Multiplant Firms and Innovation Diffusion

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Abstract

This paper provides a new explanation for why large firms tend to adopt sooner that also admits the possibility of exceptions in which small firms adopt sooner. The analysis focuses on the adoption of an innovation of uncertain profitability by a large firm with two plants and a small firm with one. Production costs are increasing at the margin in each plant, but economies of multiplant operations are possible. These have conflicting effects on the incentive to adopt. The large firm earns more from adoption of a success. However, when an adopter must shut down to learn about the innovation, the loss of multiplant cost economies reduces the large firm's incentive to adopt. If there are no multiplant economies, then the large firm is more likely to lead the diffusion because its greater return from adoption of a success dominates. However, if there are multiplant economies, and the large firm's resulting learning cost disadvantage dominates, then the small firm is more likely to lead the diffusion.

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1 Introduction

One of the empirical regularities associated with the adoption of new technology in oligopolies is that large firms tend to adopt sooner than small firms (e.g., see Davies (1979), Mansfield (1968, 1971), or Stoneman (1983, 1995)). The primary reason given for this, of course, is that large firms expect a greater return from adoption. However, large firms do not always adopt first, as can be seen from the diffusion of the basic oxygen furnace and continuous casting in the U.S. steel industry (Adams and Mueller (1982)). This paper provides a new explanation for why large firms tend to adopt sooner that also admits the possibility of exceptions in which small firms adopt sooner.

The analysis focuses on the adoption of an innovation of uncertain profitability when a firm's size is measured by the number of plants it operates. As is well-known, one reason for operating multiple plants is production costs that are increasing at the margin. Another reason is economies of multiplant operations. The empirical evidence on whether there are such economies is mixed (see, for example, Scherer, et al. (1975)). It often shows that there are none. Moreover, when such economies do exist, the consensus is that they involve savings in nonproduction costs, such as costs of transportation, distribution, and/or inventory. Multiplant operation may also involve economies of massed reserves (the cost savings associated with retaining proportionately fewer spare parts, backup machines, and repairpersons in reserve).

Interestingly, these two reasons for operating multiple plants can have conflicting effects on the incentive to adopt. A firm with more plants certainly earns more from (complete) adoption of a success. However, if there are adjustment costs associated with adoption, then nonproduction cost economies actually result in a smaller incentive to adopt for a large firm. Suppose there are two firms, a large firm with two plants and small firm with one plant. Also suppose that, when the innovation is first installed in a plant, the adopter must shut down that plant while it experiments with (tries to implement) the innovation in order to learn if it is a success or not. That is, the opportunity cost of initial adoption includes a "learning cost" in the form of profit foregone during the experimental implementation period. This learning cost can be greater for a large firm because the cost savings from multiplant operations are lost, or at least reduced, when it shuts down one of its plants to adopt. That is, the profit lost when that plant is shut down exceeds the "production profit" in either plant, and thus can exceed the profit lost by the small firm if it shuts down to adopt.

This learning cost provides an incentive to wait and learn about the innovation from the rival's adoption (see Adams and Mueller (1982) for examples of this phenomenon in the U.S. steel industry). The incentive to free ride on rival adoption implies the subgame perfect Nash equilibrium in pure strategies must be either no adoption or a diffusion. In fact, for some probabilities of success a diffusion is the unique subgame perfect Nash equilibrium. Joint adoption occurs only if both firms randomize in equilibrium, and in this case a diffusion led by the large firm or the small firm is also possible. If there are no economies of multiplant operations, then the large firm leads the diffusion because the greater return from adoption of a success dominates. However, if there are such economies, and the large firm's resulting learning cost disadvantage dominates, then the small firm leads the diffusion.

By now there is a fairly large theoretical literature on innovation adoption and diffusion.[1] These studies typically assume that firms are identical, and the exceptions do not focus on differences in the size of the firm.[2] One noteworthy exception is David (1969), who analyzes a capital-embodied new process with lower variable cost but higher fixed cost. He shows that a diffusion occurs if wages rise over time relative to capital costs (notice this is very similar to Fellner's (1951) argument that a diffusion occurs as the cost of maintaining a plant with the old technology rises over time). Large firms adopt sooner because their larger outputs mean larger labor savings. Most empirical studies simply conjecture large firms adopt first because they expect to earn more from adoption. For example, Davies (1979) assumes a firm adopts if the expected time to pay off the adoption cost is less than a critical pay-off period. Thus, large firms adopt sooner because their higher profits allow them to pay off the adoption cost sooner.

