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Monopolistic competition and the diffusion of new technology

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This article analyzes the adoption and diffusion of new technology in a market for a differentiated product with monopolistic competition. I show that in a noncooperative equilibrium ex ante *identical firms adopt a new technology at different dates. This equilibrium can be described by a simple distribution function. For nonidentical firms, I state the conditions under which a positive relationship between firm size and speed of adoption exists. The model integrates rank and stock effects. I demonstrate that increased competition often promotes diffusion.*

1. Introduction

■ The productivity- and welfare-enhancing powers of a new product are realized only when the product is adopted by its potential users. With respect to technological change, the adoption of new technologies ranks in importance with firms' research and development activities (see OECD, 1997). Firms usually adopt new technologies sequentially rather than simultaneously, and in most cases the vast majority of eventual users adopt well after the introduction of a new product. Empirical studies have shown that observed patterns of adoption can often be described by S-shaped or sigmoid diffusion curves.[1]

This article is a contribution to the explanations of these regularities that take the adoption decision of an individual firm as the starting point.[2] This decision is explained explicitly out of the profit-maximizing behavior of the firm. Adoption costs are assumed to be falling over time. Diffusion, i.e., sequential rather than simultaneous adoption by individual firms, may result for two reasons.

(i) Rank effects: the potential users differ with respect to the (expected) returns from adoption. The reasons are differences in firm size, R&D expenditures, market

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[1] For an overview see Thirtle and Ruttan (1987).

[2] A different branch of studies on diffusion is based on the "epidemic" approach, where the rate of adoption at a certain date depends on the stock of users who have already adopted. This setting yields a differential equation and results in the above-described diffusion pattern. For further discussion of this approach as well as a survey of the equilibrium models and the empirical findings of the analysis of diffusion, see Karshenas and Stoneman (1995).

shares (see Karshenas and Stoneman, 1993, 1995), or even the prior beliefs about the profitability of a new technology (see Jensen, 1982).

(ii) Stock effects: in an industry with *a priori* identical firms, diffusion will occur if payoffs from adoption depend on the stock of firms already using a new technology. This was shown by Reinganum (1981a, 1981b). She assumed a pattern of profits that emerges, for instance, in a Cournot oligopoly.

The model of monopolistic competition presented in this article allows the integration of both effects and enables one to address Schumpeterian themes in the analysis of the adoption of a new technology. In particular, one can examine the influence of both firm size and the intensity of competition on the pace and pattern of diffusion.

Monopolistic competition is formalized here using a derivation of Dixit and Stiglitz (1977) and Spence (1976). The "large group" assumption (Chamberlin, 1965) underlying this market structure ensures virtually no strategic interaction among firms. Nevertheless, individual firms have monopoly power because they produce a special brand of a differentiated product. Because of these two features, models of monopolistic competition combine the simplicity of decision-theoretic models with the notion of competition and rivalry prevalent in strategic (or game-theoretic) models.[3]

The model presented here uses a setting similar to Reinganum (1981a, 1981b). The results of this article thus can be most easily evaluated by comparing them to the results of Reinganum's so-called game-theoretic approach. The equilibrium in my model can be described by a simple distribution function. Diffusion, rather than simultaneous adoption, is the outcome of the model. This holds true even for *ex ante* identical firms. My model shows that it is not the existence of strategic interactions that leads to diffusion but rather an impact of other firms' actions on the payoffs of an individual firm. It is the result of stock effects. For the case of "small" agents, this result confirms a principle stated by Quirmbach (1986): stock effects imply an asymmetry in payoffs of adoptions, which give rise to differing rather than uniform adoption dates in both market and planner solutions.

In the equilibrium of my model, the profits of firms adopting at different dates are equalized. Rent equalization is not a feature of Reinganum's models. In the Nash equilibria derived by Reinganum, "the early adopter does better than the later one," as Fudenberg and Tirole (1985, p. 384) show. Reinganum's result is due to the assumption that firms must precommit to an adoption date at the outset of the game. If firms (in a duopoly) can observe and respond immediately to their rival's actions, profits are equalized due either to preemptive adoption or to collusion with a "late" uniform adoption date (Fudenberg and Tirole, 1985). My model shows that neither preemptive adoption nor collusion occurs if the agents are "small." In a sense, the model derives Reinganum-type equilibria for the case of no precommitment.

In contrast to Fudenberg and Tirole's approach, in my model the number of firms can be varied without posing problems. This makes it is easy to address the question of market entry. Although I assume a fixed number of firms most of the time, in some examples I shall explore the effect of free entry. The model of monopolistic competition can also take into account heterogeneity among firms. Particularly, I consider differences in firm size. The model predicts a positive relation between firm size and the speed of adoption. This result presumes that adoption costs are independent of firm size.

Two further properties of the model are worth mentioning. The model makes it possible to derive hypotheses for empirical studies directly from the explicit equilibrium distribution rather than from first-order conditions alone. As I shall show, in the case

[3] For the classification, see Beath, Katsoulacos, and Ulph (1995).

of stock effects the former method predicts signs for coefficients that are the opposites of the ones predicted by the latter method. Furthermore, increased competition is shown to often promote diffusion and to lead invariably to an earlier start of the diffusion process. Note that more competition here means a lower degree of (exogenous) product differentiation and therefore more intense price competition.

