. The lower output of D_2 weakens the effectiveness of a further reduction in its marginal cost through a decrease in the wholesale price.

We should also note that the *terms of trade effect* is stronger when the new technology is more effective, that is, the wholesale price(s) charged to the technology adopter(s) decreases with Δ and thus with δ. It is clear that this occurs because the higher that δ is, the greater is the cost reduction that an adopter enjoys, and thus the greater is its output. Moreover, since the cost advantage of the technology leader D_1 becomes more pronounced when δ increases, it follows that the output of the technology laggard D_2 shrinks, and thus w_2 increases with δ.

Substituting (4) into (1) and (2), we obtain the equilibrium per-period quantities and downstream profits

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

We now address the choice of adoption date T_i by D_i at $t = 0$. It is clear that D_i will choose T_i to maximize the discounted sum of its infinite stream of per-period profits. In particular, the maximization problems that D_1 and D_2 face are

$$\max_{T_1} \Pi_{D_1}(T_1, T_2) = \int_0^{T_1} \pi_{D_0} e^{-rt} dt \; + \int_{T_1}^{T_2} \pi_{D_l} e^{-rt} dt \; + \int_{T_2}^{\infty} \pi_{D_b} e^{-rt} dt - k(T_1) \tag{6}$$

and

$$\max_{T_2} \Pi_{D_2}(T_1,T_2) = \int_0^{T_1} \pi_{D_0} e^{-rt} dt \ + \int_{T_1}^{T_2} \pi_{D_f} e^{-rt} dt \ + \int_{T_2}^{\infty} \pi_{D_b} e^{-rt} dt - k(T_2), \qquad (7)$$

where $\pi_{D_0} = \pi^T_{D_i}(c,c)$ and $\pi_{D_b} = \pi^T_{D_i}(c-\Delta, c-\Delta)$ denote the per-period profits before (any) adoption and after (global) adoption, respectively, for D_i. In addition, $\pi_{D_l} = \pi^T_{D_i}(c-\Delta, c)$ denotes the per-period profit for D_1 as the technology leader and $\pi_{D_f} = \pi^T_{D_i}(c, c-\Delta)$ the per-period profit for D_2 as the technology laggard. The first-order conditions of (6) and (7) result in

$$I_1^T = \frac{6}{25}A^2(1-\beta)\delta(2+3\delta) = -k'(T_1^T)e^{rT_1^T} \text{ and } I_2^T = \frac{6}{25}A^2(1-\beta)\delta(2-\delta) = -k'(T_2^T)e^{rT_2^T}, \ (8)$$

where $I_1^T \equiv \pi_{D_l} - \pi_{D_0}$ and $I_2^T \equiv \pi_{D_b} - \pi_{D_f}$ are the incremental benefits from technology adoption for D_1 and D_2, respectively. Observe from (8) that the optimal adoption dates T_1^T and T_2^T are such that the incremental benefits from adoption for each D_i are equal to its marginal cost of waiting. In addition, in line with the literature on technology adoption in one-tier industries (e.g., Reinganum, 1981a&b; Quirmbach, 1986; Milliou and Petrakis, 2011), firms always have incentives to adopt the technology ($I_i^T > 0$) and that first adoption leads to higher incremental benefits than second adoption ($I_1^T > I_2^T$). This, along with our assumptions regarding the cost of adoption, implies that $T_1^T < T_2^T$, and thus that in equilibrium there is technology diffusion.

The following proposition describes how the bargaining power distribution and the effectiveness of the new technology influence the adoption pattern.