The next section introduces the two-stage model of adoption under uncertainty, and discusses the Nash equilibria in the period-two subgames. Section 3 derives initial subgame perfect adoption behavior and the conditions un-

[1] See Reinganum (1989), Rogers (1995), and Stoneman (1995) for surveys.

[2] In decision-theoretic studies, Jensen (1982) assumes firms differ in their prior beliefs, Bhattacharya, Chatterjee, and Samuelson (1986) assume they receive different information, and Jensen (1988) assumes they have different capacities to process information. In a game-theoretic model, Stenbacka and Tombak (1994) assume that there is an implementation period of uncertain length after adoption, and that the firms differ in their hazard rates for the date of successful implementation. Goetz (2000) extends their work to show that the firm with the higher hazard rate adopts sooner and earns more, in expectation. In both of these the firms are the same size.

der which each firm leads the diffusion. An algebraic example with linear demand and quadratic cost is also provided. Section 4 then concludes, and proofs are relegated to the Appendix.

2 A Model of Cost-Reducing Technology

Consider a two-period model of a duopoly faced with an exogenously developed innovation. The new technology can succeed or fail in that it may or may not reduce marginal cost at all output levels. When it appears, each firm's common knowledge estimate of the probability of success is $p \in [0, 1]$. The large firm L has two plants and the small firm S has one plant. The innovation is adopted by converting a plant to the new technology. That is, the innovation must be a new machine, technique, or process that can be grafted onto existing plants. Conversion at any date is instantaneous and costless, but the first adoption by either firm does not immediately reveal if the innovation succeeds or fails. That is, after initial adoption, the adopter must spend one period trying to implement the new technology to learn if it succeeds or not. That is, although conversion is costless, initial adoption is not because it entails a learning cost, the loss of profit from shutting a plant down to experiment with the innovation and learn whether it succeeds. The true nature of the innovation is revealed to all at the end of the learning period. If it succeeds, production with it can begin immediately. If it fails, production can occur only if that plant is reconverted to the old technology.

Assumption 1. Converting a plant to the new technology, or back to the old technology, is instantaneous and costless. After initial adoption, one period is required in order to determine whether the innovation is a success or failure. No production can occur in the plant during this period. At the end of this period the success or failure of the innovation becomes common knowledge.

This assumption is made to focus the analysis sharply on the effects of shutting down to adopt and learn about the innovation. One can also view this as an extreme version of adjustment costs in investment. That is, this assumption could be replaced with the following one. Conversion requires a lump-sum cost and adoption at any date takes time, during which the plant is shut down, or output is substantially reduced, but the initial adoption takes longer than subsequent ones (e.g., due to learning-by-doing in adoption).

Now consider the natural assumptions on the firms' flow profits. Each firm's profit at any date depends on how it and its rival use their plants. Each plant can be operated with the new technology, if it succeeds (denoted by n), operated with the old technology (denoted by o), or shut down (denoted by d). Let L's two plants be denoted by (a_1, a_2) and S's plant be denoted by a_3, where $a_j \in \{n, o, d\}$ for $j = 1, 2, 3$. Then the industry profile of plants $(a_1, a_2; a_3)$ determines flow profits, which are written as $\Pi_L(a_1, a_2; a_3)$ for L and $\Pi_S(a_1, a_2; a_3)$ for S.

First assume that pre-innovation profit is positive, old plants can be always operated at a profit (i.e., a success is not drastic), and profit from a plant shut down is zero.

Assumption 2. Plants with the old technology earn positive profit if operated, but zero profit if shut down.

(a) $\Pi_L(o, o; a_3) > \Pi_L(o, d; a_3) > \Pi_L(d, d; a_3) = 0$ for any a_3.

(b) $\Pi_S(a_1, a_2; o) > 0$ $\Pi_S(a_1, a_2; d) = 0$ for any (a_1, a_2).

Next, assume plants with the same technology are identical. This has two implications. Given a_3, the plant profiles (a_1, a_2) and (a_2, a_1) must give L and S the same profit. Similarly, if each firm operates one plant with the same technology, then each should earn the same profit.

Assumption 3. Plants with the same technology are identical.

(a) $\Pi_i(a_1, a_2; a_3) = \Pi_i(a_2, a_1; a_3)$ for all $(a_1, a_2; a_3)$ and $i = S, L$.

(b) $\Pi_L(a_1, d; a_3) = \Pi_S(a_1, d; a_3)$ for $a_1 = a_3 = n$ or $a_1 = a_3 = o$.

