Price Competition and Compatibility in the Presence of Positive Demand Externalities

Jinhong Xie • Marvin Sirbu
William E. Simon Graduate School of Business Administration, University of Rochester, Rochester, New York 14627
Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

In many cases, the benefit to a consumer of a product increases with the number of other users of the same product. These demand interdependencies are referred to in the literature as *positive demand externalities* or *network externalities*. This paper examines the dynamic pricing behaviors of an incumbent and a later entrant, with special attention to the impacts of demand externalities, compatibility, and competition on prices and profits. Defining market power as the ability to price above a competitor without losing market share, we show how demand externalities and installed base combine to confer market power. We model optimal pricing as a differential game with the optimal price trajectory established as Nash open-loop controls. For a duopoly durable goods market with strong demand externalities, the results show an increasing price trajectory can be optimal. As expected, a new entrant is better off if its products are compatible with those of the incumbent, especially when demand externalities are strong and the installed base of the incumbent is large. Less intuitively, the incumbent as well may be better off agreeing on common standards. The comparison of monopoly and duopoly shows that under strong demand externalities and a small installed base, the incumbent profits from compatible entry.
(*Diffusion; New Products; Dynamic Pricing; Duopoly Competition; Network Externalities; Compatibility; Standards*)

1. Introduction

Demand externalities are an important feature of many services and durable goods industries. For example, the value to a user of an electronic mail service depends upon how many other users subscribe to the service. The larger the number of other users one can reach, the more valuable the service. Facsimile machines are an example of a durable good which exhibits demand externalities: owning a fax machine is more desirable if other consumers own them. Demand externalities may also arise for complementary goods. For example, the larger the installed base of personal computers, the more software will be written for PCs. The availability of software will in turn make PCs more valuable to potential customers.

Product complexity and risk aversion can lead to positive demand externalities for a wide range of products. Kalish (1985) notes, "As the product is introduced, there is uncertainty associated with the product's experience-type attributes. The value of the new product to a risk-averse customer is lower than the product's value if all experience information was available. As more customers adopt the innovation, more of the uncertainty is removed and the valuation of the product increases." Thus, as the installed base increases, word of mouth reduces the uncertainty of potential consumers, resulting in an increase in risk-adjusted product valuation and hence potential demand.

Compatibility is an important issue in a market with demand externalities. For communications networks, the question is whether subscribers of one network can communicate with subscribers of other networks. For durable goods, such as modems, facsimile machines, or videoconferencing equipment, the question is whether

0025-1909/95/4105/0909$01.25

equipment from one vendor can interwork with equipment from a different vendor. For complementary goods A and B, the issue is whether goods of type B produced for use with one line of products of type A can be used with a different line of products of type A. Compatibility influences the extent of the externality, thereby influencing the optimal strategy. Where positive demand externalities result from the reduction of uncertainty, "compatibility" refers to the extent to which one product is similar enough to benefit from the same word of mouth or installed base effect as another product. Incompatibility means that customer knowledge and uncertainty reduction gained from installation and use of a product do not influence the uncertainty about competitive products.

The purpose of this paper is to understand the influence of demand externalities on the dynamics of new product markets with multiple suppliers. We want to know:

(1) How do competition and compatibility affect the competitors' profitability? If the new entrant can choose to be compatible with the incumbent, should it do so? If the incumbent can control compatibility (e.g., via patent protection), should it permit or prohibit compatible entry?

(2) To what extent do demand externalities and installed base confer market power on an incumbent?

(3) How should pricing by an incumbent respond to a new entrant? How should a new entrant price to successfully compete?

(4) How do the answers to these questions vary with the extent of demand externalities and the size of the installed base of the incumbent at the time of entry?

1.1. Prior Research

Three streams of work underlie the present paper: (1) studies of the diffusion of new products and the effect of price on market dynamics; (2) studies of pricing strategies in the presence of competition; and (3) studies of markets with demand externalities.

In Bass' original diffusion model (Bass 1969), product price does not appear explicitly as a variable. Since then, several researchers have incorporated the effect of price on demand and diffusion within a Bass model framework (Robinson and Lakhani 1975, Bass 1980, Dolan and Jeuland 1981, Clarke et al. 1982, Jeuland and Dolan 1982, Jain and Rao 1990). Optimal monopolistic pricing has been studied extensively by Kalish (1983, 1985).

In the last decade, several researchers have applied differential game theory to optimal dynamic pricing problems in competitive environments. Dockner (1985) extends the Robinson-Lakhani model to a duopoly which looks for a Nash equilibrium in open-loop controls. Erickson (1983) studies an oligopoly market and provides numerical solutions for a wide range of parameter combinations. Eliashberg and Jeuland (1986) analyze dynamic pricing strategies in a two-period context—a monopoly period followed by a duopoly period. Dockner and Jørgensen (1988) survey the literature on optimal pricing strategies for new products in dynamic oligopolies and develop a more general framework which provides an analytic solution of the Erickson model. The oligopolistic pricing decision has also been studied by Thompson and Teng (1984), Gaugush (1984), Rao and Bass (1985), and Nascimento and Vanhonacker (1987).

The increasing importance of standardization, particularly in information technology markets (Cargill 1989), has led to a number of recent papers examining demand externalities and product compatibility. The majority of these works, however, treat market size and diffusion as exogenously given. Katz and Shapiro (1985, 1986) combine assumptions of demand externalities and oligopoly in a two-period game theoretic model. Consumers are assumed to perfectly forecast sales of each product in future periods in estimating the demand externality benefits of alternative product choices; the papers focus on the private and social welfare effects of compatibility. Farrell and Saloner (1986) also examine the effects of compatibility and installed base on new entrants; potential users arrive over time at an exogenously determined rate and select between an incumbent standard and a new technology. Farrell and Gallini (1988) show that under some circumstances a monopolist should encourage compatible entry, for example, technology licensing to a second source. A more recent paper by Katz and Shapiro (1992) considers the optimal time for a new entrant to challenge an incumbent in a market with demand externalities. The model makes very particular assumptions about the underlying cost structures of the competitors. It also assumes that customers enter the market at an exogenously determined rate. Beggs and Klemperer (1992) have examined competition among duopolists in an infinite period dynamic model without demand externalities but with switching costs.

Rohlfs (1974) studies a demand function with positive demand externalities. By combining Rohlfs' demand function with a diffusion equation to describe the process by which subscribers actually sign up in a service market, Dhebar and Oren (1985, 1986) create a dynamic model of market growth for a market with a single supplier. They characterize an optimal dynamic pricing strategy that maximizes the present value of future profits in the presence of demand externalities. Theirs is the only prior work in the area of demand externalities that determines the arrival rate of customers within the model.

Markets with demand externalities constitute an increasingly important set of industries, and the behavior of markets with demand externalities differs markedly from those without. Previous authors have studied problems of diffusion, optimal pricing under competition, and demand externalities, either singly or taken *two at a time. This paper combines all three elements* in a single model. By including diffusion within the model, we are not obliged to assume, as have most of the previous studies of demand externalities, that quantities purchased in each period are completely independent of product prices.

1.2. Organization of the Paper

In §2 we derive a model of duopolistic dynamic demand in the presence of demand externalities that is a function of both price and installed base.

In §3, under very general assumptions about demand and diffusion, optimal pricing strategies are found as the solution to an open-loop Nash equilibrium game. Optimal strategies in the presence of demand externalities are contrasted to optimal strategies when they are not present. We examine the impact of compatibility vs. incompatibility on firms' profitability given optimal pricing.

In §4, we define market power as the ability to price above competitors while still outselling them, and show *how demand externalities and installed base combine* to confer market power.

In §5, we look at some numerical examples which illustrate the optimal pricing behaviors and compatibility issues discussed earlier. Section 6 summarizes our results.

2. A Model of Duopolistic Dynamic Demand and Diffusion

In this paper we consider two firms providing competing but differentiated durable goods characterized by positive demand externalities. Consumers may buy zero or one of these goods but not both; there are no repeat purchases. Limited resale is permitted as discussed in *footnote 3. Since the goods are durable, installed base* equals cumulative sales. The firms are permitted to continuously vary their prices over time.

2.1. Dynamic Duopolistic Demand in the Presence of Demand Externalities

Kalish (1983, 1985) and Feichtinger (1982) analyze pricing for a single supplier where the market potential is a function of price. Dhebar and Oren (1985, 1986) examine a market in which the potential demand depends on the market price *and* installed base, but their model can only be applied to a market with one producer. Nascimento and Vanhonacker (1987) use a bivariate distribution describing the heterogeneity in reservation prices across the population, without demand externalities, to study the strategic pricing of a differentiated durable in a dynamic duopoly. We wish to formulate a demand model that incorporates the effects of both price and installed base in a market with multiple suppliers.

Consider first a monopoly market without demand externalities. Assume a heterogeneous population where each individual perceives a benefit w from the product and w is randomly distributed across the population with density function $f(w)$. Following Kalish (1985), for a given price p at time t, the dynamic potential demand (or more simply the dynamic demand) for the monopolist's product is

$$D_m(p) = \int_p^{\infty} f(w)dw. \qquad (2\text{-}1)$$

$D_m(p) \in [0, 1]$ is the fraction of the total population which would have a positive consumer surplus if they paid a price p to obtain a product with benefit w.[1]

[1] To simplify the presentation, we present the following discussion in terms of normalized sales and demand.

Now consider the effect of demand externalities. Since the consumption benefit will increase with the installed base, users will perceive a higher benefit w from the product when the installed base is larger. As a result, as the installed base increases, the density function shifts in the direction of having higher values for large w.

