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The diffusion of a durable embodied capital innovation

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Abstract

This paper shows that some important results of the literature on the diffusion of innovations may change in a significant way when it is simultaneously considered that (i) there are costs of producing the innovation and (ii) the potential adopters' demands are interdependent.

Keywords: Durable goods monopolist; Diffusion of innovations; Technological policy; Interdependent demands

JEL classification: D42; O38

1. Introduction

This paper considers a monopolist (patenter) that produces a durable embodied capital innovation at some cost and sells it to other firms whose demands for the innovation are interdependent (i.e., the value of the innovation to one firm depends upon the number of other firms which also adopt it). Under these circumstances, it is shown that the conclusions of the literature with regard to the implications that different methods of selling the innovation (e.g., auction or fixed-fee) have for adoption levels, consumer surplus and welfare, as well as the effects that public intervention has on the processes of adopting innovations, may both change in significant ways. The simultaneous consideration of interdependent demands for a durable innovation and the costs of producing the units of that innovation is the main contribution this study makes to these literatures.

Katz and Shapiro (1986) show that if the potential adopters' demands are interdependent, then the patenter prefers the auction method to the fixed-fee method. However, Kamien and Tauman (1986) show that while this is true, consumers are better off under the fixed-fee strategy. In this paper, it is shown that if there are costs of producing the innovation, this last conclusion may change. In fact, the adoption levels, and therefore consumer surplus, may be greater when the innovation is sold by means of an auction method.

It is also well-known in the literature that when a monopolist sells an innovation, the diffusion path is different, in general, than the diffusion path that is optimal from the social point of view. This fact

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has prompted some economists to consider public intervention as a means to attain the social optimum. However, the theoretical literature on the effects of public intervention in the diffusion process of innovations has not considered the case in which the potential adopters' demands are interdependent. This paper shows that this interdependence may play an important role, insofar as it implies that the socially optimal diffusion path may be achieved through taxes, rather than the subsidies that previous studies have indicated are required (see, e.g., Ireland and Stoneman, 1986; Saracho and Usategui, 1994).

Finally, the literature (e.g., Bulow, 1982) has also emphasized that, fundamentally, it is the distinction between the renter and the seller (or the seller who can commit and the one who cannot) that makes the problem of a durable goods monopolist interesting. This distinction has generated many studies that compare different issues (e.g., sales and welfare) under these two situations. Kahn (1986), for example, shows that social welfare is greater if the monopolist cannot commit to a future schedule of production; others have found the opposite to be true. This paper suggests a new situation, namely the interdependence of potential adopters' demands in the presence of costs of producing an innovation, in which social welfare may be greater when the monopolist can commit than when he cannot.

2. The model

In this section we analyze a related version of the model of Kamien and Tauman (1986). Consider a discrete two-period framework ($t = 1,2$) and an industry consisting of $N > 1$ identical firms. The industry produces a homogeneous good with constant marginal cost, $c > 0$. The inverse demand function for this good is given by $P = a - bX$, where a,b are positive constants, $a > c$, and X is the aggregate quantity produced. In addition to this industry, there is a monopolist (patenter) who produces a durable embodied capital innovation. Firms have perfect information and perfect foresight and may use the innovation in both periods with no depreciation. The innovation reduces each firm's marginal cost from c to $c - \varepsilon$. The marginal cost of producing the innovation in period t, c_t, is constant, but it decreases over time (that is, $c_1 > (1 + v)c_2$, where v is the discount factor).[1]

Following Kamien and Tauman (1986), the interaction between the monopolist, the N firms and their market is characterized, in each period, by the following three stage game. In the first stage, the monopolist sets either an innovation fee or the number of units to be auctioned. In the second stage, each firm decides independently and simultaneously whether or not to buy one unit of the new equipment.[2] In the final stage, all of the firms engage in a quantity competition game.[3] Kamien and Tauman (1986) and Katz and Shapiro (1986) show that in a static context, given a number of licenses K, the license fee (P^F) and/or the bid paid (P^A) are equal to the incremental profit of being a licensee, in equilibrium. That is, $P^F = e^F - f^F K$ and $P^A = e^A - f^A K$, where

[1] This assumption is a necessary condition in order for the efficient adoption level to increase over time. It may be explained by the existence of exogenous technological progress.