Finally, assume adoption of a successful new technology has the usual effects of increasing the adopter's profit but decreasing a nonadopter's profit.

Assumption 4. If the innovation succeeds, adoption in one plant increases the adopter's profit and decreases its rival's profit. Adoption in all plants increases profit for both firms, but the increase is greater for the large firm.

(a) $\Pi_L(n, a_2; a_3) > \Pi_L(o, a_2; a_3)$ for all a_2 and a_3.

(b) $\Pi_S(a_1, a_2; n) > \Pi_S(a_1, a_2; o)$ for all (a_1, a_2).

(c) $\Pi_L(a_1, a_2; n) < \Pi_L(a_1, a_2; o)$ for all (a_1, a_2).

(d) $\Pi_S(n, n; a_3) < \Pi_S(n, o; a_3) < \Pi_S(o, o; a_3)$ for all a_3.

(e) $\Pi_i(n, n; n) > \Pi_i(o, o; o)$ for $i = S, L$.

(f) $\Pi_L(n, n; n) - \Pi_L(o, o; o) > \Pi_S(n, n; n) - \Pi_S(o, o; o)$.

Three remarks are in order. First, notice that *Assumptions* 2(a), 3, and 4(a) imply that, under the same technology, the large firm earns greater flow profit than the small one. *Assumption* 4(f) says that the large firm's gain from adoption of a success in both of its plants exceeds the small firm's gain in its one plant. Nothing else is assumed about how firm size affects flow profits at this time (this issue is deferred until Section 3). Second, these profits should be viewed as the Nash equilibrium profits of a static market game in which firms maximize profit by choosing outputs if they produce a homogeneous product, or by choosing either outputs or prices if they produce differentiated products. That is, assuming the firms earn positive profits is not very restrictive because it rules out only Bertrand competition with a homogeneous product. Third, *Assumptions* $2-4$ can be derived from any of several algebraic examples of such duopolies. An example with linear demand and quadratic cost is presented in Section 3.

To find the subgame perfect Nash equilibria, the analysis begins with determination of Nash equilibrium behavior in each of the subgames that can arise in period two. First note that, if neither firm adopts initially, then neither firm adopts in period two either. If a firm did adopt in period two, the required learning period under *Assumption* 1 implies a firm cannot benefit from a success until the next period, so no firm adopts in the "last" period.[3] In this case period two profits are $\Pi_L(o,o;o)$ and $\Pi_S(o,o;o)$.

Suppose instead that the innovation is adopted initially in at least one plant, so its success or failure becomes common knowledge at the end of period one. Then Assumptions 1 and 2 guarantee that, if the innovation is a failure, then both firms revert to the old technology for period two and again earn profits $\Pi_L(o,o;o)$ and $\Pi_S(o,o;o)$. If the innovation is a success, then *Assumption* 4 implies industry-wide adoption of the new technology because conversion of the remaining plants is costless, and so the firms earn profits $\Pi_L(n,n;n)$ and $\Pi_S(n,n;n)$ in period two.

3 Initial Equilibrium Behavior

Given the Nash equilibrium subgame payoffs when the true state is revealed, the payoffs to the entire game can now be written in reduced form as functions of only the firms' actions in period one. Let firm i's action (pure strategy) be σ_i, the number of plants in which it adopts, so $\Sigma_L = \{0,1,2\}$ and $\Sigma_S = \{0,1\}$ are the strategy sets. Let $P_L(\sigma_L,\sigma_S)$ and $P_S(\sigma_L,\sigma_S)$ be the expected payoffs to L and S from period one actions (σ_L,σ_S), given equilibrium

[3] This is true for any game with a finite number of stages. However, it is worth noting that this result also holds in an infinite horizon model with learning period of length $T>0$. In such a model, if no firm adopts initially, then absent some *duex ex machina* (to tell the firms the truth, or change their profits or conversion cost), nothing changes to induce a firm to adopt in the future.

behavior in the period two subgames. A subgame perfect Nash equilibrium (SPNE) in pure strategies for this dynamic adoption game is then a period-one strategy pair (σ_L^*, σ_S^*), and corresponding equilibrium behavior in the period-two subgames, such that $P_L(\sigma_L^*, \sigma_S^*) \geq P_L(\sigma_L, \sigma_S^*)$ for all $\sigma_L \in \Sigma_L$ and $P_S(\sigma_L^*, \sigma_S^*) \geq P_S(\sigma_L^*, \sigma_S)$ for all $\sigma_S \in \Sigma_S$.