Proposition 1 *A decrease in the upstream bargaining power β and an increase in the effectiveness of the new technology δ accelerate technology adoption by both downstream firms, that is, $\frac{\partial T_i^T}{\partial \beta} > 0$ and $\frac{\partial T_i^T}{\partial \delta} < 0$, but increase the time span between the adoption dates of the downstream firms, that is, $\frac{\partial (T_2^T - T_1^T)}{\partial \beta} < 0$ and $\frac{\partial (T_2^T - T_1^T)}{\partial \delta} > 0$.*

The higher the upstream bargaining power, the later the downstream firms adopt the new technology. The intuition for this is straightforward. We know from above that D_i obtains the share of its joint profits with U_i that corresponds to its bargaining power. As a consequence, the higher the upstream bargaining power, the smaller is D_i's share of the joint profits, and thus the weaker are its incentives to undertake costly technology adoption. From now on we refer to the negative impact of the upstream bargaining power on technology adoption incentives as the *profits sharing effect*.

The *profits sharing effect* is stronger for the first adopter than for the second adopter, that is, the incentives for the first adopter increase more than those for the second adopter when β decreases. This is because the increase in the joint profits of D_1 and U_1 induced by first adoption is greater than that in the joint profits of D_2 and U_2 induced by second adoption. More specifically, first adoption results in a high cost advantage for D_1 relative to D_2 not only because D_1 then utilizes a more efficient technology but also because it enjoys a positive *terms of trade effect*. By contrast, second adoption does not generate any cost advantage for D_2, it simply eliminates the cost advantage of D_1. A consequence of this is that, as stated in Proposition 1, the difference in adoption dates between the first and second adopter increases when the upstream bargaining power decreases.

As expected, both first and second adoption occur earlier when the new technology is more effective. In our setting, this holds not only because the new technology delivers greater cost reductions but also because the *terms of trade effect* is stronger, as mentioned previously, and thus the effective cost reduction is greater. Proposition 1 also indicates that the more effective the new technology, the longer is the time span between first and second adoption. This is because an increase in δ, similarly to a decrease in β, leads to a greater increase in profits for first adoption than for second adoption.

4 Impact of Vertical Relations: Outsourcing vs. Insourcing

In this section we examine how vertical relations affect the speed of technology adoption by comparing optimal adoption dates between a one-tier market and a vertically related market, which corresponds to a comparison between in-house input production and input outsourcing.

To perform the comparison, we first need to examine, similar to the literature on technology adoption (e.g., Reinganum, 1981a&b; Quirmbach, 1986; Milliou and Petrakis, 2011), what happens in a 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 $w_i = f_i = 0$.[13] Obtaining the optimal adoption dates

[13] It follows 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.

for a one-tier market and comparing them with those for a vertically related market, we find the following.[14]

Proposition 2 *(i) First adoption occurs earlier in a vertically related market than in a one-tier market if and only if the upstream bargaining power is sufficiently low, that is,* $\beta < \beta_1(\delta)$*, where* $\partial\beta_1(\delta)/\partial\delta > 0$*.*

(ii) Second adoption occurs earlier in a vertically related market than in a one-tier market if and only if the new technology is not too effective and the upstream bargaining power is sufficiently low, that is, $\delta < \frac{4}{27}$ *and* $\beta < \beta_2(\delta)$*, where* $\partial\beta_2(\delta)/\partial\delta < 0$*.*

Interestingly, technology can be adopted earlier with outsourcing than with insourcing. In other words, the presence of vertical relations can accelerate technology adoption. This holds for first adoption in areas A and B of Figure 2, i.e., when the upstream bargaining power is sufficiently low. For second adoption, it holds only in area A of Figure 2, that is, when both the upstream bargaining power and the effectiveness of the new technology are sufficiently low.

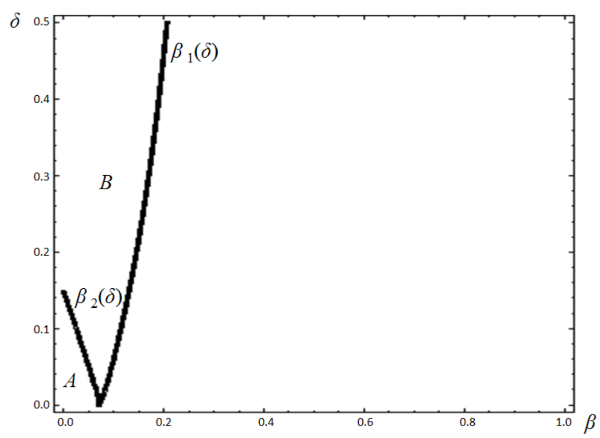

Figure 2: Comparison of the adoption dates with outsourcing and insourcing

The intuition for this finding is as follows. It is well known from the literature that when a firm's output increases, its incentives to become more efficient, and thus its incentives to invest in a cost-reducing technology, become stronger. This is the so-called *output effect*.[15] In

