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THE TIMING OF NEW TECHNOLOGY ADOPTION: THEORETICAL MODELS AND EMPIRICAL EVIDENCE

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This paper surveys the theoretical literature on the timing of new technology adoption. It presents the state of the art as it falls into two major categories, depending on whether the particular model deals with uncertainty regarding the arrival and value of a new technology and/or strategic interaction in the product market. Empirical evidence is reviewed, and recommendations are given for future research.

1 INTRODUCTION

The timing and nature of new technology adoption are fundamental issues in the understanding of firm performance, competitiveness and productivity growth. Krugman (1994), for instance, attributes the slowdown in the US productivity growth in the early 1970s, among other reasons, to the long time lag between the generation and the proper exploitation of a new set of technologies. Similarly, recent empirical research for ten OECD countries suggests that technology diffusion has contributed substantially to total factor productivity (TFP) growth, and that the purchase of new technology has typically more impact on TFP growth than direct research and development (R&D) spending (OECD, 1996).

There are two commonly observed empirical regularities or 'stylized facts' of new technology adoption. First, the adoption of new technology is in general anything but instantaneous, or, as expressed by Schumpeter, 'we see all around us in real life faulty ropes instead of steel hawsers, defective draught animals instead of show breed, the most primitive hand labor instead of perfect machines' (1934, pp. 14–15). A prominent example of the initial delay in adoption is the basic oxygen furnace (BOF), a major technical breakthrough in the process of steel-making. This technology was developed in 1949, but the first major producer in the US steel industry waited until 1964 to adopt it. In 1968 only 12.2 per cent of the US steel capacity made use of the BOF. Only by 1980 had this figure risen to 80 per cent, indicating the general profitability of adopting the BOF (see Oster, 1982; Sumrall, 1982). Second, once initial adoption occurs, the

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inter-firm diffusion path tends to be S-shaped, i.e. some firms adopt early and others late, with an accelerating adoption process initially followed by a decelerating process when most firms have adopted (see, for example, Griliches, 1957; Mansfield, 1961, 1968).

This paper surveys the theoretical research that is concerned with the first stylized fact of new technology adoption. The aim is to identify some robust principles of the initial delay in the adoption of new technology, and thus to gain a better understanding of how the diffusion process starts. It updates earlier surveys of the adoption and diffusion literature (Tirole, 1988; Reinganum, 1989; Beath *et al.*, 1995; Karshenas and Stoneman, 1995) and synthesizes them on this theme. For a recent review of the literature on the second stylized fact, i.e. the S-shaped diffusion curve, see Geroski (2000).[1] The present paper puts a special emphasis on the relevant models that have been amended in the past few years and on some of those amendments in order to give both an introduction to this line of research and an idea of how the literature might be usefully extended in the future.[2]

The theoretical models of adoption timing can be classified according to the differences in the factors which provide the particular focus of analysis. Table 1 presents the state of the art in the field as it falls into two major categories, depending on whether the particular model deals with uncertainty regarding the arrival and value of a new technology and/or strategic interaction in the product market. The top-left corner of Table 1 includes theoretical models of adoption timing that abstract from both aspects, rivalry and uncertainty about the technology's arrival date and value. These studies stress other factors that influence the timing of adoption. The observed delay in the adoption of new technology could be due to the interaction of demand-side and supply-side forces. For example, expected reductions in the supplier's cost of producing a new technology may delay adoption (Stoneman and Ireland, 1983; Ireland and Stoneman, 1986).[3] Jovanovic and Lach (1989) emphasize learning-by-doing effects that reduce the variable costs of production. These effects lower the benefits of switching to a new technology and hence may create a barrier to adoption.[4] Chari and Hopenhayn (1991) develop a vintage human capital model in which each technology requires vintage-specific skills.

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[1] For a survey of the theoretical literature on R&D, see Kamien and Schwartz (1982) and Beath *et al.* (1995).

[2] There is hence some partial overlap between this survey and some of the earlier ones with respect to the seminal contributions on adoption timing. The overlap is limited, however, to the minimal extent that is required for a good understanding of the recent extensions and amendments.