The remainder of the article is organized as follows. Sections 2 and 3 describe the basic model and derive the noncooperative equilibrium. Section 4 is devoted to an integration of rank effects into the basic model and an examination of the implications that can be drawn from stock effects for empirical studies. In Sections 2, 3, and 4 the number of firms is assumed to be fixed. Section 5 examines the influence of changes in different parameters on the equilibrium distribution, and it considers the question of entry. Section 6 concludes.

2. The basic model

■ I consider the evolution of an industry in continuous time. In this industry, a continuum of firms produces different varieties of a differentiated product. For the moment I assume that there is no entry, but a fixed measure n of active firms. For simplicity I refer to this measure as the "number of firms."

The preference ordering of identical consumers is described by the intertemporal utility function

$$U = \int_0^\infty e^{-rt}(x_0(t) + \log C(t))\, dt, \tag{1}$$

where $x_0(t)$ is the consumption of the numeraire in time t and $C(t)$ is a consumption index of the Dixit-Stiglitz type with

$$C(t) = \left(\int_0^n y(j,\ t)^\alpha\, dj\right)^{1/\alpha} \quad \text{and} \quad 0 < \alpha < 1.$$

Here $y(j,\ t)$ is the amount of variety j of the differentiated product demanded by a consumer at time t. Because of the quasi-linear instantaneous utility function, the demand function for the differentiated goods does not change over time. Furthermore, demand is independent of the consumers' income, as long as total discounted income of each consumer is greater than $1/r$. I assume this to be the case. I denote the number of consumers by E. As each consumer's spending on the differentiated product is equal to one, E is equal to the total instantaneous expenditure on the differentiated product. With the above assumptions, one gets the instantaneous aggregate demand function $Y(j,\ t)$ for variety j at time t (see, for instance, Grossman and Helpman, 1991):

$$Y(j,\ t) = \frac{p(j,\ t)^{1/(\alpha-1)}}{\displaystyle\int_0^n p(z,\ t)^{\alpha/(\alpha-1)}\, dz} E, \tag{2}$$

where $p(j,\ t)$ is the price of variety j in time t.

The demand function (2) is isoelastic with the elasticity of demand $\sigma = 1/(1-\alpha)$. Actions of rivals that result in price changes enter the demand function through the integral in the denominator. In this article this term is referred to as the "price index," although it differs from the price index used by Dixit and Stiglitz (1977) and does not have all the properties of a conventional price index. As is well known (see Dixit and Stiglitz, 1977, and Grossman and Helpman, 1991), this demand function gives rise to a simple markup pricing rule for given marginal costs c. For the profit-maximizing price p one gets

$$p = c/\alpha. \tag{3}$$

Firms produce with constant marginal costs $\bar{c}$. In time $t = 0$ a new technology becomes available that, once adopted, allows production with lower marginal costs $\hat{c}$. The discounted costs X of purchasing the new technology and integrating it in the production process depend on the date T, at which production should take place at the lower marginal costs. The function $X(T)$ is assumed to be decreasing and convex in T so that $X'(T) < 0$ and $X''(T) > 0$. I also assume $X(0) = \infty$ and $X(\infty) = 0$. With this adoption-cost function, earlier adoption is more expensive, and eventually all firms adopt.

The adoption-cost function $X(T)$ allows for two different interpretations with respect to the underlying adoption process in the model presented here. First, the adoption process could be understood as a "time-consuming activity" that implies a certain adjustment path (see Reinganum, 1989). Second, adoption costs could consist only of the cost of purchasing the new capital-embodied technology. Firms are then able to choose instantaneous adoption at every moment of the game (see Fudenberg and Tirole, 1985). An ongoing decrease of the price of the respective capital good may be due to technical progress.

The operating profits π of a single firm can be determined as a function of its own and its rivals' behavior. Operating profits are defined as the difference between revenue and variable costs. Because of the above-mentioned pricing rule, the price a firm charges depends only on whether or not the firm has adopted the new technology. The adoption decision determines the level of marginal cost. The actions of rivals enter the firm's profit function via the price index. This term may be simplified, based on the fact that competitors will also charge prices according to the above rule. Assuming that a fraction q of the rivals have already adopted, the price index may be written as follows:

$$\int_0^n p(z)^{\alpha/(\alpha-1)}\,dz = \alpha^{\alpha/(1-\alpha)} n\{q(\hat{c}^{\alpha/(\alpha-1)} - \bar{c}^{\alpha/(\alpha-1)}) + \bar{c}^{\alpha/(\alpha-1)}\}. \tag{4}$$

Using the pricing rule and the term for the price index, operating profits are

$$\pi_0^{q(t)} = (1 - \alpha)\frac{\bar{c}^{\alpha/(\alpha-1)}}{\{q(t)(\hat{c}^{\alpha/(\alpha-1)} - \bar{c}^{\alpha/(\alpha-1)}) + \bar{c}^{\alpha/(\alpha-1)}\}}\frac{E}{n} \tag{5}$$

for a firm that has not yet adopted by time t, where $q(t)$ is the fraction of all firms that have adopted before t. Henceforth, subscripts 1 and 0 indicate whether or not a firm has adopted. The superscripts denote the fraction of rivals who already use the new technology. The flow of profits is

$$\pi_1^{q(t)} = (1 - \alpha)\frac{\hat{c}^{\alpha/(\alpha-1)}}{\{q(t)(\hat{c}^{\alpha/(\alpha-1)} - \bar{c}^{\alpha/(\alpha-1)}) + \bar{c}^{\alpha/(\alpha-1)}\}}\frac{E}{n} \tag{6}$$

for a firm that has already adopted in t. The adoption behavior of the rivals enters the profit function of a single firm only by the fraction q of firms that have adopted. Because this fraction changes over time it is described as a function of t.