[14] Since technology adoption in a one-tier market has already been analyzed in detail in the literature (e.g., Reinganum, 1981a&b Quirmbach, 1986; Milliou and Petrakis, 2011), we only analyze this briefly in Appendix A.

[15] Bester and Petrakis (1993) first identified the *output effect* in a one-tier market in which firms invest in cost-reducing R&D. Milliou and Petrakis (2011) showed how the *output effect* affects the timing of technology adoption in a one-tier market.

our setting, the *output effect* is present for with both outsourcing and insourcing, although it is stronger with the former. There are two reasons for this. The first is that D_i faces a lower effective cost under outsourcing than under insourcing owing to the subsidization of downstream production, and thus it produces more under outsourcing. The second is the positive *terms of trade effect*, which is present only under outsourcing. In particular, when D_i invests in technology adoption, its effective cost reduces by more and thus its output increases by more under outsourcing than under insourcing owing to the improvement in trade terms.

In light of the above, we would expect that a firm should always adopt technology earlier under outsourcing than under insourcing. However, Proposition 2 indicates that this does not always hold. This is because there is an additional effect under outsourcing that is absent under insourcing that weakens the adoption incentives: the *profits sharing effect* (Proposition 1). When the upstream bargaining power is low, the *profits sharing effect* is weak and is dominated by the *terms of trade effect*; hence, the first adopter adopts the technology earlier under outsourcing than under insourcing. This also holds for the second adoption, but only if the new technology is not too effective. This is because under outsourcing, the unfavorable impact of the *terms of trade effect* on the technology laggard becomes more severe as the technology becomes more effective.

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

In this section we investigate whether and how the contract type used in a vertically related market affects the timing of adoption. To do so, we examine what happens when vertical trading occurs via linear wholesale price contracts.

In the first stage of every period $t \geq 0$, each (U_i, D_i) pair maximizes (3) in terms of w_i after setting $f_i = 0$ and substituting w_j^T with w_j^W, where w_j^W is the equilibrium wholesale price of the pair (U_j, D_j). The resulting equilibrium wholesale prices are

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

Under wholesale price contracts, the equilibrium wholesale prices behave in exactly the opposite way than under two-part tariff contracts. In particular, under wholesale price contracts the equilibrium wholesale prices depend on the bargaining power distribution, as is already known from the literature (Milliou and Petrakis, 2007). Moreover, equilibrium wholesale prices increase with the upstream bargaining power and exceed the upstream marginal cost, that is, double marginalization is present. The novel finding here is that under wholesale price contracts, the equilibrium wholesale price charged to D_i increases when the latter adopts the technology; thus, the adopter's *effective* cost reduction is lower than Δ. This clearly implies that in the case of wholesale price contracts, the *terms of trade effect* is negative instead of positive. The reversal of the *terms of trade effect* is driven by the fact that under wholesale price contracts, the only tool that an upstream firm has for achieving positive profits is the wholesale price. When D_i adopts the new technology, it becomes more efficient and thus its upstream supplier increases the wholesale price charged. Moreover, we find that the *terms of trade effect* is more negative for an adopter in periods in which it is the technology leader than in periods in which both firms have adopted the technology.