[3] For a discussion of the role of expectations concerning the future rate of technological change, see Rosenberg (1976).

[4] Related is the work by Jovanovic and Nyarko (1996) and Karp and Lee (2000).

Table 1
A Classification of Theoretical Models

Interaction in the product market	*Arrival and value of new technology*	
	Certain	*Uncertain*
Non-strategic	Stoneman and Ireland (1983) Farrell and Saloner (1985) Ireland and Stoneman (1986) Jovanovic and Lach (1989) Chari and Hopenhayn (1991) Götz (1999)	Jensen (1982, 1988a, 1988b) Balcer and Lippman (1984) Bhattacharya *et al.* (1986) McCardle (1985) Chatterjee and Eliashberg (1990) Mariotti (1992) Weiss (1994) Kapur (1995) Farzin *et al.* (1998) Vettas (1998) Doraszelski (2000a, 2000b) Thijssen *et al.* (2000) Alvarez and Stenbacka (2001)
Strategic	Reinganum (1981a, 1981b) Fudenberg and Tirole (1985) Hendricks (1992) Riordan (1992) Riordan and Salant (1994) Dutta *et al.* (1995) Hoppe and Lehmann-Grube (2001a, 2001b)	Jensen (1992a) Lippman and Mamer (1993) Stenbacka and Tombak (1994) Bergemann and Välimäki (1997) Boyer *et al.* (1998) Décamps and Mariotti (1999) Götz (2000) Hoppe (2000a, 2000b) Huisman and Kort (2000)

They find that such specificities lead to a slow diffusion of technologies into use. In the presence of network externalities, the value of adopting depends positively on the number of other adopters (Farrell and Saloner, 1985). Hence each firm may have an incentive to wait until more eager firms have adopted the new technology. Götz (1999) analyses adoption and diffusion in a market for a differentiated product with monopolistic competition. Strategic interaction among firms is ruled out by assuming that the actions of a single firm do not affect the payoffs of the other firms. His model predicts a positive relation between firm size and the speed of adoption.

The approaches included in the top-right and bottom-left corners of Table 1 focus solely on either uncertainty in the adoption process or strategic interaction among competing firms. These models will be described in Section 2 and Section 3, respectively. Finally, the bottom-right corner of Table 1 includes approaches that attempt to deal with both phenomena, uncertainty and rivalry. Section 4 will consider these models. Recent empirical evidence on adoption timing is reviewed in Section 5. Section 6 concludes with some recommendations for future research.

2 UNCERTAIN PROFITABILITY OF ADOPTION

This section reviews theoretical models of adoption timing in which the critical factor of the firms' adoption behaviour is uncertainty about the profitability of a new technology or the rate of technological progress. The predictions of the studies can be summarized as follows. In the presence of uncertainty, the expected post-adoption profit depends on the belief that the adoption of the new technology is profitable. A firm will find it optimal to adopt if and only if the current estimate of the likelihood that the innovation is profitable exceeds a reservation level and if it is not more profitable to wait for new information or the arrival of better technology. That is, uncertainty about the value of a new technology reduces or increases a firm's adoption incentive at any date, depending on whether beliefs are pessimistic or optimistic, whereas the possibility of resolving uncertainty over time by collecting information about the unknown value or the arrival of better technology unambiguously introduces an incentive to delay adoption. The uncertainty may also be reduced by observing the experience of other adopters, which generates an incentive to wait until another firm moves first.

2.1 Information Acquisition and Technological Progress

The seminal contribution on adoption timing under uncertainty is the work of Jensen (1982). He considers a decision-theoretic model in which a firm is confronted by a new technology and must decide if and when to adopt. The model assumes that the firm is unable to estimate the value of a new technology with certainty. The present discounted value of the future stream of revenues resulting from adoption is R_1 with probability $\theta \in [0, 1]$, and R_0 with probability $1 - \theta$, where $R_0 < R_1$. The true value of θ is unknown but can take only one of two states, θ_1 and θ_0, where $0 < \theta_0 < \theta_1 < 1$. It is further assumed that $\theta_0 R_1 + (1 - \theta_0) R_0 - K < 0 < \theta_1 R_1 + (1 - \theta_1) R_0 - K$, where $K > 0$ denotes the fixed cost of adoption. The adoption of the new technology is hence profitable (i.e. a success) if $\theta = \theta_1$ and unprofitable (i.e. a failure) if $\theta = \theta_0$.