These payoffs are the discounted profits from both stages, expected in period one, when the common estimate of the probability of success is $p \in [0, 1]$. If the common discount factor is $\beta > 0$, then

$$P_L(2, \sigma_S) = \beta[p\Pi_L(n, n; n) + (1 - p)\Pi_L(o, o; o)] \text{ for all } \sigma_S, \tag{1}$$

$$P_L(1, 1) = \Pi_L(o, d; d) + \beta[p\Pi_L(n, n; n) + (1 - p)\Pi_L(o, o; o)], \tag{2}$$

$$P_L(1, 0) = \Pi_L(o, d; o) + \beta[p\Pi_L(n, n; n) + (1 - p)\Pi_L(o, o; o)], \tag{3}$$

$$P_L(0, 1) = \Pi_L(o, o; d) + \beta[p\Pi_L(n, n; n) + (1 - p)\Pi_L(o, o; o)], \tag{4}$$

$$P_S(\sigma_L, 1) = \beta[p\Pi_S(n, n; n) + (1 - p)\Pi_S(o, o; o)] \text{ for all } \sigma_L, \tag{5}$$

$$P_S(1, 0) = \Pi_S(o, d; o) + \beta[p\Pi_S(n, n; n) + (1 - p)\Pi_S(o, o; o)], \tag{6}$$

$$P_S(2, 0) = \Pi_S(d, d; o) + \beta[p\Pi_S(n, n; n) + (1 - p)\Pi_L(o, o; o)], \tag{7}$$

and

$$P_i(0, 0) = \Pi_i(o, o; o) + \beta\Pi_i(o, o; o)] \text{ for } i = S, L. \tag{8}$$

The learning cost implies that the SPNE cannot have initial adoption either by L in both plants or by both L and S in one plant. That is, L never adopts in both plants because it learns as much from adoption in one plant, and it earns positive profit from operating its second plant with the old technology, $P_L(1, \sigma_S) > P_L(2, \sigma_S)$ for all σ_S by *Assumption* (2*a*). Moreover, because L can learn from S's adoption, L never adopts if S does, $P_L(0, 1) > P_L(1, 1) > P_L(2, 1)$ again by *Assumption* (2*a*). Analogously, S never adopts if L does because $P_S(1, 0) > P_S(1, 1)$ by *Assumption* (2*b*).

Thus, there are only three possible period-one outcomes (in pure strategies) in the SPNE: no adoption, $(\sigma_L^*, \sigma_S^*) = (0, 0)$; L adopts initially in one plant but S does not, $(\sigma_L^*, \sigma_S^*) = (1, 0)$; or S adopts initially but L does not, $(\sigma_L^*, \sigma_S^*) = (0, 1)$. Essentially, the issue is which firm, if any, adopts first. Hence, it is essential to compare each firm's incentive to adopt first, $F_L(p) = P_L(1, 0) - P_L(0, 0)$ and $F_S(p) = P_S(0, 1) - P_S(0, 0)$ where

$$F_L(p) = \beta p[\Pi_L(n, n; n) - \Pi_L(o, o; o)] - [\Pi_L(o, o; o) - \Pi_L(o, d; o)] \tag{9}$$

and

$$F_S(p) = \beta p[\Pi_S(n,n;n) - \Pi_S(o,o;o)] - \Pi_S(o,o;o). \tag{10}$$

In each of these, the first term is the discounted expected gain from a success. The second (bracketed) term is the learning cost of initial adoption. Each firm has an incentive to adopt initially only if the expected gain exceeds this certain learning cost.

Naturally, neither firm adopts initially if the innovation is a certain failure ($p = 0$) because the learning cost is paid, and there is no expected gain, $F_L(0) = -[\Pi_L(o,o;o) - \Pi_L(o,d;o)] < 0$ and $F_S(0) = -\Pi_S(o,o;o) < 0$. However, even if the innovation is a certain success ($p = 1$), L adopts initially only if

$$\beta[\Pi_L(n,n;n) - \Pi_L(o,o;o) > \Pi_L(o,o;o) - \Pi_L(o,d;o) \tag{11}$$

and S adopts initially only if

$$\beta[\Pi_S(n,n;n) - \Pi_S(o,o;o)] > \Pi_S(o,o;o). \tag{12}$$

These conditions reemphasize the critical role of the length of the learning period. That is, although this model has two periods, these periods do not need be of equal length. One can interpret higher values of β as corresponding to innovations for which the learning period is short compared to the useful life of a success. Under this interpretation, the only restriction on β is that it is positive, because it can exceed 1 if the learning period is short enough.[4] Indeed, it is possible that $\beta > 1$ is necessary for (11) and/or (12) to hold, and thus for adoption to occur for any p.