Before deriving the noncooperative solution of the model, I want to mention some properties of the payoffs (5) and (6).

Property 1. The operating profit of a firm decreases as the number of firms producing with the new technology increases.

Property 2. The profit increase $\pi_1^{q(t)} - \pi_0^{q(t)}$ induced by the adoption diminishes as the share of firms that have already adopted grows.

The second property is especially interesting in connection with Reinganum (1981a, 1981b) and Quirmbach (1986). It shows that the demand functions derived from the Dixit-Stiglitz utility function imply a payoff structure similar to the one Reinganum assumed for the case of a discrete number of firms: "the increase in profit rates due to adopting $(m - 1)$th is greater than that due to adopting mth" (Reinganum, 1981b, p. 619). According to Quirmbach (1986) this satisfies a necessary condition for diffusion. In a recent empirical article, Stoneman and Kwon (1996) show that profit flows in actual diffusion processes exhibit Property 2. They derive significant stock effects in the case of the adoption of microprocessors in the U.K. engineering and metalworking sector, thus underpinning the importance of developments in the output market for a firm's decision to adopt a new technology.

3. The noncooperative equilibrium of the model

■ The starting point for the derivation of an equilibrium distribution $q(t)$ is the individual firm's choice of the optimal adoption date.[4] A firm maximizes the discounted value of total profits by choosing the adoption date T. Denoting the profit function as $\Pi(T)$, the optimization problem of the firm is as follows:

$$\max_T \Pi(T) = \int_0^T e^{-rt}\pi_0^{q(t)}\,dt + \int_T^\infty e^{-rt}\pi_1^{q(t)}\,dt - X(T). \tag{7}$$

The profit depends on the firm's own adoption date as well as on the adoption dates of its rivals summarized by the distribution function $q(t)$ with $t \in [0, \infty)$. The distribution $q(t)$ indicates how firms spread across potential adoption dates. The range of $q(t)$ is the unit interval. If the distribution function is continuous, the profit function can be differentiated with respect to T. One gets the first-order condition of the profit-maximization problem:

$$\frac{d\Pi(T)}{dT} = e^{-rT}(\pi_0^{q(T)} - \pi_1^{q(T)}) - X'(T) = 0. \tag{8}$$

The first term of the derivative in (8) gives the (discounted) value of the decrease in

[4] Here a heuristic approach is used in the sense that I choose individual firms as a starting point, although a single firm is of no importance at all when the industry consists of a continuum of firms. It serves to develop an economic intuition for the results derived later on.

profits induced by adopting marginally later. In the optimum this must be equal to the resulting decrease in cost. The cost decrease is the second term.

To get a concave profit-maximization problem I make the following assumption.

Assumption 1.

$$re^{-rT}(\pi_1^0 - \pi_0^0) - X''(T) < 0 \quad \text{for all } T.$$

This assumption ensures that the second-order condition is satisfied for a firm whose rivals never adopt. Furthermore, it is assumed that a finite solution of the optimization problem exists both for a single adopting firm and for a firm choosing to adopt later than all of its rivals. In the latter case, $q(t) = 1$ holds.

Now I am ready to derive the equilibrium distribution. This is done in Proposition 1. Before that I make a definition and state two lemmas.

A distribution $q(t)$ is a Nash equilibrium distribution if it satisfies the following conditions:

(i) Given that the rival firms are distributed across the adoption dates according to $q(t)$, the profit Π of a single firm must be equal for all dates for which the density is positive. This requirement is necessary because none of the *ex ante* identical firms would choose an adoption date for which the payoff is less than for other dates. The density cannot be positive at that date.

(ii) For all dates where the density vanishes, profits must be less than or equal to profits at dates with a positive density. This is a usual condition for a Nash equilibrium; an equilibrium strategy must not be dominated by another strategy.

From the first-order condition (8), Lemmas 1 and 2 follow.

Lemma 1. The range for which the density can be strictly positive is restricted to the interval $[T_L, T_H]$, where T_L and T_H are defined by

$$e^{-rT_L}(\pi_1^0 - \pi_0^0) = -X'(T_L) \tag{9}$$

and

$$e^{-rT_H}(\pi_1^1 - \pi_0^1) = -X'(T_H) \tag{10}$$

respectively.

Proof. See the Appendix.

Lemma 2. The density function is strictly positive in the interval $[T_L, T_H]$.[5]

Proof. See the Appendix.

Now I am ready to state the main proposition of this section of the article.