With demand externalities, the dynamic demand is

$$D_m(p, x) = \int_p^{\infty} f(w, x)dw, \qquad (2\text{-}2)$$

where $f(w, x)$ is the density function of product benefit over the entire population and x, measured as a fraction of the total population, is the cumulative sales to date, which by assumption is also the current installed base. For positive demand externalities, it is clear that the dynamic demand should satisfy:

$$\frac{\partial D_m}{\partial x} > 0 \quad \text{for all } p. \qquad (2\text{-}3)$$

Now let's look at a market with two competing firms. Each individual receives product benefit w_i from the product of firm i ($i = 1, 2$). At any point in time an individual is either a potential buyer of firm 1, a potential buyer of firm 2, or not a potential buyer. The consumer surplus function of individual k is assumed to be:

$$U_i^k = w_i^k - p_i \quad \text{and} \quad U_0^k = 0,$$

where U_i^k is the consumer surplus that the individual obtains from purchasing the product of firm i. The individual will

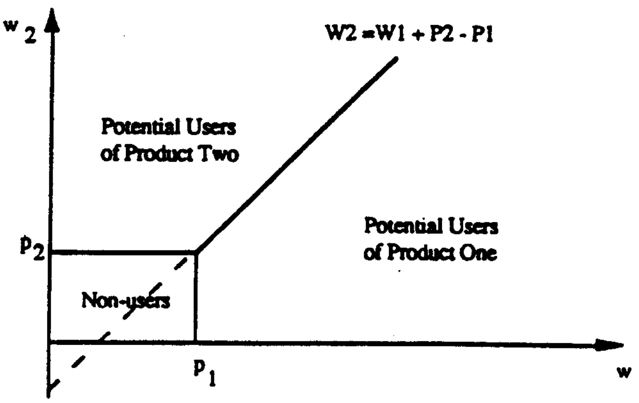
(a) not be a potential buyer of either product if $U_i^k < 0$, for $i = 1, 2$;

(b) be a potential buyer of product i if $U_i^k > 0$ and $U_i^k > U_j^k$, $i, j = 1, 2, j \neq i$.

When faced with two competitive products, both of which provide positive consumer surplus, the consumer buys only one product—the one which provides the higher surplus. Figure 1 classifies each individual in product benefit space for given prices.

Turning to the definition of compatibility, let y_i be the *effective* installed bases that consumers use to evaluate the consumption benefit derived from product i. Without considering expectations of market growth, y_i is a function of the current *individual* installed bases x_1 and x_2. If the two products in a durable good duopoly

Figure 1 **Classification of Individuals in the Product Benefit Space**



market are incompatible, then the effective installed base is equal to the individual installed base[2]

$$y_i = x_i, \quad i = 1, 2. \qquad (2\text{-}4)$$

For a market with compatibility the effective installed base is equal to the sum of the individual installed bases

$$y_i = x_1 + x_2, \quad i = 1, 2. \qquad (2\text{-}5)$$

If expectations of future market growth play an important role in the consumption decision, the effective installed base will be a function of expected market size, which may in turn be a function of current installed base, current sales, current price, firm reputation, advertising and other variables. To avoid further complicating our model, this research does not consider the impact of expectation.

Assume w_1 and w_2 have a joint density function. Then the duopolistic dynamic demand in a market with demand externalities can be written as:

$$D_1(p_1, p_2, x_1, x_2) = \int_{p_1}^{\infty} \int_0^{w_1+p_2-p_1} f(w_1, w_2, y_1(x_1, x_2), y_2(x_1, x_2))dw_2dw_1, \qquad (2\text{-}6)$$

[2] Similarly, for a network service, a duopoly market is considered not interconnected if the effective installed base is equal to the individual installed base.

$$D_2(p_1, p_2, x_1, x_2) = \int_{p_2}^{\infty} \int_0^{w_2+p_1-p_2} f(w_1, w_2, y_1(x_1, x_2), y_2(x_1, x_2)) dw_1 dw_2, \quad (2\text{-}7)$$

where $f(w_1, w_2, y_1(x_1, x_2), y_2(x_1, x_2))$ is the joint product benefit density function for the two products across the entire population. The dynamic demand D_i includes the x_i individuals who have already bought product from firm i and the nonusers who are currently willing to buy from firm i but have not yet done so. Of course, at equilibrium we must have $D_i(p_1, p_2, x_1, x_2) = x_i$.

We see from Figure 1 that the duopolistic dynamic demand given by (2-6) and (2-7) satisfies:

$$\frac{\partial D_i}{\partial p_i} \leq 0, \quad \frac{\partial D_i}{\partial p_j} \geq 0, \quad i, j = 1, 2, i \neq j, \quad (2\text{-}8)$$

which are the standard assumptions for oligopoly.

By definition, the presence of positive demand externalities implies that the total demand will increase with an increase in the installed base of either competitor. This is true whether or not the firms' products are compatible, because an increase in the installed base can only increase the perceived benefit of a product and cannot decrease it, leading to Equation (2-9):

$$\frac{\partial D}{\partial x_i} > 0, \quad \text{where } D = D_1 + D_2, i = 1, 2. \quad (2\text{-}9)$$

It is not obvious, however, how the demand for the products of each firm will change separately with an increase in the installed base. When the two products are incompatible, we expect an increase in the installed base of firm i will increase the benefit only of product i but not of product j. So, the dynamic demand is an increasing function of one's own installed base. When firm j's installed base increases, the value of product j increases; as a result, some former potential users of firm i may become potential users of firm j because of a higher surplus. Thus, the dynamic demand is monotonically decreasing in the competitor's installed base. These conclusions are embodied in Equation (2-10):

$$\frac{\partial D_i}{\partial x_i} > 0, \quad \frac{\partial D_i}{\partial x_j} < 0, \quad i, j = 1, 2, i \neq j, i, j \text{ not compatible}. \quad (2\text{-}10)$$

When the two products are compatible, however, the effect of an increase in the installed base of firm i has an ambiguous impact on the demand for its own products. While the *total* potential demand must increase, (Equation (2-9)), the existence of competition may result in either an increase or decrease in the potential demand for firm i, depending on how the increase in installed base affects the *relative* attractiveness of the products of firms i and j. Thus, Equation (2-10) may *not* hold when the two firms' products are compatible.

2.2. The Diffusion Model

We assume the sales rate is linear in the unfulfilled demand $(D_i - x_i)$; then the diffusion process can be expressed as:

$$\dot{x}_i = B_i(x_1, x_2)(D_i(p_1, p_2, x_1, x_2) - x_i), \quad D_i \geq x_i, \quad (2\text{-}11)$$

where B_i is the hazard rate. Note that if p_i and p_j change such that $D_i \leq x_i$, the sales of good i halt. As in Kalish (1983), we argue the optimal pricing policy of firm i will never lead to $D_i < x_i$, so we need focus only on the case of $D_i \geq x_i$.[3]

The diffusion process includes an *imitation* effect, when

[3] D_i is presumed to be the sum of the installed base plus all those who find the product to have positive consumer surplus but have simply not yet acted. D_i may decline for one of two reasons: increasing p_i or decreasing p_j. If D_i should decline then there may be consumers who are included in the installed base, x_i, but not in D_i. If $(D_i - x_i)$ is to measure correctly the unfulfilled demand for good i, we must assume that individuals in the installed base who no longer find the expense for good i to be justified, or who would derive greater net benefit from good j, sell good i in the secondary market to those who prefer it. Under this assumption, $(D_i - x_i)$ will continue to correctly characterize unfulfilled demand. Resale does not affect the dynamic demand. As in Kalish we argue that firm i will never find it optimal to increase its own price to the point where $D_i < x_i$. If a reduction in price by firm j would lead to $D_i < x_i$, we assume that firm i responds by lowering its price—even adopting a negative price—so that D_i is never less than x_i. Note also that given our formulation of joint demand, actions by firm j can result in a reduction in D_i, but cannot cause a previous customer of firm i to wish to leave the market altogether. Thus, it will always be possible for firm i to maintain $D_i \geq x_i$. A negative price at which $D_i = x_i$, leads to zero sales, so we have the same result as if we had simply defined $\dot{x}_i = 0$ for $D_i < x_i$, but we avoid dealing explicitly with boundary effects. In practice, D_i is generally not close to x_i during the early stages of the product life cycle on which we focus our attention here.

$$\frac{\partial B_i(x_i, x_j)}{\partial x_i} > 0, \qquad (2\text{-}12)$$

i.e., the hazard rate of diffusion increases with past sales due to word of mouth or potential customers *imitating* past customers. By extension, $\partial B_j(x_i, x_j)/\partial x_i > 0$ implies a cross-imitation effect.

3. Effect of Competition and Compatibility on Profit under Optimal Dynamic Pricing

Section 2 introduced a general dynamic model for demand and diffusion for a market with demand externalities. In this section we show how to calculate the optimal pricing strategy for the firm under different assumptions about market structure. We then consider some general propositions about how competition and compatibility affect the present value of future profits when each firm is presumed to follow its optimal pricing strategy.