Theorem 1 *Under Assumptions 1-4, the only possible outcomes in period one of the SPNE are as follows:*

(i) If (11) *holds and* (12) *does not, there exists unique* $p_L \in (0,1)$ *such that no firm adopts if* $p \leq p_L$ *and* L *adopts in one plant if* $p \geq p_L$*.*

(ii) If (12) *holds and* (11) *does not, there exists unique* $p_S \in (0,1)$ *such that no firm adopts if* $p \leq p_S$ *and* S *adopts if* $p \geq p_S$*.*

[4] For example, consider a continuous-time model in which the length of the learning period is $T > 0$, and the innovation can be used forever after. If the interest rate is r, then the learning period payoffs are discounted by $\frac{1-e^{-rT}}{r}$ and the remaining payoffs by $\frac{e^{-rT}}{r}$. An increase in T then increases the weight $\frac{1-e^{-rT}}{r}$ on the learning period payoffs and decreases that on the remaining payoffs. Moreover, the payoffs in $(1)-(8)$ can be obtained by dividing these continuous-time payoffs by $1 - e^{-rT}$ and setting $\beta = \frac{e^{-rT}}{1-e^{-rT}}$. This "modified" discount factor is decreasing in T, and greater than 1 for all $T < \frac{\log 2}{r}$.

(iii) If (11) *and* (12) *both hold, then no firm adopts if* $p \leq \min\{p_L, p_S\}$*, L adopts in one plant if* $p \geq p_L$*, S adopts if* $p \geq p_S$*, and L adopts with probability* $\mu_L(p)$ *and firm S adopts with probability* $\mu_S(p)$ *if* $p \geq \max\{p_L, p_S\}$*, where* $\mu_L(p) \in (0,1)$ *for* $p \in (p_S, 1)$ *and* $\mu_S(p) \in (0,1)$ *for* $p \in (p_L, 1)$.

For low probabilities of success, $p < \min\{p_L, p_S\}$, the unique SPNE is neither firm adopts initially, and the innovation is never adopted. For intermediate probabilities, the unique SPNE is one firm adopts initially: L if $p_L < p_S$ and $p \in (p_L, p_S)$, and S if $p_S < p_L$ and $p \in (p_S, p_L)$. But for high probabilities, $p > max\{p_L, p_S\}$, there are multiple SPNE: either firm adopts initially, or both randomize and adopt with positive probability. That is, the pure strategy SPNE involves no adoption or a diffusion.

It is worthwhile to note that, for a success, a diffusion is the unique SPNE outcome for intermediate probabilities of success. If $p_S < p_L$ and $p \in (p_S, p_L)$, then S adopts in period one, and L follows by adopting in both plants in period two. This is an intraindustry diffusion led by S. But if $p_L < p_S$ and $p \in (p_L, p_S)$, then L adopts in one plant in period one, and it adopts in its second plant and S follows in period two. This is an intrafirm diffusion within L as well as an intraindustry diffusion led by L. Of course, these outcomes can also occur for high probabilities, but not uniquely (in the mixed strategy equilibrium, initial adoption by neither firm or both firms can occur with positive probability). Nevertheless, a diffusion occurs as the unique SPNE for some p unless $p_L = p_S$, an unlikely "razor's-edge" case in this model.

Given these results, it is natural to say that L is "more likely" to lead a diffusion when $p_L < p_S$, and S is more likely to lead when $p_S < p_L$. Whether L is more likely to lead depends on the relative magnitudes of the learning costs. To see this, note that

$$p_L = \frac{\Pi_L(o, o; o) - \Pi_L(o, d; o)}{\beta[\Pi_L(n, n; n) - \Pi_L(o, o; o)]} \tag{13}$$

and

$$p_S = \frac{\Pi_S(o, o; o)}{\beta[\Pi_S(n, n; n) - \Pi_S(o, o; o)]}. \tag{14}$$

In each of these, the numerator is the firm's learning cost, while the denominator is the firm's discounted gain from industry-wide adoption of a success in period two. Because L's gain from adoption is larger by *Assumption* $4(f)$, it is more likely to lead unless its learning cost is also larger.