Proposition 1. The function

[5] Note that this lemma excludes an equilibrium in which all firms choose a uniform adoption date. The reason for this nonexistence is the nondifferentiability of the profit function for dates where a jump in the distribution function occurs. For further discussion, see Reinganum (1981a), Götz (forthcoming), or the working paper version of this article, which is available from the author's homepage at http://mailbox.univie.ac.at/~a4411mav/.

$$q(t) = \begin{cases} 0 & \text{for } t \leq T_L \\ -e^{-rt}\dfrac{(1-\alpha)E}{X'(t)n} - \dfrac{\overline{c}^{\alpha/(\alpha-1)}}{(\hat{c}^{\alpha/(\alpha-1)} - \overline{c}^{\alpha/(\alpha-1)})} & \text{for } T_L \leq t \leq T_H \\ 1 & \text{for } T_H \leq t \end{cases} \tag{11}$$

is a Nash equilibrium distribution in adoption dates for the industry considered. It describes the unique equilibrium share of firms making use of the new technology at some time t. This share is strictly increasing in the interval $[T_L, T_H]$.

Proof. From Lemmas 1 and 2 it immediately follows that for $q(t)$ to be an equilibrium distribution it has to satisfy the following conditions:

$$\frac{d\Pi(T)}{dT} = 0 \quad \text{for all } T \in [T_L, T_H] \tag{12}$$

and

$$q(t) = 0 \quad \text{if } t < T_L \quad \text{and} \quad q(t) = 1 \quad \text{if } t > T_H. \tag{13}$$

From (12) the equilibrium distribution can then be determined explicitly (for the corresponding range). Making use of (5) and (6) in (8), condition (12) becomes

$$\frac{d\Pi(T)}{dT} = e^{-rT}\left((1-\alpha)\frac{\overline{c}^{\alpha/(\alpha-1)} - \hat{c}^{\alpha/(\alpha-1)}}{\{q(T)(\hat{c}^{\alpha/(\alpha-1)} - \overline{c}^{\alpha/(\alpha-1)}) + \overline{c}^{\alpha/(\alpha-1)}\}}\frac{E}{n}\right) - X'(T) = 0. \tag{14}$$

This condition can now be solved for $q(t)$, and one immediately gets the respective part of equation (11). Because there is only a single solution for this simple equation, the resulting distribution function must be unique.

Continuity of the distribution function, which is asserted in the above proposition by using weak inequalities, is proved by inserting T_L and T_H in (11) and taking into account conditions (9) and (10). Together with Assumption 1, the first-order condition (8) ensures that $q(t)$ is strictly increasing. This is equivalent to the density being positive over the interval $[T_L, T_H]$. *Q.E.D.*

The equilibrium derived here is a flow of adoptions between T_L and T_H such that all firms make the same profits. The result provides no information about the behavior of a single firm in equilibrium. Nevertheless, the proportion of firms that have already adopted at a certain time is unique. It is instructive to compare the equilibrium derived here with the results of Reinganum (1981a, 1981b) and of Fudenberg and Tirole (1985). A common feature of all of these approaches is the occurrence of diffusion. In contrast to Reinganum, however, the model presented here does not exhibit different profits for firms adopting at different dates. The main objection of Fudenberg and Tirole does not apply to my approach. Contrary to Fudenberg and Tirole, preemptive adoption or collusion to a "late" uniform adoption date cannot occur in the equilibrium of my model. No firm will adopt earlier than T_L, the adoption date of a firm whose rivals never adopt, or later than T_H. The reason is that the agents are "small" in the Chamberlin model. The actions of a single firm do not affect the payoffs of its rivals and therefore firms cannot act strategically. The resulting equilibrium is similar to Reinganum's with the exception of a continuum of agents and rent equalization.

4. Rank and stock effects

■ **Rank effects.** In this subsection I present an extension of the basic model in order to capture rank effects. I also show how the introduction of some differences in firms' characteristics solves the problem that the basic model does not determine the adoption date of individual firms but only the aggregate diffusion pattern. A simple way to incorporate rank effects into the basic model is to add one more parameter $A(j)$ into the Dixit-Stiglitz consumption index $C(t)$ in the following way:

$$C(t) = \left(\int_0^n (A(j)y(j, t))^\alpha \, dj\right)^{1/\alpha}.$$

With respect to $A(j)$, I assume that $A(j) > 0$ for all j, and that $A(j)$ is a continuous and monotonously decreasing function of the firm index j. That is, firms are ranked in terms of the parameter in such a way that firms with higher consumer valuations have a lower index number. The parameter captures the idea that consumers value some varieties more than others, whether for reasons of design or other product characteristics. The aggregate demand function resulting from this specification is

$$Y(j, t) = \frac{A(j)^{\alpha/(1-\alpha)} p(j, t)^{1/(\alpha-1)}}{\int_0^n p(z, t)^{\alpha/(\alpha-1)} A(z)^{\alpha/(1-\alpha)} \, dz} \cdot E. \tag{15}$$

Equation (15) shows that higher values of A imply higher demand *ceteris paribus* and that firm sizes are different. The optimal pricing rule for an individual firm does not change when $A(j)$ is introduced. Given an arbitrary adoption pattern of the rivals, the gain from adopting the new technology turns out to be

$$\pi_1(j) - \pi_0(j) = \frac{(1 - \alpha)A(j)^{\alpha/(1-\alpha)} E}{\int_0^n c(j)^{\alpha/(\alpha-1)} A(j)^{\alpha/(1-\alpha)} \, dj} (\hat{c}^{\alpha/(\alpha-1)} - \bar{c}^{\alpha/(\alpha-1)}). \tag{16}$$

This term is increasing in $A(j)$, so the gain from adoption is always greater for larger firms, as is assumed in the rank models.