3.1. Optimal Pricing Under Different Market Structures

Optimal Monopoly Pricing. As a baseline for comparison with duopoly markets we first consider a monopoly market. Let π_m be the present value of all profits over the planning horizon. Then the optimal pricing problem for a monopoly can be formulated as follows:

$$\underset{p(t)}{\text{Max}}\ \pi_m = \int_0^T e^{-\delta t}[p - c]g\,dt, \qquad (3\text{-}1)^4$$

subject to: $\dot{x}(t) = g$

$$= B(x)(D(x, p) - x), \quad x(0) = x_0, \qquad (3\text{-}2)$$

where δ is the discount rate, T is the planning horizon, and $c = c(x(t))$ is the unit cost or marginal cost. We expect c to exhibit learning effects, $dc/dx < 0$, but do not require it; our results depend only on the assumption that $c = c(x(t))$. g is the diffusion equation, which we assume is the hazard rate B times the unfulfilled demand. Following Kalish (1983) the optimal pricing trajectory $p(t)$ must satisfy:

$$p = \frac{-g}{\partial g/\partial p} + c - \lambda, \qquad (3\text{-}3)$$

where λ is the costate variable.

Kalish (1983) shows that if: (1) the discount rate is zero, (2) the dynamic monopoly demand depends only on price, and (3) there is no imitation effect (i.e., $\delta = 0$; $D_m = D(p)$; and $\partial B/\partial x = 0$), then the optimal pricing strategy is monotonically decreasing. How do positive demand externalities change the optimal pricing trajectory? Keeping the other conditions the same, we find the optimal pricing path given by Equation (3-3) is *increasing* if the positive effect of the installed base on the potential demand is strong. More specifically, the optimal price path is increasing at any point in time t' if and only if:

$$\frac{\partial D_m}{\partial x} > 1 - \frac{(D_m - x)\cdot \partial^2 D_m/\partial x \partial p}{2|\partial D_m/\partial p|},$$

$$t = t', \quad \text{where } D_m = D(x, p). \qquad (3\text{-}4)$$

Equation (3-4) will be satisfied if $\partial D_m/\partial x$ is large enough. A large $\partial D_m/\partial x$ means that every new user greatly increases the benefit as perceived by other potential users, significantly increasing the number of people who are willing to buy at the current price, i.e., demand externalities are strong. In the appendix[5] we show an example where the condition of equation (3-4) is satisfied and where, as expected, the optimal price trajectory is increasing.

Optimal Duopolistic Pricing under a Nash Game. The duopolist's optimal pricing problem is to determine a pricing strategy, $p_i(t)$, that will maximize its discounted profits over the planning horizon taking the competitor's price into account. We model this as a differential game problem and look for a noncooperative Nash equilibrium. Let π_i be the discounted value of all

[4] The optimal pricing problem for a network service market requires only a slight modification to the objective function:

$$\underset{p(t)}{\text{Max}}\ \pi_m = \int_0^T e^{-\delta t}[p - c]x\,dt,$$

since subscribers pay a subscription fee periodically.

[5] The appendix, with complete proofs of the propositions, was judged too lengthy to include in this publication. It is available from the authors, or can be retrieved via the Internet using worldwide web from: URL = http://www.cs.cmu.edu/afs/andrew.cmu.edu/usr/ms6b/www/competition_and_externalities.appendix.ps.gz

future profits of firm i ($i = 1, 2$); the optimal pricing problem of firm i can be formulated as:

$$\underset{p_i(t)}{\text{Max}}\ \pi_i = \int_0^T e^{-\delta t}[p_i - c_i]g_i\,dt, \tag{3-5}$$

subject to:

$$\dot{x}_j(t) = g_j(D_j(p_1, p_2, x_1, x_2), x_j, x_j(0) = x_{j0},$$
$$j = 1, 2, \text{ where} \tag{3-6}$$

$$g_j = B_j(x_1, x_2)(D_j(p_1, p_2, x_1, x_2) - x_j). \tag{3-7}$$

In Equation (3-6), the dynamic demand is determined not only by the prices of the two firms' products but also by their installed bases—implying demand externalities. We assume that the dynamic demand satisfies the conditions given by Equation (2-10), and again that $c_i = c_i(x_i(t))$.

Following Dockner and Jørgensen (1988), we assume that g_i satisfies the following assumptions:

$$\frac{\partial g_i}{\partial p_i} < 0, \tag{3-8}$$

$$\frac{\partial g_i}{\partial p_j} > 0, \tag{3-9}$$

$$\frac{\partial g_i}{\partial p_i} + \frac{\partial g_i}{\partial p_j} < 0, \tag{3-10}$$

$$\frac{\partial^2 g_i}{\partial p_i \partial p_j} \le 0. \tag{3-11}$$

These assumptions indicate that (1) the sales rate is a decreasing function of one's own price but an increasing function of the competitor's price, i.e., the two products are substitutes; (2) the influence of one's own price change is stronger than that of the competitor's; (3) the negative impact of one's own price change on sales rate is stronger (weaker) when the competitor's price is higher (lower). Our model differs from those of Dockner and Jørgensen (1988) in that we posit a diffusion process in which potential demand is a joint function of price and installed base, whereas the latter assume a growth process in which price effects and installed base effects are multiplicatively separable.

The Nash equilibrium is a pair of strategies such that each strategy is the best response for the other strategy. Given that its competitor does not deviate from its strategy, firm i would not find it beneficial to deviate from its own strategy. The pricing policies are established as open-loop strategies, which means that the firms commit themselves to using pricing strategies based on time only. The Hamiltonian for the optimal pricing problem of Equation (3-5) is:

$$H_i(x_1, x_2, p_1, p_2, \lambda_i^i, \lambda_j^i) = e^{-\delta t}\{(p_i - c_i + \lambda_i^i)g_i + \lambda_j^i g_j\}, \quad i \ne j. \tag{3-12}$$

The optimal trajectories x_i, λ_j^i and λ_i^i must satisfy the differential Equation (3-6) and

$$\dot{\lambda}_j^i = \delta\lambda_j^i - e^{\delta t}\frac{\partial H_i}{\partial x_j}, \quad \lambda_j^i(T) = 0, \quad i \ne j; \tag{3-13}$$

$$\dot{\lambda}_i^i = \delta\lambda_i^i - e^{\delta t}\frac{\partial H_i}{\partial x_i}, \quad \lambda_i^i(T) = 0, \quad i \ne j. \tag{3-14}$$

The optimal price trajectory should satisfy the first-order necessary condition:

$$\frac{\partial H_i}{\partial p_i} = e^{-\delta t}\left\{g_i + [p_i - c_i + \lambda_i^i]\frac{\partial g_i}{\partial p_i} + \lambda_j^i\frac{\partial g_j}{\partial p_i}\right\} = 0, \quad i \ne j. \tag{3-15}$$

Finally, the optimal pricing trajectory for firm i is the solution to the following equation:

$$p_i = \frac{-(\lambda_j^i \partial g_j/\partial p_i + g_i)}{\partial g_i/\partial p_i} + c_i - \lambda_i^i, \quad i \ne j. \tag{3-16}$$

3.2. Effect of Competition and Compatibility on Profitability

In a market with demand externalities, the firms' profitability is affected by the choice to be compatible or incompatible with the competition. Is an incumbent always better off to be a monopolist? Should an incumbent prevent or permit compatibility when a new entrant enters? The following proposition states the effect of competition and compatibility on the incumbent's profitability.

PROPOSITION 3-1. (*i*) *The profit of the incumbent in a duopoly market where the two products are incompatible is always lower than its monopoly profit.* (*ii*) *The profit of the incumbent in a duopoly market where the two products are compatible may be higher than its monopoly profit.*

"Profit" refers to the present value of future profits over the planning horizon given that firms follow the optimal pricing strategies which satisfy Equations (3-3) *or* (3-16).

PROOF. See appendix.

Proposition 3-1 compares the profit a firm obtains when it is the only producer in the market with the case of duopolistic competition. The first statement is intuitive. The incumbent would always be worse off to have an incompatible competitor, because the incompatible entrant provides an alternative for the potential customers of the incumbent; this reduces the demand of the incumbent and constrains the incumbent's pricing. However, the second statement is not so intuitive. It says that by having a compatible competitor, the incumbent may actually realize greater profits than it would have realized had it continued as a monopolist. This is an interesting result. A compatible entrant has two opposing effects on the incumbent's profitability. On one hand, the incumbent's product will be valued based on the total installed base, not on its installed base alone, which makes the incumbent's product more attractive. On the other hand, the entrant, by providing an alternative for the potential customers of the incumbent, may attract customers away from the incumbent or force it to lower prices to maintain sales. The second statement of Proposition 3-1 tells us that an incumbent facing a new entrant may not always want to discourage compatibility even when it has the power to do so. Under certain conditions, the overall effect of competition and compatibility on the incumbent's profitability may be positive. In that case, the incumbent should facilitate compatibility.

One of the numerical examples given in §5 (Figure 5) shows that in a market with strong demand externalities, the incumbent obtains a higher profit by having a compatible entrant if the entry happens before the incumbent has built a large installed base. However, if at the time of entry the incumbent has developed a significant installed base, the existence of a compatible competitor reduces the incumbent's profit. It also shows that in a market with weak demand externalities, the incumbent would always be better off to be the monopolist than to have a competitor.

The following corollary discusses the effect of compatibility on the firms' profits when the two firms are symmetric. The two firms are considered a *symmetric duopoly* if: (a) the joint density function of product benefit is symmetric in the product benefit space; (b) the hazard rates are symmetric; (c) the initial conditions are identical; and (d) product costs are symmetric (Equations (3-17)–(3-20)):

$$f(w_1, w_2, y_1(x_1, x_2), y_2(x_1, x_2)) = f(w_2, w_1, y_2(x_1, x_2), y_1(x_1, x_2)), \quad (3\text{-}17)$$

$$B_1(x_1, x_2) = B_2(x_2, x_1), \quad (3\text{-}18)$$

$$x_1(0) = x_2(0), \quad (3\text{-}19)$$

$$c_1 = c_2. \quad (3\text{-}20)$$

COROLLARY 3-1. *For a symmetric duopoly where each follows the optimal pricing strategies which satisfy equation (3-16), the present value of future profits of each firm are greater with compatibility than without compatibility.*

PROOF. See appendix.