The fact that the *terms of trade effect* is negative under wholesale price contracts favors the technology laggard; D_2 pays a lower wholesale price when its rival adopts the technology. This occurs because U_2 wants to guarantee that D_2 remains in the market; otherwise, U_2 will make zero sales and profits. Moreover, the more effective the new technology is, and thus the more efficient the adopter becomes, the more negative is the *terms of trade effect.* In turn, the wholesale price charged to the technology laggard is even lower. Finally, as δ increases, in line with the above discussion, the wholesale price charged to a technology adopter increases.

Substituting (9) into (2), we obtain the per-period profits of D_i as

$$\pi_{D_i}^W(c_i, c_j) = \frac{4(2-\beta)^2[a(4+\beta) - (8-\beta)c_i + 2(2-\beta)c_j]^2}{9(16-\beta^2)^2}. \tag{10}$$

At $t = 0$, D_1 and D_2 choose T_1 and T_2 to maximize (6) and (7) 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

$$I_1^W = \frac{4(8-\beta)(2-\beta)^2 \delta A^2[2(4+\beta) + (8-\beta)\delta]}{9(16-\beta^2)^2} = -k'(T_1^W)e^{rT_1^W} \tag{11}$$

and

$$I_2^W = \frac{4(8-\beta)(2-\beta)^2 \delta A^2[2(4+\beta) + 3\beta\delta]}{9(16-\beta^2)^2} = -k'(T_2^W)e^{rT_2^W}. \tag{12}$$

We confirm that under wholesale price contracts, the downstream firms always have incentives to adopt the technology and there is technological diffusion in equilibrium. We also confirm that the effects of the upstream bargaining power and of the effectiveness of the new technology on the optimal adoption dates are similar to the effects under two-part tariff contracts ($\frac{\partial T_i^W}{\partial \beta} > 0$ and $\frac{\partial T_i^W}{\partial \delta} < 0$). The former result clearly reveals that the *profits sharing effect* is also present in the case of wholesale price contracts. However, according to the following proposition, the optimal adoption dates crucially differ among the two contract types.

Proposition 3 *(i) First adoption occurs earlier under two-part tariff contracts than under wholesale price contracts if and only if the upstream bargaining power is sufficiently low, that is,* $\beta < \beta_3(\delta)$*, where* $\partial\beta_3(\delta)/\partial\delta > 0$*.*

(ii) Second adoption occurs earlier under two-part tariff contracts than under wholesale price contracts if and only if the new technology is not too effective and the upstream bargaining power is sufficiently low, that is, $\delta < \frac{4}{27}$ *and* $\beta < \beta_4(\delta)$*, where* $\partial\beta_4(\delta)/\partial\delta < 0$*.*

Technology adoption can take place earlier under two-part tariff contracts than under wholesale price contracts. This holds for first adoption as long as the downstream firms are powerful enough (areas A and B in Figure 3). It also holds for second adoption, but only if the downstream firms are powerful enough and the new technology is not too effective (area A in Figure 3). The intuition for this finding draws again on the interaction of the *terms of trade effect* and the *profits sharing effect*. We know that the *terms of trade effect* is positive under two-part tariffs and negative under wholesale price contracts. An immediate implication is that the output effect is weaker under wholesale price contracts and thus favors later adoption under this contract type. By contrast, the *profits sharing effect* favors faster adoption under wholesale price contracts. This holds because under wholesale price contracts, owing to the lack of the fixed fees, each D_i obtains a greater share of the joint profits than the share corresponding to its bargaining power. As a result, when D_i adopts the technology, it obtains a greater share of the resulting higher profits than it would obtain under two-part tariffs, and thus it has stronger incentives to adopt the technology. The more powerful the upstream firms are, the more the *profits sharing effect* works in favor of wholesale prices and thus leads to earlier adoption under such contracts. In fact, when the technology is effective enough, second adoption always occurs earlier under wholesale price than under two-part tariff contracts. This is because as δ increases, in contrast to what happens under wholesale price contracts, the *terms of trade effect* under two-part tariff contracts becomes more unfavorable for the technology laggard.