The firm starts with a subjective prior estimate of probability $g \in [0, 1]$ that $\theta = \theta_1$. By waiting the firm learns about the profitability of adoption. That is, it observes a sequence of signals $Z_1, \ldots, Z_n$ which are assumed to be independent and identically distributed, where $Z = 1$ if the signal is favourable to the innovation and $Z = 0$ if not. The observations are used to update the firm's belief about the technology's value in a Bayesian fashion.[5] After n observations, k of which were favourable, the firm's posterior belief that $\theta = \theta_1$ is hence given by

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[5] See, for example, DeGroot (1970, Ch. 2).

$$p(\theta_1 \mid n, k, g) = \left[1 + \left(\frac{\theta_0}{\theta_1}\right)^k \left(\frac{1-\theta_0}{1-\theta_1}\right)^{n-k} \frac{1-g}{g}\right]^{-1}$$

At each point in time, the firm may choose to stop information accumulation and adopt the new technology, or it may continue to gather information.[6] Let $V^{\mathrm{A}}(\cdot)$ denote the expected value from adoption and $V^{\mathrm{W}}(\cdot)$ denote the expected value of waiting one period and continuing optimally. Using dynamic programming techniques, Jensen (1982, Theorem 1) shows that there exists a unique $p^* \in [0, 1]$ such that $V^{\mathrm{A}}(p) \gtreqless V^{\mathrm{W}}(p)$ if and only if $p \gtreqless p^*$. The firm's optimal adoption policy is hence to wait if $p < p^*$ and adopt at the first date n for which $p \geq p^*$. Notice that p^* represents the minimum level of confidence in the innovation which the firm must have for adoption. If p is too small, i.e. the firm is too sceptical, then the firm will delay adoption. However, by the law of large numbers, a firm's estimate of θ will converge to the true value over time. Hence, a profitable new technology will eventually be adopted. Nevertheless, it is possible that the firm adopts an unprofitable technology due to optimistic prior beliefs or the receipt of wrong signals.

The Jensen model has been generalized in different ways. Under the assumption that all information is costly, McCardle (1985) shows that the firm's optimal decision rule involves two thresholds: if the estimate of the profitability of adoption is sufficiently high, the firm stops collecting information and adopts the new technology, whereas it rejects the new technology if the lower threshold is crossed. Similarly, Bhattacharya *et al.* (1986) consider a decision-theoretic model in which, at any point in time, an individual firm has three options: it can adopt a new technology of uncertain profitability, it can reject it, or it can wait and run a costly experiment which yields information about its value.[7] The studies reveal that costly information acquisition may lead to rejection, i.e. an infinite delay in the adoption of a profitable new technology. Considering a costless as well as a costly information source, Jensen (1988a) finds that the optimal decision rule need not have a reservation property. As the probability of success, p, rises from 0 to 1, the optimal policy may take the form of (wait, buy, wait, buy, adopt) if information costs are positive but sufficiently small. Hence, depending on the value of p, a firm may choose to accelerate learning by buying additional information. Note that the presence of the costless information source prevents an infinite delay in the adoption of a profitable new technology. The impact of a firm's capacity

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[6] Note that, in this model, rejection of the new technology is equivalent to an infinitely long delay of adoption. This is due to the absence of any explicit costs of taking an observation.