Corollary 3-1 indicates that in a symmetric duopoly market, the overall impact of compatibility is positive. Both firms will always be better off to be compatible than incompatible, no matter what the installed base at $t = t_0$ (provided they are equal).

We turn now to an examination of the effects of demand externalities and installed base on market power.

4. Market Power

By market power we mean the ability to charge a higher price than one's competitor while maintaining a higher sales rate. Differences in installed base, intrinsic product benefit, or rate of diffusion may give one firm market power over its competitor. In this section we derive the necessary conditions for a firm to have market power and show how demand externalities and installed base combine to confer market power.

We start by considering a specific functional form for the product benefit density function—the product of two exponentials:

$$f(w_1, w_2, y_1(x_1, x_2), y_2(x_1, x_2)) = \alpha_1(y_1)\,\mathrm{Exp}[-\alpha_1(y_1)w_1]\alpha_2(y_2)\,\mathrm{Exp}[-\alpha_2(y_2)w_2], \quad (4\text{-}1)$$

where α_i is a measurement of product benefit, $\alpha_i > 0$, $i = 1, 2$. A smaller α_i corresponds to a benefit density function with a larger mean benefit received from the products of firm i. Firm i experiences positive demand externalities if and only if

$$\frac{d\alpha_i(y_i)}{dy_i} < 0. \quad (4\text{-}2)$$

Equation (4-2) implies that the product benefit received from product i depends on the effective installed base of firm i. The value of $d\alpha_i(y_i)/dy_i$ measures the strength of demand externalities. It is easy to see that the dynamic demand function derived from Equation (4-1) satisfies all required properties discussed above (Equations 2-8)–(2-10)).

An exponential density function implies an asymmetric distribution of product benefit in which the bulk of consumers perceive a product benefit below average, but a few consumers perceive a very high product benefit. We assume this form for the benefit density function for three reasons. First, exponential functions are frequently used in marketing models (Lilien and Kotler 1983; Evans 1985), and many authors have demonstrated that linear, multiplicative, and exponential models give very similar results (e.g., Bolton 1989). Second, the assumption of an exponential form in equation (4-1) still leaves room for wide variation in the incorporation of installed base, since the coefficient α_i is constrained only to be everywhere positive and, in the case of positive demand externalities, to have a negative derivative (Equation (4-2)). Finally, the assumption of an exponential product benefit function provides some analytic convenience.

For incompatible products, i.e. $y_i = x_i$, we define two values, E_i, and E_j as follows:

$$E_i = \frac{(B_i + B_j)\alpha_j}{(B_j + B_i x_i - B_j x_j)(\alpha_i + \alpha_j)}, \quad (4\text{-}3)$$

$$E_j = \frac{(B_i + B_j)\alpha_i}{(B_i + B_j x_j - B_i x_i)(\alpha_i + \alpha_j)}, \quad i, j = 1, 2, i \neq j. \quad (4\text{-}4)$$

E_i and E_j are functions of product benefit, hazard rate, and installed bases. We prove in the appendix that the relative magnitudes of E_i and E_j determine whether one of the firms will have market power and, if so, which one. We find that if these two values are not equal to each other, there must be one and only one firm, say i, which has market power in the sense that it will be able to find a price, $\bar{p}_i$, at which firm i is guaranteed to have a higher sales rate than its competitor ($\dot{x}_i \geq \dot{x}_j$) whatever its competitor's (positive) price. In other words, if firm i, with market power, sets its price below the ceiling $\bar{p}_i$, no matter how low firm j drops its prices, it cannot expect to outsell firm i. An important finding here is that $\bar{p}_i$ does not depend on p_j. We call $\bar{p}_i$ an absolute price boundary. However, if firm i does not focus on market share but is more interested in increasing its contribution margins, it may price above $\bar{p}_i$. In this case, firm j will be able to find a price, $\bar{p}_j$, below which firm j will have a higher sales rate, and above which firm j will lose ground. We call $\bar{p}_j$ a relative price boundary since $\bar{p}_j$ depends on p_i. When E_i equals E_j, there is no absolute price boundary. The lower priced firm will have a higher sales rate.

The above results can be summed up in the following propositions and corollary.

PROPOSITION 4-1. *For a duopoly market in which the joint density function of product benefit is given by equation (4-1) and the market dynamics are expressed by equation (2-11), if $E_i > E_j$, then there exists an absolute price boundary, $\bar{p}_i > 0$, such that if firm i prices under $\bar{p}_i$, there is no nonnegative price firm j can charge in order to have a higher sales rate than firm i. Formally, at any time t';*

$$\text{if } E_i > E_j \text{ and } p_i \leq \bar{p}_i,$$

$$\text{then } \dot{x}_i(t') \geq \dot{x}_j(t') \quad \text{for any } p_j > 0.$$

The ceiling price $\bar{p}_i$ is given by

$$\bar{p}_i = \frac{\ln E_i}{\alpha_i}. \quad (4\text{-}5)$$

PROPOSITION 4-2. *If the firm with market power (firm i) prices above $\bar{p}_i$ given by Equation (4-5) then there exists a relative price boundary $\bar{p}_j$, such that if the competitor (firm j) prices below $\bar{p}_j$, it is guaranteed to outsell the firm with market power. Formally, at any time t'*

$$\text{if } E_i > E_j \text{ and } p_i > \bar{p}_i,$$

$$\text{then } \dot{x}_i(t') \leq \dot{x}_j(t') \quad \text{if and only if } p_j \leq \bar{p}_j.$$

Where $\bar{p}_j$ is given by

$$\bar{p}_j = \frac{\ln\left(\dfrac{B_j + \dfrac{(B_i\alpha_i - B_j\alpha_j)\,\mathrm{Exp}(-\alpha_i p_i)}{(\alpha_i + \alpha_j)}}{B_i\,\mathrm{Exp}(-\alpha_i p_i) - B_i x_i + B_j x_j}\right)}{\alpha_j}. \quad (4\text{-}6)$$

COROLLARY 4-1. *If $E_i = E_j$, then $\dot{x}_i(t') \geq \dot{x}_j(t')$ if and only if $p_i \leq p_j$.*

The propositions above quantify the notion of market power by showing how a combination of product benefit, hazard rate, price, and installed base can be translated into a guaranteed ability to have a higher sales rate than the competitor whatever the competitor's price. All else being equal, we would expect (1) that the firm with higher intrinsic product benefit would have market power relative to its competitor, and (2) that a firm with a higher hazard rate—for example, due to heavier advertising—would have market power relative to its competitor. It can be proved easily that both of these conjectures hold for our model (let $e_{ij} = E_i - E_j$, then, $\partial e_{ij}/\partial \alpha_i < 0$, and $\partial e_{ij}/\partial B_i > 0$).

Note that the above propositions assume a very general form for the hazard rate, $B_i = B_i(x_i, x_j)$ and do not assume the existence of positive demand externalities. The results depend only on the assumption of an exponential distribution of product benefit, as given in Equation (4-1).

In the presence of positive demand externalities, we expect that a larger installed base would increase the dominant firm's market power. If firm i has market power, then an increase in $\bar{p}_i$ implies greater scope for firm i to raise prices while still outselling its competitor. In the appendix, we show that $\partial \bar{p}_i/\partial x_i > 0$ if and only if

$$\frac{\partial B_i}{\partial x_i} M - B_i(B_i + B_j)\alpha_j(\alpha_i + \alpha_j) - \frac{d\alpha_i}{dx_i} L > 0, \text{ where} \quad (4\text{-}7)$$

$$M = \alpha_i B_j(\alpha_i + \alpha_j)(1 - x_i - x_j) > 0, \quad (4\text{-}8)$$

$$L = (B_i + B_j)\alpha_j(B_j + B_i x_i - B_j x_j) + \frac{E_i}{\alpha_i} \ln E_i > 0. \quad (4\text{-}9)$$

In Equation (4-7) the hazard rates B_i and B_j are always positive. $\partial B_i/\partial x_i$ measures the imitation effect and is assumed nonnegative (Equation (2-12)). From Equation (4-2) we know that more negative values of $d\alpha_i/dx_i$ correspond to stronger positive demand externalities. Equation (4-7) shows that installed base can confer market power in two ways: first, by increasing the imitation effect, and second, by increasing positive demand externalities. Without imitation effect and demand externalities (i.e., $\partial B_i/\partial x_i = 0$ and $d\alpha_i/dx_i = 0$), Equation (4-7) shows that increases in installed base can only decrease $\bar{p}_i$, i.e., decrease the firm's market power. This is because a large installed base is also equivalent to a high realized demand, hence saturation, and that has a negative impact on sales. However, if demand externalities are strong enough, even without imitation effect, an increase in installed base may unambiguously raise the price ceiling under which the dominant firm can always outsell its competition. We summarize these observations in the following corollary.

COROLLARY 4-2. *Suppose one firm (firm i) has market power ($E_i > E_j$). If demand externalities for this firm are strongly positive such that*

$$\frac{d\alpha}{dx_i} < -\frac{B_i(B_i + B_j)(\alpha_i + \alpha_j)\alpha_j}{L}, \quad (4\text{-}10)$$

then an increase in installed base increases the firm's ability to raise prices and still outsell its competitor.