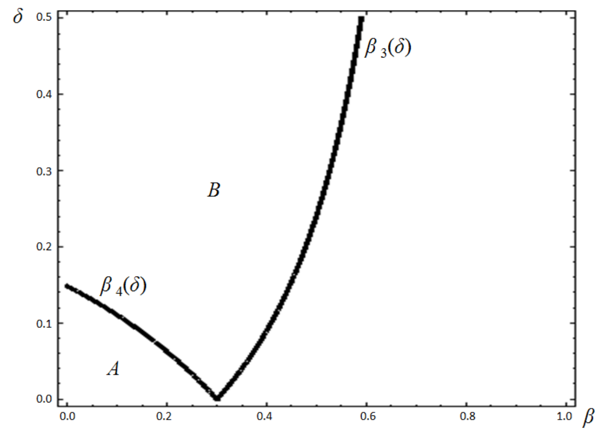

Figure 3: Comparison of the adoption dates with two-part tariffs and wholesale price contracts

The contract type also crucially affects the impact of vertical relations on adoption timing. In particular, under wholesale price contracts, in contrast to what happens under two-part tariffs, the optimal adoption dates are always later under outsourcing than under insourcing. This holds because, owing to the presence of double marginalization and the negative *terms of trade effect*, the output is lower and thus the *output effect* is weaker in a vertically related market in comparison to a one-tier market.

6 Extensions

Next, we extend our model in various dimensions to examine the robustness of our main results and explore the role of some of our assumptions.

6.1 Preemption Game

In the preemption game, each D_i observes its rival's actions with no information lags and can respond immediately and costlessly to its adoption decision. This is a closed-loop scenario regarding the adoption dates of the firms.[16] It is well known (Fudenberg and Tirole,

[16] In a closed-loop scenario, downstream firms may also use history-dependent output strategies. In a continuous-time set-up with no information lags, like ours, downstream firms can reach a collusive outcome

1985) that in the preemption game, in contrast to the precommitment game in which the first adopter obtains higher discounted profits, symmetric firms receive the same discounted profits in equilibrium. If this were not so, the second adopter, who makes lower profits than the first adopter, would have incentives to preempt the latter, that is, to adopt the new technology slightly earlier than the first adoption date. As a consequence, technology diffusion also occurs in the preemption equilibrium.

In particular, the adoption strategy of D_2 is as follows. Given any adoption date for D_1, D_2 adopts the technology at $\tau_2^T = \arg\max_{\tau_2} \Pi_{D_2}(\tau_1, \tau_2)$, where $\Pi_{D_2}(\tau_1, \tau_2)$ is given by (7) after replacing T_i with τ_i if $\Pi_{D_2}(\tau_1, \tau_2^T) \geq \Pi_{D_1}(\tau_1, \tau_2^T)$; otherwise, $\tau_2^T(\tau_1) = \tau_1 - \varepsilon$, where $\varepsilon > 0$ but is arbitrarily small. Note that in the former case, τ_2^T does not depend on τ_1 because D_2 decides on its adoption date as a single player in the continuation of the game. Faced with preemption by D_2, D_1 adopts the technology as late as possible, and in particular at τ_1^T such that $\Pi_{D_1}(\tau_1^T, \tau_2^T) = \Pi_{D_2}(\tau_1^T, \tau_2^T)$. Note that the first-order condition for the maximization problem faced by D_2 is the same as in the precommitment game; hence, $\tau_2^T = T_2^T$. Moreover, as the firms' discounted profits are the same in equilibrium, we obtain from (6) that

$$\pi_{D_l}^T - \pi_{D_f}^T = \frac{r[k(\tau_1^T) - k(T_2^T)]}{e^{-r\tau_1^T} - e^{-rT_2^T}}. \tag{13}$$