[2] The adoption levels must be integers. All of the results that are obtained in this paper do not depend upon this restriction, however. Numerical examples are available from the author upon request.

[3] If $(a - c) < \varepsilon N$, then, at some point, the firms which had not yet adopted the innovation might be driven out of the market. Without loss of generality, we shall assume that $(a - c) \geq \varepsilon N$ and, therefore, all of the firms remain active.

$$e^{\mathrm{F}} = \frac{\varepsilon N[2(a - c + \varepsilon) + \varepsilon N]}{b(N + 1)^2}, \quad f^{\mathrm{F}} = \frac{2\varepsilon^2 N}{b(N + 1)^2}, \tag{1F}$$

$$e^{\mathrm{A}} = \frac{\varepsilon[2(a - c) + \varepsilon(N + 1)]}{b(N + 1)}, \quad f^{\mathrm{A}} = \frac{2\varepsilon^2}{b(N + 1)}. \tag{1A}$$

Denote by K_1^{i} the adoption level at time $t = 1$ and K_2^{i} the final cumulative adoption level (i.e., the sum of adoption levels at time $t = 1$ and $t = 2$), where i = F represents the case in which the innovation is sold at a fixed-fee and i = A the case in which it is sold by means of an auction method. In this model, therefore, the license fees and/or bids paid in equilibrium (i.e., P_t^{i} with $t = 1,2$ and i = F,A) must satisfy $P_1^{\mathrm{i}} - vP_2^{\mathrm{i}} = e^{\mathrm{i}} - f^{\mathrm{i}}K_1^{\mathrm{i}}$ and $P_2^{\mathrm{i}} = e^{\mathrm{i}} - f^{\mathrm{i}}K_2^{\mathrm{i}}$, where e^{i}, f^{i}, with i = F,A, are those from (1F) and (1A). Note that if the monopolist cannot commit to a future schedule of production, then the durable goods monopoly problem of Bulow (1982) arises and the model must be solved by backward induction. The monopolist will sequentially solve the following problems:

Find at $t = 2$, given K_1^{i}, the $K_2^{\mathrm{i}}(K_1^{\mathrm{i}})$ that maximizes $(e^{\mathrm{i}} - f^{\mathrm{i}}K_2^{\mathrm{i}} - c_2)(K_2 - K_1^{\mathrm{i}})$; and then find at $t = 1$, the K_1^{i} that maximizes $[e^{\mathrm{i}} - f^{\mathrm{i}}K_1^{\mathrm{i}} + v(e^{\mathrm{i}} - f^{\mathrm{i}}K_2^{\mathrm{i}}(K_1^{\mathrm{i}})) - c_1]K_1^{\mathrm{i}} + v[e^{\mathrm{i}} - f^{\mathrm{i}}K_2^{\mathrm{i}}(K_1^{\mathrm{i}}) - c_2][K_2^{\mathrm{i}}(K_1^{\mathrm{i}}) - K_1^{\mathrm{i}}]$.

The interior solutions to this problem are:[4]

$$K_1^{\mathrm{i}*} = \frac{2(e^{\mathrm{i}} - c_1 + vc_2)}{f^{\mathrm{i}}(4 + v)}, \quad K_2^{\mathrm{i}*} = \frac{(6 + v)e^{\mathrm{i}} - 2c_1 - (4 - v)c_2}{2f^{\mathrm{i}}(4 + v)}. \tag{1}$$

The resolution of this model gives rise to three main results:

Result 1. The adoption levels, and therefore total consumer surplus, may be greater under an auction strategy than under a fixed-fee strategy.