[7] Bhattacharya *et al.* (1986) discuss an extension to include the effects of the behaviour of rival firms upon the firm's decision-making process. However, due to the complexity of the model they do not present a complete exposition of the equilibrium behaviour.

to obtain and evaluate information is analysed in Jensen (1988b). It is demonstrated that a greater information capacity implies not only faster learning but also a more stringent adoption criterion, which tends to make firms adopt later. That is, a greater information capacity is found to increase the value of waiting. Thijssen *et al.* (2000) study adoption timing when costless new information arrives according to a Poisson process with parameter μ. It is shown that the firm will choose to wait for more signals as μ increases. The impact of risk aversion and perceived reliability of information is analysed by Chatterjee and Eliashberg (1990). They find that lower risk aversion and greater perceived reliability of information imply earlier expected adoption.

In contrast to the Jensen (1982) model and its extensions, Balcer and Lippman (1984) assume that the value of the currently available new technology is known with certainty, but that the firm faces uncertainty about the arrival of a better version. Their analysis reveals that the announcement of a new discovery can lead to a delay in the adoption of the current technology. Uncertainty about both the launch date and the value of the new technology is considered by Weiss (1994). In his model, the firm can buy costly information regarding the size of the anticipated technological improvement in each period. Weiss shows that when larger improvements are anticipated, the firm is more prone to suspend the adoption decision for the currently available technology.

Related to the work of Balcer and Lippman (1984) and Weiss (1994) is the literature on real options or irreversible investment whose value stochastically evolves over time (e.g. McDonald and Siegel, 1986; Dixit and Pindyck, 1994). Farzin *et al.* (1998) have applied real-option methods to the problem of new technology adoption. In their model, the firm faces uncertainty about both the arrival and value of new technology. It is assumed that technologies become more valuable over time, i.e. there is no technological regress. At each date the firm learns whether an innovation occurs or not. The new technology is adopted as soon as its value exceeds a certain threshold. When the firm can adopt only once, this threshold is shown to be larger than the threshold obtained by the net present value (NPV) approach, implying a longer delay than under the NPV rule. Doraszelski (2000a) shows that the threshold derived from real-option theory exceeds the threshold implied by the NPV approach even when the firm can switch technologies $n < \infty$ times. Doraszelski (2000b) extends the model of Farzin *et al.* (1998) by explicitly distinguishing between the generation of a new technology and its further improvement. He shows that firms may have an incentive to delay the adoption of new technology until it is sufficiently advanced. Doraszelski argues that this may explain the observed lags between the generation of a new technology and its eventual adoption in the US steel industry. Alvarez and Stenbacka (2001) introduce a real-option approach based on the Green representation of

Markovian functionals for finding the optimal thresholds of adoption in the context of multistage technology projects. They show that an increase in market uncertainty, as represented by an increase in volatility, increases both the real-option value of updating a technology and that of adopting the currently available technology.

2.2 *Informational Spillover*

Another route of obtaining information is considered by Mariotti (1992). He develops a timing game of new technology adoption in which one firm's adoption experience can be observed by other firms. More precisely, the first adoption reveals the true quality of the new technology to the remaining firms. The model is structured as a game in which each firm always prefers the others to move first, i.e. a waiting game. However, waiting is costly as the expected returns from adoption are discounted. So each firm must weigh costs and benefits of delaying adoption. Mariotti considers a unique stationary equilibrium in mixed strategies in which the probability of never adopting is positive. His model may hence explain an infinite delay in the adoption of new technologies. Kapur (1995) assumes that the adoption by one firm does not fully reveal the true quality of the technology, but provides a signal that can be used by the other firms to update their beliefs about the technology. As a consequence, firms face a sequence of waiting games. When at least one firm adopts, a single waiting contest ends, and the remaining firms revise their beliefs and engage in the next waiting contest. As in Mariotti, a slow adoption of new technology is attributed to an informational externality.[8]

Vettas (1998) considers a model of new market entry to show that new product adoption is determined not only by firms' but also by consumers' learning. Precisely, firms update their beliefs about the size of the market by observing past equilibrium prices. Furthermore, consumers who face uncertainty about the product's quality can learn from other consumers' purchase decisions. Vettas shows that bilateral learning can slow down the diffusion of new technology into use. The initial length of delay, however, is not an issue in his paper.