Hence, the optimal adoption date for the first adopter depends on the difference in per-period equilibrium profits between the technology leader and the technology laggard. As in Katz and Shapiro (1987), we refer to the latter as the first adopter's preemption incentives. In a vertically related market, preemption incentives are given by $L^T = \pi_{D_l}^T - \pi_{D_f}^T = \frac{2}{5}A^2(1-\beta)\delta(2+\delta)$. It is clear that the preemption incentives are increasing in δ and decreasing in β. Moreover, from the comparison of preemption incentives in a vertically related market and a one-tier market (see Appendix A) we can conclude that the former are higher than the latter if and only if $\beta < \frac{1}{6}$. In other words, the preemption incentives are stronger in the presence than in the absence of vertical relations as long as β is sufficiently low. This is because when downstream

as long as $r > 0$. Note, however, that the collusive outcome under constant but *unequal* marginal costs for the firms crucially depends on the specific subtleties of the tacit agreement. Equal relative gains, the Kalai–Smorodinsky solution, and the Nash bargaining solution lead to very distinct tacit collusive outcomes (see e.g., Schmalensee, 1987). These outcomes then have a crucial impact on upstream–downstream bargaining over the two-part tariff terms, and thus on the incremental benefits and preemption incentives for technology adoption. As a consequence, comparison of the adoption dates under input outsourcing and insourcing crucially depends on the collusive outcome assumed each time.

firms are relatively powerful in the market, they extract a higher share of the per-period joint profits of the vertical chain. It is also because the difference between the technology leader and laggard profits is higher in a vertically related than in a one-tier market since the former is more heavily subsidized than the latter.

The optimal adoption dates in a vertically related market and a one-tier market cannot be compared analytically. Letting $k(t) = e^{-(\alpha+r)}$ with $\alpha = 20$ and $r = 0.1$, our numerical simulations qualitatively confirm the results of Proposition 2: in the preemption game, first adoption takes place earlier under outsourcing than under insourcing, that is, $\tau_1^T < \tau_1^I$, if and only if the downstream bargaining power is sufficiently high. As we already know, the same holds for second adoption, that is, $\tau_2^T < \tau_2^I$, if and only if the downstream bargaining power is sufficiently high and the new technology is not too effective. For example, we find that when $\delta = 0.1$, $\tau_1^T < \tau_1^I$ if $\beta < 0.3$ and $\tau_2^T < \tau_2^I$ (i.e., $T_2^T < T_2^I$) if $\beta < 0.03$. For higher values of δ, such as $\delta = 0.3$, $\tau_2^T < \tau_2^I$ never holds. More importantly, we find that in the preemption game, the range of β values for which first adoption occurs earlier under outsourcing than under insourcing is *greater* in comparison to the precommitment game; for example, if $\delta = 0.1$, $\tau_1^T < \tau_1^I$ for all $\beta < 0.3$, while $T_1^T < T_1^I$ for a smaller range of β ($\beta < 0.2$).[17]

6.2 Product Differentiation

We assumed so far that the downstream firms produce a homogenous good. We consider now the case in which their products are differentiated, so the demand function faced by each D_i is $p_i(q_i, q_j) = a - q_i - \gamma q_j$, where γ ($0 \leq \gamma < 1$) is the degree of product substitutability. The lower γ, the more differentiated the products are. We confirm our main result regarding the difference in speed of adoption between vertically related and one-tier markets if and only if product differentiation is not too high. Intuitively, the closer substitutes the products are, the greater is the subsidization and the stronger is the positive terms of trade effect and thus the stronger is the output effect in a vertically related market. It follows that when product differentiation is too high, the output effect is relatively weak in a vertically related market and is offset by the profits sharing effect. Then both first and second adoption occur earlier in a one-tier market than in a vertically related market.

[17] For further details see Alipranti et al. (2015).