The adoption levels obviously depend on the method by which the innovation is sold. Substituting (1F) and (1A) into (1), it is clear that $K_1^{\mathrm{A}*} < K_1^{\mathrm{F}*}$ implies $(c_1 - vc_2)b(N + 1) < N\varepsilon^2$, and $K_2^{\mathrm{A}*} < K_2^{\mathrm{F}*}$ implies $[2c_1 + (4 - v)c_2]b(N + 1) < (6 + v)N\varepsilon^2$; therefore, $K_1^{\mathrm{A}*}$ and/or $K_2^{\mathrm{A}*}$ can be greater than $K_1^{\mathrm{F}*}$ and $K_2^{\mathrm{F}*}$, respectively.[5] It can be shown that this result is maintained in more general frameworks, as, for example, the continuous-time framework of Quirmbach (1986). The economic intuition behind this finding is that the marginal revenue functions under the two different sale methods may cross for adoption levels smaller than N, since given an adoption level less than N: (a) the price paid for the innovation is bigger if the method of selling is the auction (Katz and Shapiro, 1986); and (b) with the auction strategy, the demand for the innovation is more inelastic. Furthermore, the use of the innovation by the firms increases the total output of the industry. The greater are the adoption levels, the larger is this increase. We thus conclude that, in contrast to the findings of Kamien and Tauman (1986), consumers may prefer the innovation to be sold by means of an auction rather than for a fixed-fee.

[4] The consideration of corner solutions ($K_1 = 0$ or $K_2 = N$) does not generate additional results.

[5] An example is: $P = 800 - 13X$, $v = 1$, $N = 15$, $c = 40$, $c_1 = 250$, $c_2 = 120$, $\varepsilon = 18$; then, $K_1^{\mathrm{F}*} = 2.48$, $K_2^{\mathrm{F}*} = 6.06$ and $K_1^{\mathrm{A}*} = 3.40$, $K_2^{\mathrm{A}*} = 7.55$.

Result 2. The socially optimal diffusion process may be achieved, on occasion, by means of taxes.

From the social point of view, two relevant questions are the following: Are successful innovations disseminated to the socially optimal extent? If not, may public interventions help implement the optimal social welfare schedule?

Social welfare is defined as the consumer surplus plus the gross profits of the industry (gross of the price paid by the innovation), minus the cost of producing it. Obviously, if there were no costs of producing the innovation, it would be socially desirable that all firms adopt it in the first period. In this model, the optimal adoption levels from the social point of view, K_t^{W*}, are:

$$K_t^{W*} = \max\left\{0, \min\left[\frac{(a-c)(N+2)\varepsilon + \varepsilon^2(N+1)^2 - b(c_t - vc_{t+1})(N+1)^2}{\varepsilon^2(3+2N)}, N\right]\right\}, \text{ where } c_3 = 0, \tag{2}$$

Substituting (1F) and (1A) into (1) and comparing it with (2), it can be seen that adoption levels under either method do not coincide, in general, with the optimal diffusion schedule. More precisely, the set $\{K_t^{j*}\}$, j=F,A,W, and $t=1,2$, does not maintain the same order in all circumstances. Hence, it is straightforward to conclude that selling an innovation by means of an auction instead of a fixed-fee method is not necessarily inferior, from the social point of view. Also, it is well-known in the literature that firms are made worse off on account of the innovation and consumers are made better off. These two effects are ignored by the seller, and, in the presence of costs of producing the innovation, they imply that the adoption levels may be larger or smaller than the optimal ones.[6] As a result, public intervention might help implement the best scheme.

Now consider the case when each adopter of the innovation in period t receives a fixed quantity subsidy $D_t>0$ (or pays a lump sum tax, i.e. $D_t<0$). Under this public intervention, the license fees and/or bids paid in equilibrium (denoted by $P_t^{i,D}$, with i=F,A) must satisfy $P_1^{i,D} - D_1 - v(P_2^{i,D} - D_2) = e^i - f^i K_1^i$ and $P_2^i - D_2 = e^i - f^i K_2^i$. Hence, the adoption levels ($K_t^{i,D*}$) are:

$$K_1^{i,D*} = K_1^{i*} + \frac{2(D_1 - vD_2)}{f^i(4+v)}, \text{ and } K_2^{i,D*} = K_2^{i*} + \frac{2D_1 + (4-v)D_2}{2f^i(4+v)}.$$

Therefore, if $D_t>0$, with $t=1, 2$, then $K_2^{i,D*} > K_2^{i*}$. Given that K_2^{i*} may be bigger than K_2^{W*}, as shown above, we conclude that efficient adoption levels may be achieved by means of lump sum taxes.[7]

Result 3. If the monopolist can establish a credible commitment, there may not be any loss in social welfare.