5. Numerical Analysis

Given a specific form for the joint product benefit density function, $f(w_1, w_2, y_1(x_1, x_2), y_2(x_1, x_2))$, it is possible to calculate the optimal price trajectories and, more generally, the dynamic behavior of the system. In this section, results for several such systems of equations are presented.

5.1. Model and Parameters

The numerical analyses focus on the situation where the incumbent (firm 1) has a substantial installed base x_{10} at the time a new entrant (firm 2) enters with $x_{20} \approx 0$. We consider the joint density function introduced in Equation (4-1), where $\alpha_i(y_i)$ is given by

$$\alpha_i(y_i) = \frac{1}{v + y_i/a}, \quad i = 1, 2. \quad (5\text{-}1)$$

Equation (5-1) implies that the two products are assumed to have similar distributions of product benefit across the population, and they differ, if at all, only in the effective installed base. Over the range of values used in our simulation,

$$\frac{\partial D^i}{\partial y_i} > 0 \quad \text{and} \quad \frac{\partial D^i}{\partial y_i \partial a} < 0. \quad (5\text{-}2)$$

Equation (5-2) implies the market exhibits positive demand externalities and the parameter a is a measure of the strength of the demand externalities. We explore the impact of demand externalities by varying the value of a: a small a corresponds to a situation with strong demand externalities and a large a to a situation with weak demand externalities. Equation (5-2) assumes that the product benefit function is the same when $y_i = y_j = 0$, no matter what the value of a, which means that markets with different strength of demand externalities have the same demand curve when the effective installed bases are zero. To explore the impact of installed base, we vary the size of the installed base of the incumbent at the time when the new entrant enters the market.

We assume that $B_i(x_i, x_j)$ is a linear function in cumulative sales volume:

$$B_i(x_i, x_j) = b_{i0} + b_{ii}x_i + b_{ij}x_j, \quad i, j = 1, 2, i \neq j, \quad (5\text{-}3)$$

where b_{i0} is referred to as the "coefficient of innovation"; b_{ii} and b_{ij} are referred to as "coefficients of imitation." We consider both zero and nonzero values for b_{ii} and b_{ij}. Where we have assumed an imitation effect, we set $b_{ii} > b_{ij}$ on the assumption that the firm's own cumulative sales have a stronger impact than the competitor's sales.

We assume the following marginal cost function:

$$C_i = c_{i0}(M_0 x_i)^{-k}, \quad i = 1, 2, \quad (5\text{-}4)$$

where c_{i0} is the cost of the first unit (which we will assume is the same for the two products), M_0 is the total market size, and k is the learning parameter.[6] Table 1 gives the parameter values used in the numerical investigation. These values were selected from the range of "typical" values found in Sultan et al. (1990).

Optimal solutions are derived over a finite horizon of 20 time periods. The resulting optimal price trajectory is calculated using the BVPFD subroutines from the IMSL library which solves two-point boundary value problems.

[6] While we investigated cases with and without learning effects ($k > 0$ and $k = 0$), the results presented below are all for $k = 0$. The assumption of learning effects did not change any of our conclusions.

Table 1 Parameter Values of Numerical Investigation

b_{i0}—innovation parameter	0.03
b_{ij}—cross-imitation parameter	0, 0.1
b_{ii}—imitation parameter	0, 0.033
$x_1(0)$—initial installed base of the first mover	0.0001, 0.1, 0.2
$x_2(0)$—initial installed base of the entrant	0.0001
a—parameter of exponential distribution	0.05, 0.25
v—parameter of exponential distribution	2
$c_{i0} = c_{j0} = c_0$—cost parameter	1.0, 2.0, 3.0
k_i—cost learning parameter	0, 0.05, 0.1
T—finite time horizon	20
M_0—size of population	100000

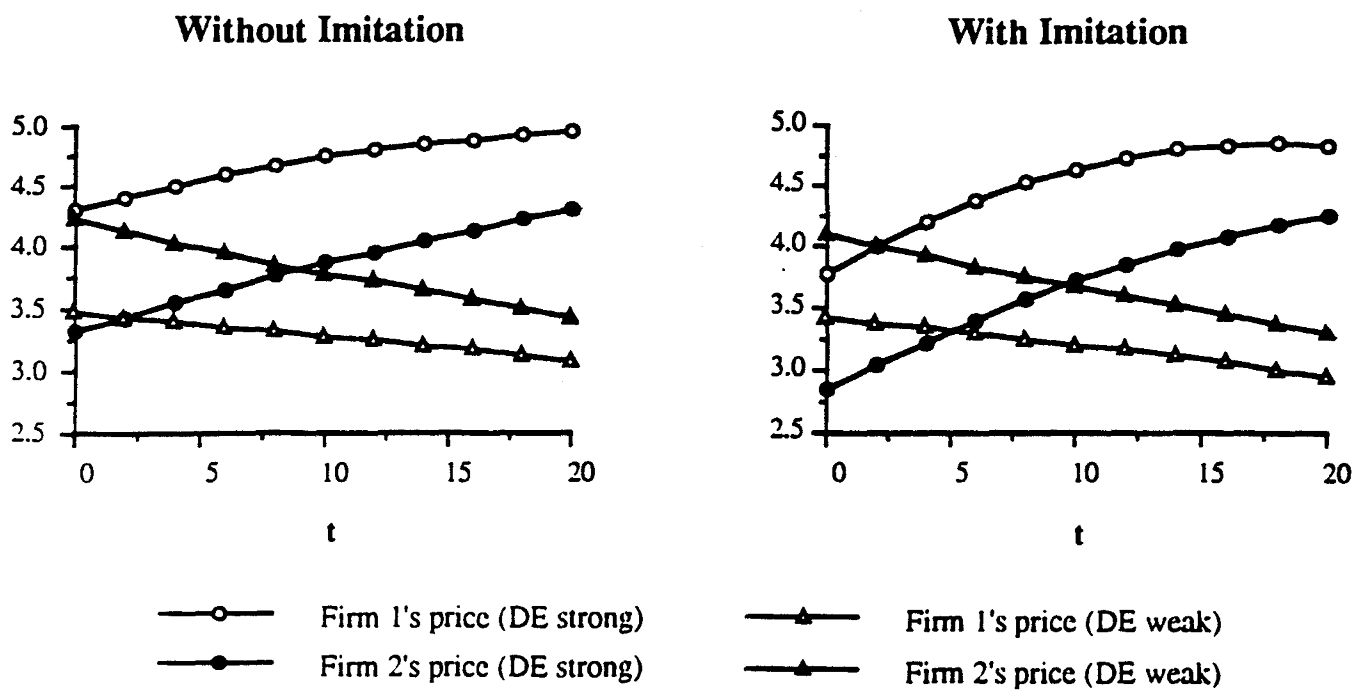
5.2. Discussion of Numerical Results

The Impact of Demand Externalities. To study the impact of demand externalities on optimal pricing and profitability in general, we look first at markets where the two products are not compatible. As in the monopoly case, when demand externalities are strong (Figure 2), the optimal duopoly pricing strategy is to gradually increase price over the time horizon or an increasing price followed by a decreasing price. This illustrates the positive effect of the installed base: the growth in the installed base substantially increases willingness to pay, allowing later buyers to be charged a higher price. When demand externalities are weaker, the installed base has very little effect on the potential demand. Thus, the optimal strategy is to start out pricing high, extracting surplus from those with higher willingness to pay, and then decreasing price monotonically over time.

Figure 3 summarizes the cumulative sales of the firms and the profits obtained by the two firms over the finite time horizon. From Figures 2 and 3, we see that when demand externalities are strong, the incumbent's price is much higher than the entrant's price, and its sales grow much faster than do the entrant's. As a result, the incumbent obtains much higher profits over the time period considered. These results indicate that strong demand externalities give the incumbent a significant advantage in profitability.

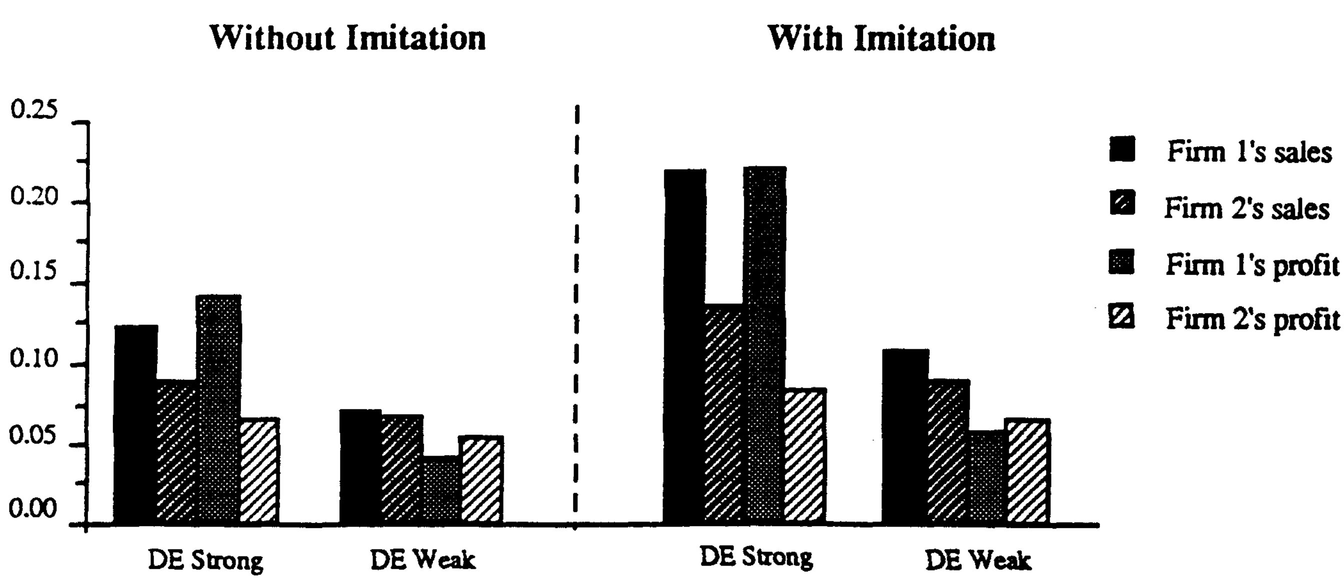
When demand externalities are weak, though the incumbent still grows faster, the entrant prices higher. As discussed above, when demand externalities are weak, a declining pricing policy is optimal. Since the population here is heterogeneous in the sense that each individual differs in the product benefits received from

Figure 2 Impact of Demand Externalities (DE)—Pricing Strategies ($x_1(0) = 0.1$, $c_0 = 2$)



the two products, and the product benefits are assumed to be independent, the appropriate price level of each product depends on its market penetration level. In a market with weak demand externalities, the entrant can, without fear of losing customers, start out with a high price to extract the maximum surplus from those users who receive a high benefit from its product, but a small benefit from the incumbent's product. For the incumbent, its larger installed base leads to the demand externality effect being dominated by the saturation effect.