The following proposition states the consequences of the heterogeneity introduced in this section.

Proposition 2. (i) A firm j will adopt earlier in equilibrium than a firm i if $A(j) > A(i)$. That is, larger firms will adopt earlier than the smaller ones.

(ii) Assume that $A(0) > A(i)$ for some $i \in (0, n)$. Denote by T_L' and T_H' the start and the end dates of the adoption process in this case. Then it holds that

$$T_L' < T_L \quad \text{and} \quad T_H' > T_H,$$

where T_L and T_H are defined in Lemma 1 above.

Proof. See the Appendix.

Proposition 2 (ii) shows that diffusion will start earlier and take longer in a model with heterogeneous firms than in the basic model.

By assuming a specific functional form for $A(j)$, namely

$$A(j) = 1 + \epsilon\left(\frac{1}{2} - \frac{j}{n}\right), \quad \text{where } \epsilon > 0,$$

it can be seen that small differences between firms lead to unique adoption dates for individual firms. As ϵ converges to zero, the diffusion pattern converges to the equilibrium distribution of the basic model, but the adoption dates of individual firms are unique.

A simple example shows that the relation between firm size and date of adoption breaks down if one abandons the indivisibility assumption with respect to the new technology. If one were to allow for a linear relationship between firm size and adoption costs, the connection between firm size and date of adoption would vanish. To see this, assume that $X(T)$ describes the per-unit costs for adoption and that total adoption costs are just $X(T)\, y_{LR}$, where y_{LR} is the long-run production level.[6] The first-order condition is

$$e^{-rT}(\pi_0(j) - \pi_1(j)) - X'(T)y_{LR}(j) = 0. \tag{17}$$

Inspection of (15) and (16) immediately shows that the terms which differ for different firms (the $A(j)$ terms in the numerators) cancel out. Therefore, firm size does not matter under these circumstances. While "most of the empirical work . . . has found a positive relation between firm size and speed of adoption" (Karshenas and Stoneman, 1995, p. 288), there are exceptions (see, for instance, Colombo and Mosconi (1995)). Contrary to pure rank-effects models, stock-effects models are able to explain diffusion also in the case where adoption costs for new technologies are not independent of firm size.

□ **Stock effects and the hazard rate.** Turning back to the basic model, I want to examine the conclusions that can be drawn from stock effects for duration models. This kind of econometric model is quite common in empirical studies of diffusion processes. Typically, the hazard rate h is estimated, where h is "defined as the probability of a firm adopting the new technology in the small time interval $t + dt$, conditional on having not adopted the technology by time t" (Karshenas and Stoneman, 1995, p. 285). Starting with Karshenas and Stoneman (1993), these models have only recently been extended to test for the empirical relevance of stock effects. Using a first-order condition like (8) and adding a stochastic error term, Karshenas and Stoneman (1993) derive the following hypothesis: the hazard rate should be negatively related to the stock of users of the new technology, if the stock effect is to be significant.

Their conclusion draws on Property 2 mentioned above. This property also holds in their model. What is important is that their hypothesis is derived from a first-order condition and not from the equilibrium (distribution) itself. I now want to show that taking the equilibrium distribution leads to the opposite hypothesis: a positive relation between the hazard rate and the stock of users of the new technology is to be expected if stock effects are important.

The hazard rate h is defined as $h(t) = \dot{q}(t)/(1 - q(t))$, where the dot denotes the time derivative that is equivalent to the density function here. To simplify calculations I use the explicit adoption-cost function $X(t) = e^{-(r+\beta)t}$, where β is a positive constant

[6] Long-run here denotes the period after the diffusion process in the industry has stopped. I therefore assume for simplicity that firms can produce above long-run capacity for a transition period.

capturing the decrease in cost induced by technical progress (see Fudenberg and Tirole, 1985). With this specification, one gets the density function

$$\dot{q}(t) = \frac{\beta(1 - \alpha)E}{(r + \beta)n} e^{\beta t}.$$

As this term is increasing in t, and the denominator of the hazard function must be nonincreasing, the hazard rate must be an increasing function of time. Because later dates must be associated with greater values of the stock of users q, empirical studies returning a positive coefficient on the stock of users would be in accordance with the basic model.

Colombo and Mosconi (1995) find a positive but not significant coefficient on the number of competitors already using the new technology. The respective coefficient in Karshenas and Stoneman (1993) is positive and significant, but the authors, having the opposite hypothesis, take that result as indicating epidemic effects. The above analysis shows that a distinction between stock and epidemic effects cannot easily be drawn. Another point worth stressing is that deriving a hypothesis only from first-order conditions may be misleading.