6.3 Price Competition

In our main model, we assumed that downstream firms compete in quantities. Examining what happens if they compete in prices and produce differentiated goods, we find, in line with our main results, that adoption can occur earlier under outsourcing than under insourcing.[18] This holds under similar conditions to those for our main model as long as product differentiation is not too high. However, the positive impact of vertical relations is not driven by the *output effect* now. In fact, strategic complementarity under price competition makes the output effect weaker under outsourcing than under insourcing. This is because the wholesale prices exceed the upstream marginal cost and the *terms of trade effect* is negative. The positive impact of vertical relations is instead driven by the presence of a novel effect under outsourcing, the *slotting allowances effect*. This refers to the fact that when downstream firms compete in prices and are powerful enough, the fixed fees turn out to be negative - they take the form of "slotting allowances". The slotting allowances increase when D_i adopts the new technology.

6.4 Input-Saving Technology

We performed our analysis so far under the assumption that the new technology reduces the exogenous cost of the adopter. What happens when, instead, the new technology saves on the input quantity used? To answer this, we introduce a per unit of input cost, z, where $0 < z < a - c$, and assume that if D_i adopts the new technology, then the input quantity required for production of one unit of final good decreases from 1 unit to $\frac{1}{1+s}$, where $s > 0$. In this setting, $e \equiv \frac{s}{1+s}\frac{z}{(a-c-z)}$, with $e < \frac{1}{2}$, captures how effective the new technology is. We confirm that all our main results also hold for an input-saving technology.

7 Concluding Remarks

We analyzed the timing of technology adoption in markets with input outsourcing, and thus in vertically related markets. The main contribution of our analysis is the demonstration that the organizational structure for production, input outsourcing or in-house input production, can crucially affect the timing of technology adoption. More specifically, we showed that firms can adopt a new technology earlier when they outsource their input production than when they

[18] Alipranti and Petrakis (2013) provide an analysis of this case.

produce the input in-house. In other words, we concluded that vertical relations and trading may speed up technology adoption. This holds when vertical trading is conducted via two-part tariff contracts and the upstream bargaining power is sufficiently low.

An additional contribution of our analysis is that we pointed out that it is important to take into account the particular features of vertically related markets to understand the diverse patterns of technology adoption timing. In particular, we showed that the bargaining power distribution and the contract type used in a vertically related market can crucially affect the speed of technology adoption. The higher the downstream bargaining power in a market, the earlier a new technology is adopted. Moreover, the use of two-part tariff contracts can lead to earlier adoption than the use of wholesale price contracts as long as the downstream firms are sufficiently powerful.

We demonstrated that our main results are valid under various extensions of our basic framework (closed-loop preemption game, product differentiation, price competition, and input-saving new technology). Nevertheless, we recognize that our paper is only the first step towards understanding the relationship between vertical relations and the timing of technology adoption. Subsequent steps could explore the timing of upstream technology adoption or how different structures for upstream and/or downstream markets influence the speed of adoption. More specifically, one could explore what would happen under non-exclusive relations in a market with an upstream monopoly or in a market with (imperfect) upstream competition could be investigated.[19] We should note, however, that serious complications would arise in the latter case, that is, in a situation in which rival upstream firms deal with the same competing downstream firms and trade through non-linear contracts.[20] These extensions are left for future research.

Appendix A: One-tier industry

Here we briefly present the analysis of adoption timing in a one-tier industry. Solving each

[19] The analysis for the upstream monopoly case can be found in Alipranti and Petrakis (2013). As demonstrated there, outsourcing under certain circumstances can also lead to faster technology adoption when downstream firms obtain the input from the same upstream monopolist.

[20] This is formally recognized by two reviews of the literature on vertically related markets. In particular, Miklos-Thal et al. (2010, p. 345) state that "The formal modeling of such "interlocking" vertical relations has proved difficult ... and we still know relatively little about many basic questions ... Interlocking relationships cause modeling issues such as either the inexistence or a large multiplicity of equilibria even in simple competition games." Similarly, Inderst (2010, p. 343) states "... the benchmark model where competing upstream firms simultaneously make take-it-or-leave-it offers to competing downstream firms, may fail to have an equilibrium in pure strategies".

firm's maximization problem in the last stage after setting $w_i = 0$, we obtain the equilibrium quantities and (gross) profits