Figure 3 Impact of Demand Externalities—Sales and Profits ($x_1(0) = 0.1$, $c_0 = 2$)



Accordingly, it is constrained in its pricing if it wishes to continue to grow. We have not examined the case in which the benefits each individual receives from the two products are positively dependent. We would expect that in that case, the incumbent would benefit more from demand externalities and, even with weak demand externalities, the entrant would be unable to price higher without losing customers to the incumbent.

From Figures 2 and 3 we see that adding an imitation effect does not change the basic conclusions discussed above. For a market with strong demand externalities, optimal pricing with imitation leads to a lower initial price and faster increases because of the contribution of imitation to the positive feedback from early sales. With imitation, prices are lower but adoptions are much quicker; as a result, firms obtain higher discounted profits and achieve greater penetration within the time horizon. In the rest of the analysis, we will consider only cases with a nonzero coefficient of imitation.

The Impact of Competition and Compatibility. We have shown in §3 that in a market with demand externalities, an incumbent may be better off or worse off to have a competitor than to continue to be a monopolist. The questions we want to answer here are: (1) Under what *conditions*, should an incumbent welcome a competitor and facilitate compatibility? (2) How do pricing strategies of an incumbent differ under monopoly versus duopoly? (3) How should pricing by an incumbent respond to a new entrant, and how should a new entrant price to successfully compete?

First, we compare optimal pricing strategies and profitability of the incumbent in the case where it is the only producer with the case where an entrant provides a partially differentiated product. We then compare pricing strategies and profitability of the incumbent and the new entrant in the cases with and without compatibility.

Figure 4 shows that the optimal pricing trajectories of the incumbent are similar in shape to the corresponding optimal monopoly pricing trajectories. The optimal pricing of the incumbent under monopoly is set at a higher level than that under incompatible duopoly, but at a lower level than under compatible duopoly.

Figure 5 compares the profits of the incumbent under monopoly, compatible duopoly, and incompatible

Figure 4 Impact of Duopolistic Competition—Pricing Strategies ($x_1(0) = 0.1$, $c_0 = 3$)

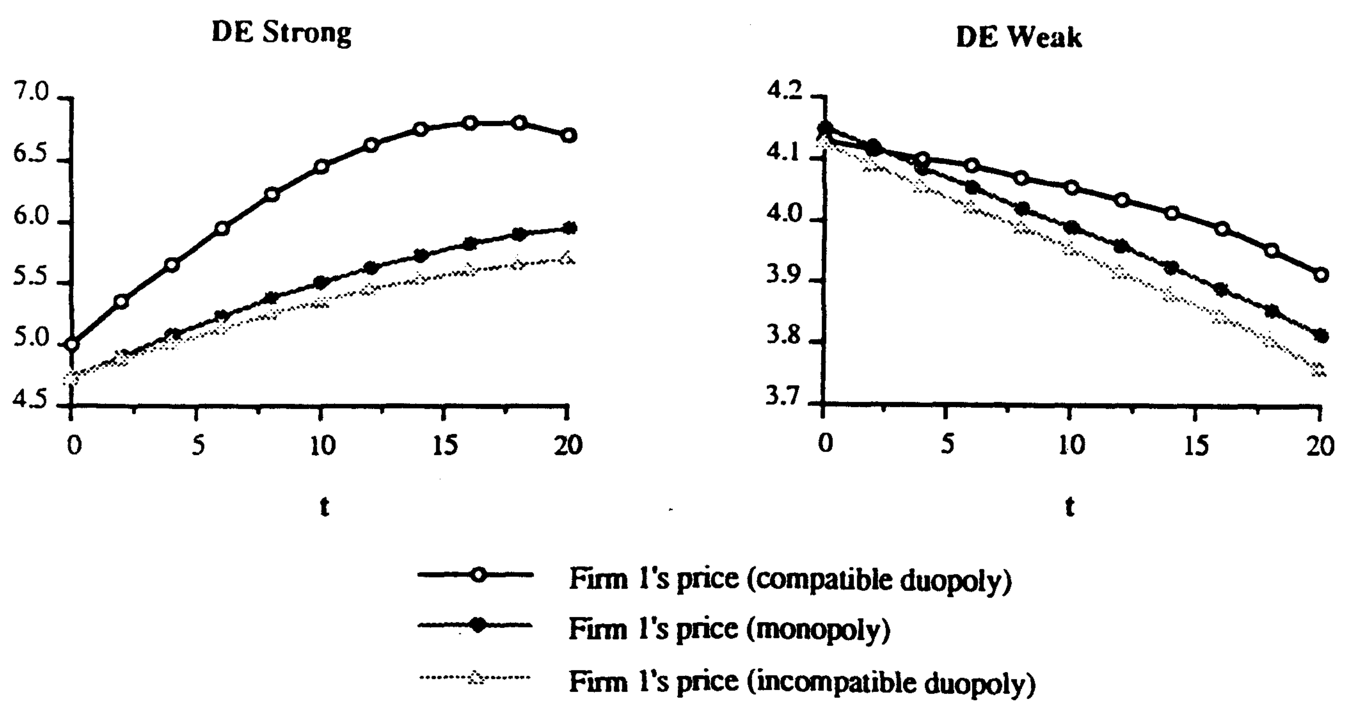
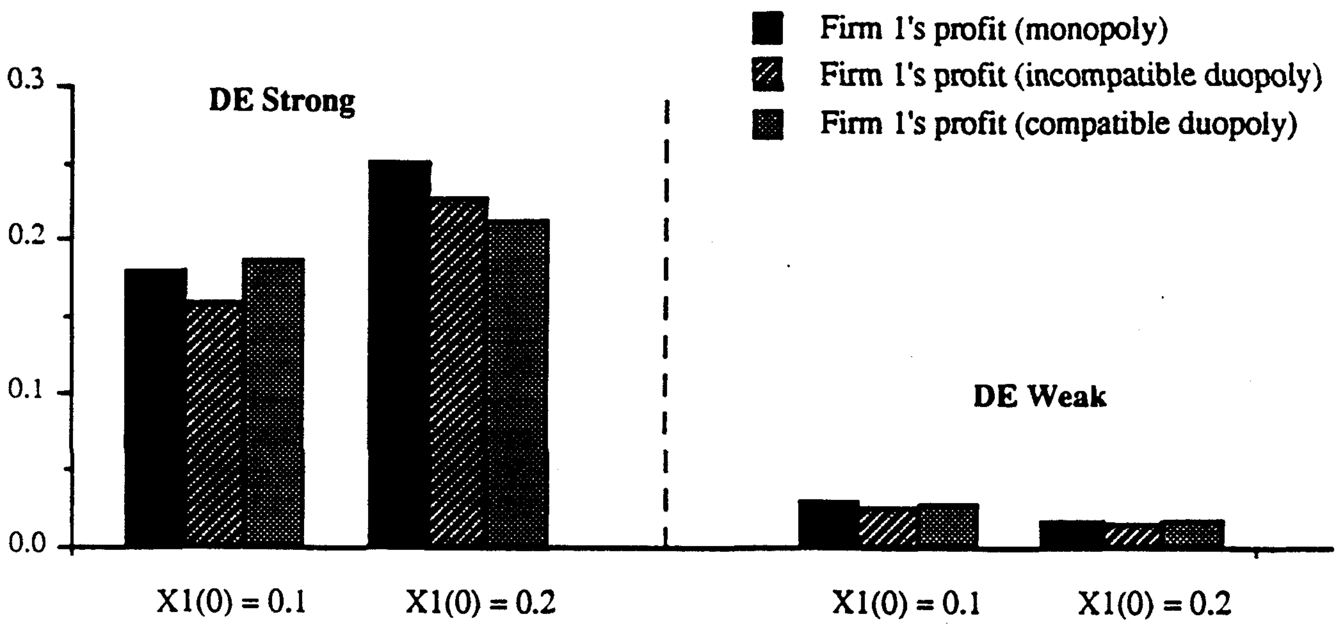