5. The effects of parameter changes: some comparative static results

■ In this section I turn to the question of how the diffusion pattern may vary with changes in parameters. Because of the representation of the equilibrium by an explicit function, comparative static results can be derived in a simple way.[7] The effects of an increase in the flow of expenditures E, an increase in the cost reduction, and a decrease of the interest rate r are discussed in detail in the working paper version of this article. There I show that all these changes speed up diffusion, as long as the number of firms is assumed to be constant. Here I want to focus on the effects of two parameters, namely the number of firms n and the parameter α, which is related to the elasticity of substitution and the elasticity of demand. Both of these parameters allow the inclusion of the Schumpeterian themes of the relation of firm size, competitiveness, and new technology. In the Chamberlin model, changes in n induce changes in firm size only, while the parameter α can be regarded as a measure of competitiveness. The effect of an exogenous change in n is stated in the next proposition.

Proposition 3. An increase in the number of firms n implies a decrease of $q(t)$ for every t in the range in which adoption takes place. Diffusion occurs more slowly, and the share of firms using the new technology is smaller at any time than in the original situation.

Proof. By partially differentiating (11) the proposition is obtained immediately. *Q.E.D.*

The increase in n implies a decrease in average firm sales measured by E/n. From the above discussion of rank effects, we know that decreasing the firm size delays adoption, if adoption costs are independent of the firm size.

Up to now I have not dealt with the question of entry. An entry stage can easily be added to the model if one assumes that the industry emerges at $t = 0$ and that entry

[7] Of course, the simplicity is due to the explicit utility and demand function used. It seems to be essential to use special functional forms in order to derive a wide range of results. This can be seen from Reinganum (1981b) and Quirmbach (1986), who use linear functions.

causes sunk costs. Sunk costs seem to be substantial in markets for differentiated products (see, for example, Romer, 1990, and Sutton, 1991). With sunk costs, entry cannot take place after the start of the market, otherwise (identical) firms entering at the starting date would earn positive profits. At the start of the industry, firms will enter as long as the discounted equilibrium profits (denoted above as $\Pi(T)$ for a firm adopting at T) are greater than the sunk costs. In the Appendix it is shown that the profits decrease when the number of firms increases. Given the sunk costs and parameters relating to the new technology, one gets a unique number of active firms. Changing the level of the sunk costs will change the number of firms. Proposition 3 states the consequences for the diffusion pattern of such a change.

Given the entry framework just described, any change in parameters will lead to changes in the number of firms. The situation is different, however, if one assumes that the start of the industry occurs at some $t < 0$ and that there is uncertainty with respect to the new technology. In this case it is possible that different realizations of parameters of the technology or policy measures taken in $t = 0$ leave the number of firms unchanged (see the working paper version for examples). Especially in mature industry with sizeable sunk costs, the arrival of a new technology will often not imply changes in the number of firms.

Turning back to the comparative statics, I now consider the effect of the parameter α on the diffusion pattern. Changes in α induce large changes in operating profits and, therefore, changes in the number of firms. Nevertheless I first want to consider the case of a fixed number of firms. As a change in n leads to a change in the size of the firms, holding n fixed gives the effect of a change in competitiveness in isolation. As was shown by the discussion in Section 4, this exercise captures the total effect of the change in α, if we were in the case with (linear) size-dependent adoption costs. The change in n would not affect the diffusion pattern in that case. To analyze this case, it is more convenient to use a given number of firms than to allow for free entry and size-dependent costs.

The first point to mention about the effect of a change in α, given n, is that it is ambiguous. This can be seen from

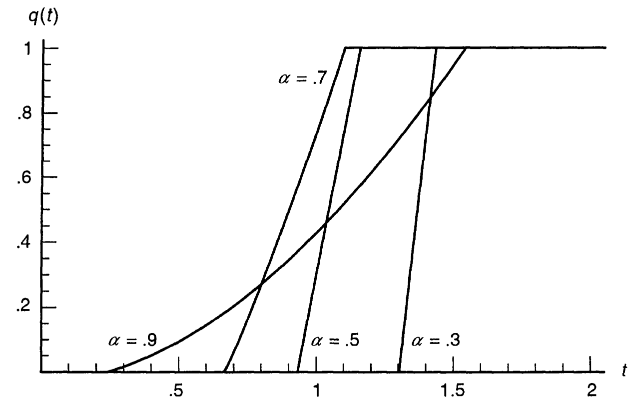
$$\frac{\partial q(t)}{\partial \alpha} = e^{-rT}\frac{E}{X'(t)n} - \frac{\log(\hat{c}/\bar{c})\left(\dfrac{\hat{c}}{\bar{c}}\right)^{\alpha/(\alpha-1)}}{\left[\left(\dfrac{\hat{c}}{\bar{c}}\right)^{\alpha/(\alpha-1)} - 1\right]^2 (1-\alpha)^2}, \tag{18}$$

which is the derivative of the relevant part of the equilibrium distribution (11) with respect to α. The first term on the right-hand side of (18) is negative ($X'(t) < 0$) and the second one—inclusive of the minus sign—is positive (note that $\hat{c}/\bar{c} < 1$!). On the one hand, the increase in α implies a greater elasticity of demand $1/(1 - \alpha)$ and leads, therefore, to a smaller markup and, *ceteris paribus,* to a smaller return to adoption. On the other hand, a given cost reduction now implies a larger shift of demand from the dearer to the cheaper varieties because of the increased elasticity of substitution. A given price reduction leads to a larger increase in demand; the new technology provides a larger profit gain and, therefore, induces earlier adoption.