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

Precommitment game: Turning to the firms' optimal adoption dates at $t = 0$, firms 1 and 2 choose T_1 and T_2, respectively, such as each 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 (6) and (7), and taking the first order conditions, we obtain

$$I_1^I = \frac{4}{9}A^2\delta(1 + \delta) = -k'(T_1^I)e^{rT_1^I} \text{ and } I_2^I = \frac{4}{9}A^2\delta = -k'(T_2^I)e^{rT_2^I}.$$

Here too $I_1^I > I_2^I > 0$, and thus there is technology diffusion in equilibrium ($T_1^I < T_2^I$). Moreover, $\frac{\partial I_i^I}{\partial \delta} > 0$, and thus $\frac{\partial T_i^I}{\partial \delta} < 0$.

Preemption game: Here too, the second adopter's optimal date is the same as in the precommitment game: $\tau_2^I = T_2^I$. Moreover, profit equalization, that is, $\Pi_1^I(\tau_1^I, T_2^I) = \Pi_2^I(\tau_1^I, T_2^I)$, leads to the following condition that determines τ_1^I

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

The preemption incentives in a one-tier industry are: $L^I = \pi_l^I - \pi_f^I = \frac{1}{3}A^2\delta(2 + \delta)$, where $\frac{\partial L^I}{\partial \delta} > 0$. Comparing the preemption incentives in a one-tier market with those in a vertically related market with two-part tariffs, we obtain: $L^T - L^I = \frac{1}{15}(1 - 6\beta)\delta(2 + \delta)$. It is clear that $L^T > L^I$ as long as $\beta < \frac{1}{6}$.

Appendix B

Proof of Proposition 1: First, from (8), we have that $\frac{\partial I_i^T}{\partial \delta} > 0$; 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. Second, by inspection of (8), we see that $\frac{\partial I_i^T}{\partial \beta} < 0$; hence $\frac{\partial T_i^T}{\partial \beta} > 0$. Finally, the properties of the timing span of adoption dates, $T_2^T - T_1^T$, are similar to those of $I_1^T - I_2^T$. By (8), we have

$$I_1^T - I_2^T = \frac{24}{25}A^2(1 - \beta)\delta^2 > 0. \tag{14}$$

As $\frac{\partial(I_1^T - I_2^T)}{\partial \delta} > 0$ and $\frac{\partial(I_1^T - I_2^T)}{\partial \beta} < 0$, we have $\frac{\partial(T_2^T - T_1^T)}{\partial \delta} > 0$ and $\frac{\partial(T_2^T - T_1^T)}{\partial \beta} < 0$. ■

Proof of Proposition 2: Taking the difference between each firm's incremental benefits in a vertically related market with two-part tariffs and in a one-tier market we obtain

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

(i) Setting $I_1^T - I_1^I = 0$ and solving for β we obtain $\beta_1(\delta) = \frac{4+31\delta}{27(2+3\delta)}$, where $\frac{\partial \beta_1}{\partial \delta} > 0$. 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 obtain $\beta_2(\delta) = \frac{4-27\delta}{27(2-\delta)}$, where $\frac{\partial \beta_2}{\partial \delta} < 0$. Note that $\beta_2(\delta) > 0$ only if $\delta < \frac{4}{27}$. 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 tariffs and with wholesale price contracts, we obtain

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

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 obtain $\delta_3(\beta) = \frac{2(4+\beta)[\beta(488-\beta(212-27\beta))-128]}{7936-\beta[12672-\beta(3480+\beta(112-81\beta))]}$. Note that $0 \leq \delta_3(\beta) \leq 0.5$ for $0.30 \leq \beta \leq 0.59$ 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) Setting $I_2^W - I_2^T = 0$ and solving for δ we obtain $\delta_4(\beta) = \frac{2(4+\beta)[\beta(488-\beta(212-27\beta))-128]}{3[\beta(3008-\beta(920-\beta(32+9\beta)))-2304]}$. 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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