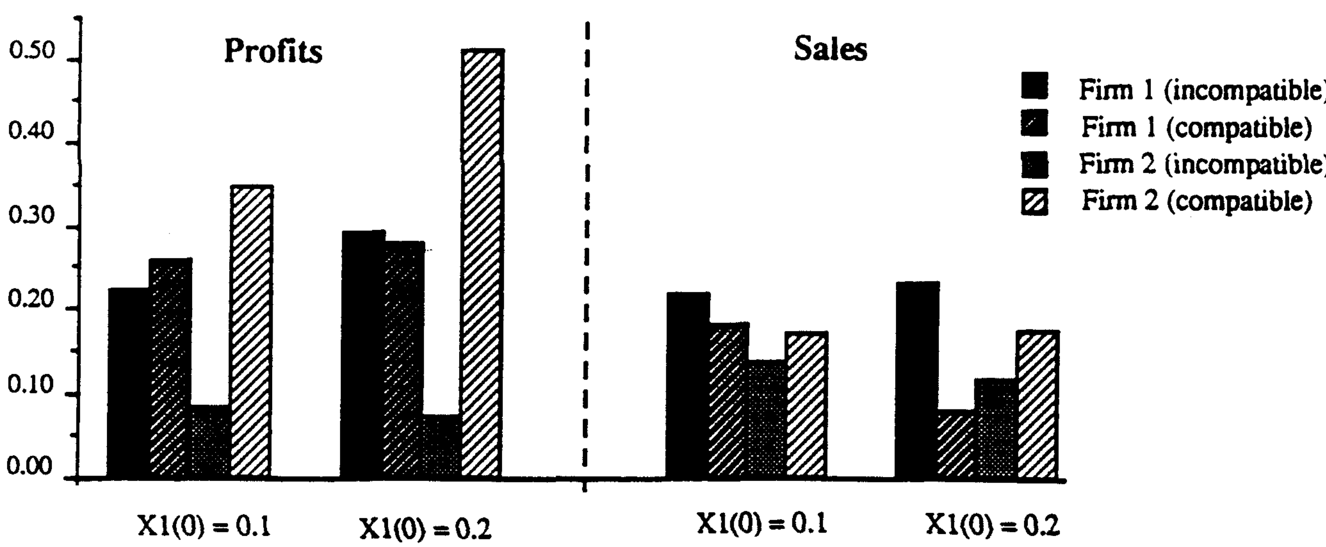
Figure 5 Impact of Duopolistic Competition—Profits (c_0 = 3)



duopoly for both strong and weak demand externalities. We find that when demand externalities are strong, the profit of firm 1 under monopoly is lower than under compatible duopoly for $x_1(0)$ = 0.1, but it is higher than under compatible duopoly for $x_1(0)$ = 0.2. The positive impact of competition on profitability resulting from compatibility may allow the incumbent to benefit from competition. However, when the incumbent's installed base is larger, it will gain less or even lose from having a new entrant. As for the case with weak demand externalities, the incumbent is better off under monopoly for both $x_1(0)$ = 0.1 and 0.2. This is because the weaker the demand externalities, the less benefit obtained from the compatible new entrant.

Is compatibility a good choice for the entrant? Figure 6 shows that the later entrant realizes a much higher

Figure 6 Impact of Compatibility—Profits and Sales (DE Strong, c_0 = 2)



profit when it is compatible with the incumbent than when it is not, especially when the initial installed base of the incumbent is large. Again, Figure 6 shows that when the initial installed base of the incumbent is small, the incumbent may also be better off agreeing on common standards ($x_1(0) = 0.1$). Since the larger the installed base of the incumbent the more relative advantage it gives up by agreeing to compatibility, the less is the incentive to support compatibility. The incumbent will suffer a pure loss from compatibility when its installed base is large enough ($x_1(0) = 0.2$). When demand externalities are strong, the incumbent grows faster if there is no compatibility than if there is. The entrant grows faster if it is compatible with the incumbent.

Figure 7 shows the firms' optimal pricing path under compatible and incompatible duopoly. One surprising result found here is that when products are compatible, the price of the later entrant is higher than that of the incumbent over the given time horizon. Again, this result can be explained by the balance of negative saturation effects and positive demand externalities coupled with the assumption of independence of product benefits.

6. Conclusions

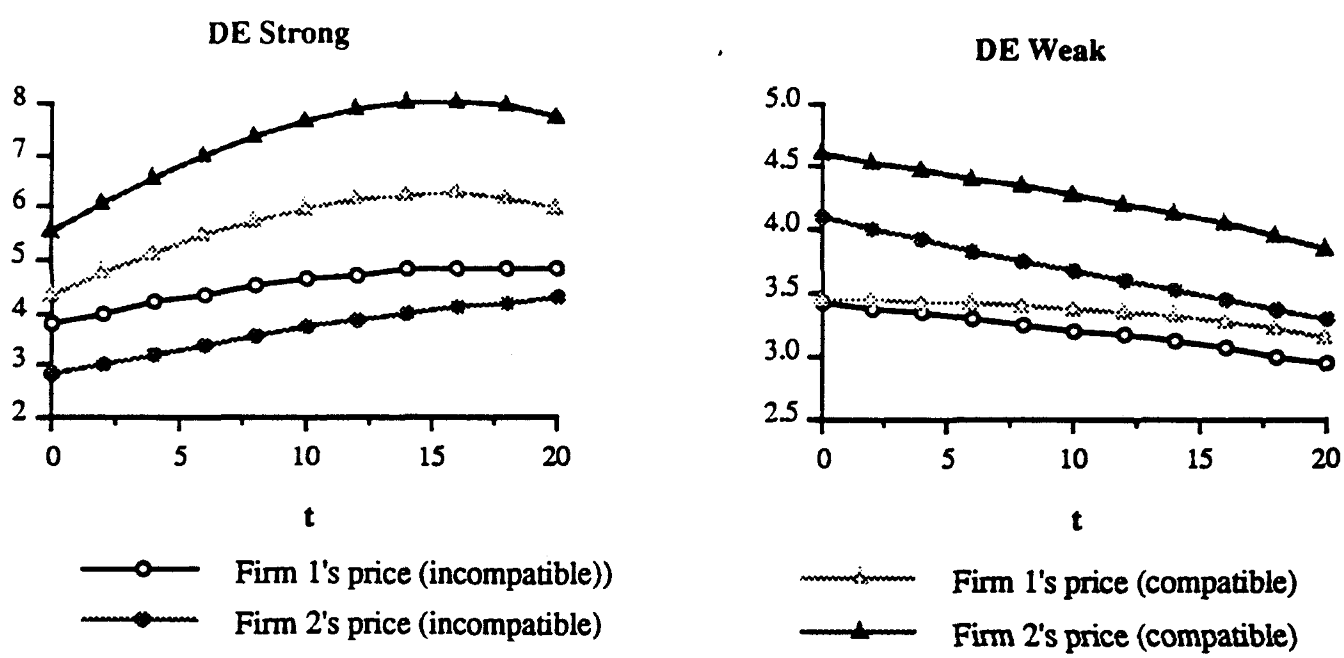
This paper examines new product markets where the consumption benefit increases with the number of other users consuming the same product. This property is an important feature of many industries, such as telecommunications and computers, where compatibility standards play an important role. This property is also a common characteristic in markets where there is uncertainty with regard to the product's experience attributes. We develop a model to incorporate the effect of demand externalities into a dynamic expression for duopolistic market potential, in which at any time, the market potential of each firm depends on the prices and installed bases of the two competing firms and the distribution of product benefit across the population. We examine optimal dynamic pricing and compatibility in the presence of demand externalities under duopolistic competition.

6.1. Summary of Results

Under very general assumptions about the nature of the demand function and the diffusion function we show that:

1. Since an entrant will provide an alternative for the

Figure 7 Impact of Compatibility—Pricing Strategies ($x_1(0) = 0.1$, $c_0 = 2$)



potential consumers of the incumbent's product, the incumbent will always prefer monopoly to incompatible duopoly. If the incumbent is joined by an entrant selling a compatible but partially differentiated product, the incumbent may realize greater profits than it would have realized had it continued as a monopolist offering a single product.

2. Compatibility increases the consumers' product benefit for both one's own product and for one's competitor's. In a symmetric duopoly market, both firms can obtain higher profits if they agree on a common standard.

By assuming a specific function form—an exponential—for the demand function, we are able to derive even stronger results. These are:

3. At each point of time, one of the firms may have the market power to guarantee that it will have a higher sales rate than its competitor no matter what its competitor's (positive) price. We show how to determine the existence of market power as a function of the installed bases, prices, diffusion parameters, and product benefit functions of the two competing firms.

4. In markets with strong demand externalities, under duopolistic competition (Nash equilibrium), the optimal pricing trajectories are similar in shape to the corresponding optimal monopoly pricing trajectories, i.e., gradually increasing prices over the time horizon or an increasing price followed by a decreasing price. The optimal price for a monopolist is higher than the price an incumbent would set when faced with an incompatible entrant, but lower than the incumbent should price when faced with a compatible entrant.

5. If a later entrant appears and the incumbent controls compatibility, the incumbent will be better off compared to incompatible duopoly—and even to monopoly—by permitting compatibility on the condition that entry occurs early in the product life cycle, but will be worse off if a substantial installed base exists.

6. If a later entrant appears, and if the entrant can choose to be compatible, the entrant will be better off making that choice—especially when demand externalities are strong and the installed base of the incumbent is large.

6.2. Business Implications

Typical new product introductions follow a pattern of a declining price trajectory designed to capture the surplus of progressively less eager consumers. For producers of products with significant positive demand externalities, the optimum strategy in these markets is to price low—even below cost—initially and raise price over time as consumer valuation of product benefit increases with the installed base. This is true under both monopoly and duopolistic competition. Successful utilization of such a strategy can be found in Apple's introductory pricing of the Macintosh and Xerox's introduction of facsimile machines (White 1973).