The crucial issue now is the effect of L's larger size on the relative magnitudes of the learning costs. Note well, however, that if there are no economies of multiplant operation, then L's learning cost is smaller,

$$\Pi_L(o, o; o) - \Pi_L(o, d; o) < \Pi_S(o, o; o), \tag{15}$$

and it is more likely to lead because (15) implies $p_L < p_S$. To see this, consider the market outcome when each firm has one (identical) plant, so they produce the same amount and earn the same duopoly profit. If one firm opens another identical plant, then in the new equilibrium it does not simply double its previous output and act as a triopolist. Although its total output surely increases, its output per plant falls, and is less than the other firms's output. Similarly, its total profit increases, but profit per plant falls and is less than the other firm's profit. This property also holds in several specific algebraic models that I have examined, including the one presented below.

As noted in the introduction, the empirical evidence on economies of multiplant operation is mixed, and tends to support such economies primarily when they involve nonproduction cost savings. If there are such cost economies, then they are lost, or at least reduced, when L shuts down one of its plants to adopt initially. These lost cost economies increase L's learning cost above production profit in the plant shut down. However, if there are no such cost economies, or they are not substantial, then L's learning cost is still smaller and it is more likely to lead.

Theorem 2 *Under Assumptions* $1-4$*, the large firm is more likely to lead if there are no economies of multiplant operation, or if they exist but are small.*

Conversely, if economies of multiplant operation are substantial, then L's learning cost is greater and it becomes possible that S is more likely to lead.

Theorem 3 *Under Assumptions* $1-4$*, the small firm is more likely to lead only if there are substantial economies of multiplant operation.*

It is worthwhile to note that a greater learning cost for L is not sufficient to guarantee that S is more likely to lead. It is necessary that L not only has a greater learning cost, but also has a learning cost disadvantage that outweighs its gain from industry-wide conversion of a success. That is, $p_S < p_L$ only if $\Pi_L(o,o;o) - \Pi_L(o,d;o) > \left[\frac{\Pi_L(n,n;n)-\Pi_L(o,o;o)}{\Pi_S(n,n;n)-\Pi_S(o,o;o)}\right] \Pi_S(o,o;o) > \Pi_S(o,o;o)$.[5]

Example. Suppose the firms produce a homogeneous good with inverse demand $P = A - (q_1 + q_2 + q_3)$ where P is price, q_i is L's output in its plant i ($i = 1{,}2$) q_3 is S's output, and $A > 0$ is a constant. L's cost function is $C_L = (k_1 q_1 + q_1^2) + (k_2 q_2 + q_2^2)$ and S's cost function is $C_S = k_3 q_3 + q_3^2$ where $k_i = k$ for the old technology and $k_i = k - \varepsilon$ for the new (successful) technology, and k and ε are constants such that $A > k > \varepsilon > 0$. Notice that this form of cost function for L assumes no economies of multiplant operation. Then $q_i(o,o;o) = \frac{3}{22}(A-k)$ for $i = 1{,}2$, $q_3(o,o;o) = \frac{2}{11}(A-k)$, $\Pi_L(o,o;o) = 6q_i(o,o;o)^2$, and $\Pi_S(o,o;o) = 2q_3(o,o;o)^2$. Similarly, $q_i(n,n;n) = \frac{3}{22}(A - k + \varepsilon)$ for $i = 1{,}2$, $q_3(n,n;n) = \frac{2}{11}(A - k + \varepsilon)$, $\Pi_L(n,n;n) = 6q_i(n,n;n)^2$, and $\Pi_S(n,n;n) = 2q_3(n,n;n)^2$. Finally, $q_1(o,d;o) = q_3(o,d;o) = \frac{1}{5}(A-k)$, $\Pi_L(o,d;o) = \Pi_S(o,d;o) = 2q_1(o,d;o)^2$. It then follows that $\Pi_L(n,n;n) - \Pi_L(o,o;o) = \frac{27}{242}[2(A-k)\varepsilon + \varepsilon^2] > \Pi_S(n,n;n) - \Pi_S(o,o;o) = \frac{16}{242}[2(A-k)\varepsilon + \varepsilon^2]$, $\Pi_L(o,o;o) - \Pi_L(o,d;o) = \frac{191}{6050}(A-k)^2 < \Pi_S(o,o;o) = \frac{400}{6050}(A-k)^2$, and $p_L = \left(\frac{191}{675}\right)\left[\frac{(A-k)^2}{2(A-k)\varepsilon+\varepsilon^2}\right] = \left(\frac{191}{675}\right) p_S < p_S$.