The results of a simulation, presented in Figure 1, give more information about the influence of α on the diffusion pattern. The functional forms and parameters used are $X(T) = \int_0^T e^{-rt}T^{-b}\,dt$, $E = 10$, $\hat{c}/\bar{c} = 2/3$, $r = 1/10$, $n = 2$, $b = 2$. The diagram suggests that an increasing degree of competitiveness in an industry leads not only to an earlier

FIGURE 1

THE DIFFUSION PATTERN AS A FUNCTION OF THE PARAMETER α



start of the diffusion process, but also to an expansion of this process. The time interval between the earliest and the latest adoption widens. As the case with $\alpha = 9/10$ shows, the second effect may be so strong that diffusion is completed later than in the case of less competition.

Now I come back to the case where the adoption costs are independent of the size of the firm. As noted above, an increase in α will decrease the number of firms as the markup and profits go down. The associated increase in firm size induces firms *ceteris paribus* to adopt earlier. To get the total effect of the change in α on the diffusion pattern in this case, I make the number of firms endogenous. I extend the above simulation in the following way: For α equal to .85 and .9, respectively, I calculate the number of firms so that total profits are zero, assuming that the market emerges at $t = 0$ and that the sunk costs are equal to the total profits earned by firms when $n = 2$ and $\alpha = .8$. These high values for α are of interest for two reasons. First, in the simulation underlying Figure 1, moving from $\alpha = .7$ to $\alpha = .9$ is the only case where increasing competition does not lead to an unambiguous move of the diffusion curve toward earlier adoption dates. Therefore the high values of α used here are the only ones where considering the change in n can make a qualitative difference. Second, they imply reasonable markups between 11 (for $\alpha = .9$) and 25 (for $\alpha = .8$) % (see Martins, Scarpetta, and Pilat, 1996).

The values for the number of firms n, the first adoption T_L, and the last adoption T_H are depicted in Table 1 for the respective values of α.[8] The results of the table can be summarized as follows: Increasing α leads to a shift of the diffusion curve to the left, if the impact of α on n is taken into account. Although the time elapsed between the first and the last adoption is longer in industries with a higher degree of competition, the last adopters adopt earlier than in the case with less competition. Therefore, increased competition promotes diffusion in the setup used in the simulation.

The results derived here shed some light on Reinganum's (1981b) results for a Cournot oligopoly with homogeneous goods. Using a linear demand function, Reinganum shows that (most) firms will delay adoption if the number of firms is increased.[9]

[8] Calculations for other values of α (e.g., .7 and .95) confirm the results depicted in the table. More familiar values for the firm numbers are obtained by multiplying expenditure E and n by a common term, say 100. In this case nothing changes except E and n.

[9] Reinganum shows that there may be one firm that adopts earlier and some late adopters whose

TABLE 1 Number of Firms and Adoption Dates as a Function of α

$\alpha = .8$	$n = 2$	$T_L = .5$	$T_H = 1.2$
$\alpha = .85$	$n = 146/100$	$T_L = .3$	$T_H = 1.1$
$\alpha = .9$	$n = 95/100$	$T_L = .2$	$T_H = 1.0$

The above discussion indicates that from the two effects associated with changes in n in the Cournot model, namely a firm-size effect and a change in the market power, the former one apparently dominates the latter one. As the analysis of the effects of α shows, more competition often speeds up diffusion. Loosely speaking, more competition in the Chamberlin model means that it is more difficult for the firms to differentiate their products. Price competition is tougher in this case. This relation also explains the surprising property that more competition is associated with fewer firms in a free-entry equilibrium.

My theoretical results are in line with empirical results. There are signs of a positive relationship between the degree of competitiveness and the speed of diffusion (see Kamien and Schwartz (1982) and, more recently, Colombo and Mosconi (1995), who found a negative but insignificant influence of the Herfindahl concentration index on diffusion in their study). But with respect to the effect of the market structure, ambiguity remains (see Karshenas and Stoneman, 1995).

6. Conclusions

■ In this article, I present a framework that allows the integration of two effects which feature prominently in the recent literature on diffusion, namely stock and rank effects. Testable hypotheses have been easily derived from the model's equilibrium, a simple distribution function.

A subject not covered in the article is welfare analysis. This is due to the fact that too many rather than no welfare results are available. The problem is that different second-best welfare measures yield quite different policy conclusions (see the working paper version). Independent of the measure one uses, however, one gets the result that a social planner would choose diffusion rather than simultaneous adoption. Developing satisfactory welfare measures and applying them to models with less specific functional forms and different market structures remains a topic of future research.

A case for governmental action directed toward the diffusion of new technology would certainly arise if there were additional market imperfections like technological externalities. In the context of the adoption of a new technology, externalities could exist on the supply side of the new technology, for instance because of learning by doing, or on the demand side, for instance as network externalities. The framework developed here seems to be sufficiently flexible and simple to include both of these effects. Furthermore, it would allow a more explicit treatment of the supply side than the mere adoption-cost function used here. Models with these components would cover the complex interactions of the demand and supply sides that may arise in the diffusion of the new technology. The development of such models appears to be a promising task for future research.

adoption date is unchanged. This case can only arise, however, if innovation is drastic in the sense that the equilibrium price falls below the original marginal costs as soon as m ($<n$) firms have adopted. The late adopters will temporarily cease production in this case. I do not consider this case here.