With respect to the issue of compatibility, the market for videoconferencing codecs provides one illustration of the issues presented in this analysis. Codecs are special purpose processors used in conjunction with conventional video cameras and monitors to reduce the bit rate of a video signal by several orders of magnitude in order to save on communications channel costs. Compatible codecs must be used at each end of the communications channel. The larger the installed base of codecs from one manufacturer, the more potential videoconferencing partners one can have, and therefore the greater the value to a potential buyer of acquiring a codec. In the last several years, developments in integrated circuits and signal processing algorithms have led to a new generation of codecs which can be used over dial-up ISDN (Integrated Services Digital Network) circuits. The market is dominated by Compression Labs and PictureTel, which sell incompatible codecs. The results of this study would suggest that, given that both are in the very early stages of market penetration, with roughly equal shares, they would be better off to agree to support a compatibility standard. In fact, the international telecommunications standardizing body, the CCITT, has promulgated such a standard, and both firms have agreed to provide upgrades to their products which will enable them to conform to the standard.

6.3. Suggestions for Future Research

Although the dynamic demand function we derived can be applied to both durable goods and network service markets, the study of optimal pricing policies in this work examines only the case of durable goods. In fact, the demand characteristic of positive demand externalities has received more attention in network services markets such as telecommunications. A crucial business decision for the network provider in a network services market is whether or not to agree to interconnect with the networks of other operators. For example, AT&T's refusal to interconnect with the independent telephone companies prior to the Kingsbury Commitment of 1913 played a crucial role in AT&T's dominance of the independent telephone companies (Gabel 1969). More recently, we have seen various electronic mail service vendors (Sprintmail, MCIMail, AT&T EasyMail) struggle with the decision of whether to interconnect in order to allow the subscribers of each of their networks to send mail to subscribers of the other networks (Schultz 1989). Since the models are similar, this should be a straightforward extension.

This research assumes that individuals make purchase decision and brand choice based on the current installed bases. It does not consider the impact of consumers' expectations of market growth on their decision. While we believe the assumption of myopic behavior may be more realistic than the assumption of perfectly fulfilled expectations used in other studies, clearly neither approach captures the reality of consumer decision making. Incorporating consumers' imperfect expectations would be an important extension but would greatly increase the complexity of the model.

A third direction for future research is to study the impact of varying degrees of product substitutability on the competitive dynamics.[7]

[7] Support for this work has been provided by a grant from Bell Communications Research. The authors wish to acknowledge many helpful discussions with David Braden, Dan Horsky, Steven Garber, Sridhar Moorthy, Benoit Morel, and Kannan Srinivasan.

References

Bass, F. M., "A New Product Growth for Model Consumer Durable," *Management Sci.*, 15, 5 (1969), 215–227.

——, "The Relationship Between Diffusion Rates, Experience Curves, and Demand Elasticities for Consumer Durable Technological Innovations," *J. Business*, 53, 2, part 2 (1980), 51–67.

Beggs, A. and P. Klemperer, "Multi-Period Competition with Switching Costs," *Econometrica*, 60, 3 (1992), 651–666.

Bolton, R., "The Robustness of Retail-Level Price Elasticity Estimates," *J. Retailing*, 65, 2 (1989), 193–219.

Cargill, C., *Information Technology Standardization: Theory, Process, and Organization*, Digital Press, 1989.

Clarke, F. H., M. N. Darrough, and J. Heineke, "Optimal Pricing Policy in the Presence of Experience Effects," *J. Business*, 55, 4 (1982), 517–530.

Clarke, D. G. and R. J. Dolan, "A Simulation Analysis of Alternative Pricing Strategies for Dynamic Environments," *J. Business*, 57 (1984), S179–S200.

Dhebar, A. and S. S. Oren, "Optimal Dynamic Pricing for Expanding Networks," *Marketing Sci.*, 4 (1985), 336–351.

—— and ——, "Dynamic Nonlinear Pricing in Networks with Interdependent Demand," *Oper. Res.*, 34, 3 (1986), 384–394.

Dockner, E., "Optimal Pricing in a Dynamic Duopoly Game Model," ZOR—*Zeitschrift fur Oper. Res.*, 29 (1985), B1–B16.

—— and S. Jørgensen, "Optimal Pricing Strategies for New Products in Dynamic Oligopolies," *Marketing Sci.*, 7, 4 (1988), 315–334.

Dolan, R. J. and A. P. Jeuland, "Experience Curves and Dynamic Demand Models: Implications for Optimal Pricing Strategies," *J. Marketing*, 45 (1981), 52–73.

Eliashberg, J. and R. Chatterjee, "Analytical Models of Competition with Implications for Marketing: Issues, Findings, and Outlook," *J. Marketing Res.*, 22 (1985), 237–261.

—— and A. P. Jeuland, "The Impact of Competitive Entry in a Developing Market upon Dynamic Pricing Strategies," *Marketing Sci.*, 5 (1986), 20–36.

Erickson, G. M., "Dynamic Pricing in Oligopolistic New Product Markets," Working Paper, University of Washington, 1983.

Evans, A., "Equalizing Grants for Public Transport Subsidy," *J. Transport Economics and Policy*, 19, 2 (1985), 105–138.

Farrell, J., "Standardization, Compatibility, and Innovation," *Rand J. Economics*, 1 (1985), 70–83.

—— and N. T. Gallini, "Second-Sourcing as a Commitment: Monopoly Incentives to Attract Competition," *Quarterly J. Economics*, 3, 4 (1988), 673–694.

—— and Garth Saloner, "Installed Base and Compatibility: Innovation, Product Preannouncements, and Predation," *American Economic Review*, 76 (1986), 940–955.

Feichtinger, G., "Optimal Pricing in a Diffusion Model with Concave Price-Dependent Market Potential," *Oper. Res. Letters*, 1 (1982), 236–240.

Friedman, J. W., *Oligopoly Theory*, Cambridge: Cambridge University Press, 1983.

Gabel, R., "The Early Competitive Era in Telephone Communications, 1893–1920," *Law and Contemporary Problems*, 34 (1969), 340–359.

Gaugusch, J., "The Non-Cooperative Solution of a Differential Game: Advertising Versus Pricing," *Optimal Control Applications and Methods*, 5 (1984), 353–360.

Jain, D. C. and R. C. Rao, "Effect of Price on the Demand for Durables: Modeling, Estimation and Findings," *J. Business and Economic Statistics*, 8, 2 (1990), 163–170.

Jørgensen, S., "Optimal Control of a Diffusion Model of New Product Acceptance with Price-Dependent Total Market Potential," *Optimal Control Applications and Methods*, 4 (1983), 269–276.

——, "Optimal Dynamic Pricing in an Oligopolistic Market: A Survey," in Dynamic Games and Applications in Economics, T. Basar (ed.), *Springer Lecture Notes in Economics and Mathematical Systems*, 265, 1986, 179–237.

Jeuland, A. P. and R. J. Dolan, "An Aspect of New Product Planning: Dynamic Pricing," in A. A. Zoltners (Ed.), *Marketing Planning Models*, North-Holland, Amsterdam, 1982.

Katz, M. L. and C. Shapiro, "Network Externalities, Competition, and

Compatibility," *The American Economic Review*, 75, 3 (1985), 424–440.

—— and ——, "Technology Adoption in the Presence of Network Externalities," *J. Political Economy*, 94 (1986), 822–841.

—— and ——, "Product Introduction with Network Externalities," *J. Industrial Economics*, March (1992), 55–83.

Kalish, S., "Monopolist Pricing with Dynamic Demand and Production Cost," *Marketing Sci.*, 2 (1983), 135–159.

——, "A New Product Adoption Model with Price, Advertising and Uncertainty," *Management Sci.*, 31 (1985), 1569–1585.

Lilien, G. L. and P. Kotler, *Marketing Decision Making: A Model-Building Approach*, Harper & Row, New York, 1983.

Mahajan, V., E. Muller, and F. M. Bass, "New Product Diffusion Models in Marketing: A Review and Directions for Research," *J. Marketing*, 54 (1990), 1–26.

Nascimento, F. and W. R. Vanhonacker, "Strategic Pricing of Differentiated Consumer Durables in a Dynamic Duopoly," Working Paper, Marketing Department, Columbia Business School, 1987.

Rao, R. C. and F. M. Bass, "Competition, Strategy, and Price Dynamics: A Theoretical and Empirical Investigation," *J. Marketing Res.*, Vol. XXII (1985), 283–296.

Robinson, B. and C. Lakhani, "Dynamic Price Models for New-Product Planning," *Management Sci.*, 21 (1975), 1113–1122.

Rohlfs, J., "A Theory of Interdependent Demand for a Communications Service," *Bell J. Economics* (1974), 16–36.

Schultz, B., "AT&T, MCI, Telenet Offer E-MAIL Links," *Communications Week*, May 8 (1989), 9.

Sultan, F., J. U. Farley, and D. R. Lehmann, "A Meta-Analysis of Applications of Diffusion Models," *J. Marketing Res.*, 27 (1990), 70–77.

Thompson, G. L. and J. Teng, "Optimal Pricing and Advertising Policies for New Product Oligopoly Models," *Marketing Sci.*, 3 (1984), 148–168.

White, G., "The Facsimile Industry—Principles & Prospects," Presented at the Executive Forum, Jerusalem Institute of Management, April (1976).

Accepted by Abraham Seidmann; received May 1992. This paper has been with the authors 7 months for 2 revisions.