4 Conclusions

This paper shows diffusions must occur, at least for some probabilities of success, if firms are not identical in size, if a plant must be shut down to adopt initially and learn about the innovation, and if adoption reveals success or failure to all after the learning period. Economies of firm size (multiplant operation) do not necessarily imply the large firm is more likely to lead a diffusion. Such economies can imply that the learning cost (the profit lost from shutting down a plant) is greater for the large firm. Hence, the small firm can adopt first if such economies exist and are large enough. However, multiplant operation also implies that the large firm's profit increase from adoption is greater, so it leads if the learning cost is not significant. Thus, this paper shows diffusions are more likely than joint adoption when firms are not identical. It also provides an intuitively appealing reason for why large firms tend to adopt first, but need not always adopt first.

[5] It is interesting to note that this condition does not depend on the discount factor β. Hence, although the length of the learning period is critical in determining whether adoption occurs, as noted above, it does not affect which firm is more likely to lead.

The analysis is easily extended in several directions. First, the same results hold for drastic innovations when *Assumptions* 3 and 4 are changed to reflect the fact an old plant may be shut down if a new plant is operated. The results also hold if the assumption of a learning period is replaced by the assumption that conversion always takes time (during which a plant is shut down), but the initial conversion takes longer than subsequent ones. This extension is more cumbersome and complicated because differential times for conversion and adoption make the use of discrete time somewhat more arbitrary. There is also a loss of profit when a firm adopts after the new technology is revealed to be a success. The main difference, however, is that initial adoption now provides a future gain. If a firm adopts initially in a plant and the innovation succeeds, then that plant is operated in the conversion period after success is revealed (rather than shut down to be converted then). Thus, both may adopt initially unless the initial profit loss outweighs this future gain for both firms. Nevertheless, L's advantage in adoption of a success persists, so it is more likely to lead unless multiplant economies give it a large learning cost disadvantage.

5 References

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6 Appendix

6.1 Subgames When Success Revealed

If L adopted in one plant and S adopted, then L adopts in its other plant in period two if $\Pi_L(n, n; n) \geq \Pi_L(n, o; n)$. If S adopted but L did not, then L adopts in both plants in period two if $\Pi_L(n, n; n) \geq \max\{\Pi_L(n, o; n), \Pi_L(o, o; n)\}$. If L adopted in both plants but S did not adopt, then S adopts in period two if $\Pi_S(n, n; n) \geq \Pi_S(n, n; o)$. Finally, if L adopted in one plant but S did not, then they play a simultaneous-move game in which each can adopt or not. S adopts, whether L does or not, if $\Pi_S(n, o; n) \geq \Pi_S(n, o; o)$ and $\Pi_S(n, n; n) \geq \Pi_S(n, n; o)$ (i.e., adopt is a strongly dominant strategy for S). In this case, L's best reply is to adopt if $\Pi_L(n, n; n) \geq \Pi_L(n, o; n)$. All these inequalities follow from the conditions in *Assumption* 4.

6.2 Proof of Theorem 1

One can show from (1) − (3) that $P_L(1, 0) - P_L(2, 0) = \Pi_L(o, d; o) > 0$ and $P_L(1, 1) - P_L(2, 1) = \Pi_L(o, d; d) > 0$ for all $p \in [0, 1]$ by *Assumption* 3(a). This proves that neither $(\sigma_L^*, \sigma_S^*) = (2, 0)$ nor $(\sigma_L^*, \sigma_S^*) = (2, 1)$ can be a SPNE. It also proves that if a mixed strategy SPNE exists, then in it L must place zero probability on initial adoption in both plants.

Next, from (2) and (4)−(6), $P_L(0, 1)-P_L(1, 1) = \Pi_L(o, o; d)-\Pi_L(o, d; d) > 0$ and $P_S(1, 0) - P_S(1, 1) = \Pi_S(o, d; o) > 0$ for all $p \in [0, 1]$ by *Assumption* 3. Hence, $(\sigma_L^*, \sigma_S^*) = (1, 1)$ cannot be a SPNE for any $p \in [0, 1]$.