Appendix

■ Proofs of Lemmas 1 and 2 and Proposition 2 follow.

Proof of Lemma 1. First I show that $T_L < T_H$. This follows from Assumption 1 and the inequality $\pi_1^0 - \pi_0^0 > \pi_1^1 - \pi_0^1$. The inequality is a special case of Property 2. The lemma is proved by inspecting (8) at the margins of the range of the distribution function. At these points $q(t)$ will be equal to zero and one respectively, and one gets the conditions (9) and (10). These conditions are satisfied for T_L and T_H respectively; at values smaller than T_L or greater than T_H, profit must be less because of the second-order condition. *Q.E.D.*

Proof of Lemma 2. To prove this statement I must first demonstrate that in equilibrium,

$$\Pi(T_L) = \Pi(T_H).$$

Suppose there were a date $\tilde{T} < T_H$ with positive density and $q(\tilde{T}) = 1$, that is, all firms have already adopted in $\tilde{T}$. In this case it would be true that $\Pi(T_H) > \Pi(\tilde{T})$ because, by Assumption 1, the profit function is concave in the interval $[\tilde{T}, T_H]$ and its maximum value is reached at T_H. Therefore, a date $\tilde{T}$ with the above-asserted property cannot exist. The density has to be positive in an arbitrarily small interval with the right boundary point T_H. Profits must be equal to $\Pi(T_H)$ in this interval.

An analogous reasoning holds for T_L. Here, $T_L < \tilde{T}$ and $q(\tilde{T}) = 0$ is chosen as a starting point. It is not possible that the share of firms having adopted is zero until time $\tilde{T}$. The profit of all dates in a small interval with the left boundary point T_L must amount to $\Pi(T_L)$.

The equality of profits is proved by observing that the density is positive at the intervals at T_L and at T_H, which can be the case only if the profits are equal in these intervals.

Second I must demonstrate that there exists no interval $[\tilde{T}, \hat{T}]$ with $T_L < \tilde{T}, \hat{T} < T_H$ such that the density is zero over that range. Again, the proof is by contradiction. Suppose that there were such an interval. Then one could assume without loss of generality that the density is positive on the interval $[T_L, \tilde{T}]$. Furthermore it would be true that $q(\tilde{T}) = q(\hat{T})$. The profit function is strictly concave on the interval $[\tilde{T}, \hat{T}]$ by Assumption 1. Because the density is assumed to be positive to the left of $\tilde{T}$ and zero to the right, concavity implies that the profit is strictly decreasing, and it follows that $\Pi(\tilde{T}) > \Pi(\hat{T})$. This implies that the density would have to vanish in $\hat{T}$ and for all subsequent dates. The density could not become positive again because the share of firms having adopted is equal to that in $\tilde{T}$, where the first-order condition (8) was satisfied by assumption. But this statement contradicts the result derived above, that density must be positive in a neighborhood of T_H. Therefore it is proved that the density must be strictly positive on the interval $[T_L, T_H]$. In this equilibrium, the proportion of the firms using the new technology must be strictly monotonically increasing. *Q.E.D.*

Proof of Proposition 2. Part (i) can be deduced, for instance, from conditions (10) and (9) and the proof of Lemma 1. The proof that $T_L < T_H$ implies that a greater gain from adoption leads to earlier adoption. In the heterogeneity case, different gains are implied by (16).

Part (ii) follows from inspection of (16), (10), and (9). Note that the gain from adopting is greater for the first adopter in the heterogeneous case (that is, a firm k with $A(k) = A(0)$) than for the first adopter in the basic model. To see this, note that $A(0) > A(j)$ for all $j > i$ by the monotonicity assumption in connection with the assumption in the proposition. Therefore,

$$\frac{A(0)^{\alpha/(1-\alpha)}}{\displaystyle\int_0^n c(j)^{\alpha/(\alpha-1)} A(j)^{\alpha/(1-\alpha)}\, dj} > \frac{1}{\displaystyle\int_0^n c(j)^{\alpha/(\alpha-1)}\, dj}.$$

The expression on the right-hand side is the respective term for the homogeneous case. The reasoning is analogous for the last adopter. In that case the inequality is reversed. *Q.E.D.*

Proof that the discounted profits $\Pi(\mathrm{T})$ *decrease with an increasing number of active firms (Section 5).* Using the equilibrium distribution $q(t)$ from equation (11), the discounted equilibrium profits $\Pi(T)$ depicted in equation (7) can be determined explicitly. One gets

$$\Pi(T) = \frac{(1-\alpha)E}{nr}(1 - e^{-rT_L} + e^{-rT_H}) - \frac{\hat{c}^{\alpha/(\alpha-1)}X(T_H) - \bar{c}^{\alpha/(\alpha-1)}X(T_L)}{\hat{c}^{\alpha/(\alpha-1)} - \bar{c}^{\alpha/(\alpha-1)}} \quad \text{for all } T \in [T_L, T_H].$$

Because of the envelope theorem, the sign of the derivative of the profit function with respect to n is determined solely by the direct effect. The indirect effect via changes in T_L and T_H cancels out. The direct effect is obviously negative. *Q.E.D.*

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