[6] Social welfare may even be below what it was before the introduction of the innovation. A numerical example can be found in footnote 5.

[7] A numerical example is: $P=800-6X$, $v=1$, $N=15$, $c=125$, $c_1=350$, $c_2=170$, $\varepsilon=34$. In this situation, $D_1=-63.84$, $D_2=-209.69$ would implement the efficient adoption levels in the case of fixed-fee, and $D_1=-67.15$, $D_2=-222.91$ in the case of auction.

A well-known result in the literature is that if the monopolist could commit to a future schedule of production, he would choose the same adoption levels as in the rental case. Let $K_t^{i,R}$ denote the adoption level at time t under sale method i, when the monopolist rents the innovation. The renter's problem is

$$\max_{\{K_1^i,K_2^i\}} [e^i - f^iK_1^i + v(e^i - f^iK_2^i) - c_1]K_1^i + v(e^i - f^iK_2^i - c_2)(K_2^i - K_1^i),$$

which solves to

$$K_1^{i,R} = \frac{e_i - c_1 + vc_2}{2f^i}, \quad K_2^{i,R} = \frac{e^i - c_2}{2f^i}.$$

Comparing the welfare under both regimes, it is possible to conclude that when the monopolist can commit to a future schedule, social welfare is not necessarily reduced.[8] More precisely, the following proposition can be proved:

Proposition. If (i) the demand for the innovation is linear and invariant over time, (ii) $c_1>(1+v)c_2$ *(i.e., it is socially optimal that there is diffusion over time), and (iii) social welfare when the monopolist can commit is larger than when he cannot, then the potential adopters' demands are interdependent.*

Proof. Suppose that the value of the innovation to each potential adopter is independent of the number of adopters.[9] Let $e-fK_t$ be the inverse demand function for the innovation, and let $W(K_1^R,K_2^R)$ be the social welfare if the monopolist can commit and $W(K_1^*,K_2^*)$ if he cannot. Social welfare is defined as the sum of the present discounted value of the potential adopters' surplus and the patenter's revenues, minus the cost of producing the innovation. Therefore,

$$\begin{aligned} W(K_1^*,K_2^*) - W(K_1^R,K_2^R) &= \left[e - c_1 + vc_2 - \frac{f(K_1^* + K_1^R)}{2}\right](K_1^* - K_1^R) \\ &\quad + v\left[e - c_2 - \frac{f(K_2^* + K_2^R)}{2}\right](K_2^* - K_2^R) \\ &= v(e - c_1 + vc_2)\left[\frac{(e - c_2)}{2(4+v)f} - \frac{(e - c_1 + vc_2)(12 + 3v)}{(32 + 8v)(4 + v)f}\right], \end{aligned}$$

which, since $c_1>(1+v)c_2$, implies that $W(K_1^*,K_2^*)-W(K_1^R,K_2^R)>0$. □

[8] A numerical example is the one given in footnote 7. In that situation, if the monopolist could establish a credible commitment, then social welfare would be 78 602.79 (and 78 390.50, otherwise) in the case of fixed-fee and 78 602.61 (and 78 392.17, otherwise) in the case of auction.

[9] This assumption implies that both methods (auction and fixed-fee) generate the same prices, adoption levels and social welfare. Furthermore, this assumption may be more appropriate in the case of product innovation, where the potential adopters are consumers, than in process innovation. If the potential adopters are firms, it is enough to assume that buyers come from a number of different industries and make up a small part of any one industry, therefore having negligible effects on consumers, had they adopted the innovation (Ireland and Stoneman, 1986).

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