The only remaining pure strategy SPNE candidates are: neither firm adopts, $(\sigma_L^*, \sigma_S^*) = (0, 0)$; L adopts in one plant but S does not, $(\sigma_L^*, \sigma_S^*) = (1, 0)$; and S adopts but L does not, $(\sigma_L^*, \sigma_S^*) = (0, 1)$. Hence, $(\sigma_L^*, \sigma_S^*) = (1, 0)$ is a SPNE if $P_L(1, 0) \geq P_L(0, 0)$ and $P_S(1, 0) \geq P_S(1, 1)$, $(\sigma_L^*, \sigma_S^*) = (0, 1)$ is a SPNE if $P_L(0, 1) \geq P_L(1, 1)$ and $P_S(0, 1) \geq P_S(0, 0)$, and $(\sigma_L^*, \sigma_S^*) = (0, 0)$ is a SPNE if $P_L(0, 0) \geq P_L(1, 0)$ and $P_S(0, 0) \geq P_S(0, 1)$. But, as shown above, $P_L(0, 1) > P_L(1, 1)$ and $P_S(1, 0) > P_S(1, 1)$for all p. Therefore, if $F_L(p) = P_L(1, 0) - P_L(0, 0)$ and $F_S(p) = P_S(0, 1) - P_S(0, 0)$, then $(\sigma_L^*, \sigma_S^*) = (1, 0)$ is a SPNE if $F_L(p) \geq 0$, $(\sigma_L^*, \sigma_S^*) = (0, 1)$ is a SPNE if $F_S(p) \geq 0$, and $(\sigma_L^*, \sigma_S^*) = (0, 0)$ is a SPNE if $F_L(p) \leq 0$and $F_S(p) \leq 0$. Furthermore, $(\sigma_L^*, \sigma_S^*) = (1, 0)$ is the unique SPNE at some p if and only if $F_L(p) > 0 > F_S(p)$ at that p, and $(\sigma_L^*, \sigma_S^*) = (0, 1)$ is the unique SPNE for some p if and only if $F_S(p) > 0 > F_L(p)$ at that p.

As noted in the text, using (3), (5), and (8) − (10), one can show that *Assumption* 3 implies $F_L(0) < 0$ and $F_S(0) < 0$, while $F_L(1) > 0$ if and only if (11) holds, and $F_S(1) > 0$ if and only if (12) holds. Because $F_L(p)$ is linear, if (11) holds, then there exists a unique $p_L \in (0,1)$ defined by (13) such that $F_L(p_L) = 0$, $F_L(p) \gtrless 0$ if and only if $p \gtrless p_L$. Similarly, because $F_S(p)$ is linear, if (12) holds, then there exists a unique $p_S \in (0,1)$ defined by (14) such that $F_S(p_S) = 0$, $F_S(p) \gtrless 0$ if and only if $p \gtrless p_S$.

Finally, let $D(p) = P_L(0,1) - P_L(1,1)$ and $E(p) = P_S(1,0) - P_S(1,1)$. Then a mixed strategy equilibrium in which L adopts in one plant with probability μ_L and S adopts with probability μ_S exists if and only if $\mu_L = \frac{F_S(p)}{F_S(p)+E(p)} \in (0,1)$ and $\mu_S = \frac{F_L(p)}{F_L(p)+D(p)} \in (0,1)$. Because $D(p) > 0$ for all p and $E(p) > 0$ for all p, it follows that $\sigma_L \in (0,1)$ if and only if $p > p_S$ and $\sigma_S \in (0,1)$ if and only if $p > p_L$.

6.3 Proof of Theorems 2 and 3

From (13) and (14), $p_L - p_S$ has the sign of $[\Pi_L(o,o;o) - \Pi_L(o,d;o)][\Pi_S(n,n;n) - \Pi_S(o,o;o)] - \Pi_S(o,o;o)[\Pi_L(n,n;n) - \Pi_L(o,o;o)]$. And because $\Pi_L(n,n;n) - \Pi_L(o,o;o) > \Pi_S(n,n;n) - \Pi_S(o,o;o)$ by *Assumption* 4(f), it follows that $p_L < p_S$ if and only if $\Pi_L(o,o;o) - \Pi_L(o,d;o) < \left[\frac{\Pi_L(n,n;n) - \Pi_L(o,o;o)}{\Pi_S(n,n;n) - \Pi_S(o,o;o)}\right] \Pi_S(o,o;o)$. So, (15) is sufficient but not necessary for $p_L < p_S$. Similarly, $p_S < p_L$ if and only if $\Pi_L(o,o;o) - \Pi_L(o,d;o) > \left[\frac{\Pi_L(n,n;n) - \Pi_L(o,o;o)}{\Pi_S(n,n;n) - \Pi_S(o,o;o)}\right] \Pi_S(o,o;o) > \Pi_S(o,o;o)$, so the converse of (15) is necessary, but not sufficient, for $p_S < p_L$.