3 STRATEGIC INTERACTION IN THE PRODUCT MARKET

This section reviews theoretical models of adoption timing in which the critical factor is strategic interaction in the product market. The predictions of the studies can be summarized as follows. Under rivalry, a firm's pre-adoption profit as well as its post-adoption profit may depend

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[8] Related to this line of research is the work by Chamley and Gale (1994) on the effect of an informational externality on investment timing.

on the number of adopters, and the adoption incentive for firms higher in the adoption order can be larger or smaller depending on the differentials in these profits. A firm's incentive to adopt a new technology at a certain point in time may therefore crucially depend on the rival firms' adoption decisions. In particular, a potential advantage from being first may introduce an incentive for preempting rival firms, thus speeding up the first adoption of a new technology. On the other hand, quality-improving technological progress may give rise to a late-mover advantage, which may slow down adoption.

3.1 Early-mover Advantages

The seminal contribution on adoption timing under rivalry is Reinganum's (1981a) game-theoretic approach. Consider a duopoly market in which each firm obtains a profit of Π_0 per period.[9] At date 0, a cost-reducing new technology is announced. Let Π_L be the profit flow to a firm that is the only adopter. Π_F denotes the profit flow to a firm when only its rival has adopted. If both firms have adopted, each receives a profit flow of Π_2. Regarding the relationships between the various profit flows it is assumed that $\Pi_L > \Pi_2 > \Pi_0 > \Pi_F > 0$ and $\Pi_L - \Pi_0 > \Pi_2 - \Pi_F$.[10] That is, adoption by one firm has a negative impact on the profits of the other firm, i.e. there is business stealing, and the increase in profits due to adoption is greater for the first adopter than for the second, i.e. there may be an incentive for preemptive adoption. The value of the innovation is known with certainty. The model is formulated in continuous time. Let r be the interest rate and T_i the adoption date of firm i. $k(t)$ denotes the undiscounted cost of bringing the new technology on line by date t. It is assumed that $k'(t) < 0$ and $k''(t) > 0$, i.e. the cost of adoption is decreasing over time but at a declining rate, $k(0)$ is sufficiently large such that an initial adoption appears unattractive, and $k(t) \to 0$ as $t \to \infty$, i.e. adoption will eventually occur given that it yields any positive returns. At date 0, the firms must simultaneously precommit to an adoption date. Notice that this set-up is equivalent to the assumption of infinitely long information lags or a so-called *open-loop* information structure.

Let $V_i(T_i, T_j)$ denote the discounted payoff of firm i when it adopts at T_i with its rival at T_j. The firm that adopts first is called the leader, while the other firm is called the follower. If firm i is the leader and adopts at T_1 and firm j follows suit at T_2, with $T_1 \leq T_2$, the respective discounted payoffs are given by

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[9] The case of n firms is considered in Reinganum (1981b).

[10] It can be shown that the assumptions are satisfied in a linear Cournot duopoly model. As pointed out by Quirmbach (1986), declining incremental benefits are necessary for sequential adoption ('diffusion') to occur.

$$V_i(T_1, T_2) = \int_0^{T_1} \Pi_0 \exp(-rt)\,\mathrm{d}t + \int_{T_1}^{T_2} \Pi_{\mathrm{L}} \exp(-rt)\,\mathrm{d}t + \int_{T_2}^{\infty} \Pi_2 \exp(-rt)\,\mathrm{d}t - k(T_1)\exp(-rT_1) \quad (1)$$

$$V_j(T_2, T_1) = \int_0^{T_1} \Pi_0 \exp(-rt)\,\mathrm{d}t + \int_{T_1}^{T_2} \Pi_{\mathrm{F}} \exp(-rt)\,\mathrm{d}t + \int_{T_2}^{\infty} \Pi_2 \exp(-rt)\,\mathrm{d}t - k(T_2)\exp(-rT_2) \quad (2)$$

The objective of each firm is to choose an adoption date so as to maximize its discounted payoff, taking the other firm's choice as given. The model has a unique Nash equilibrium (T_1^*, T_2^*), where $T_1^* = \arg\max_{T_1} V_i(T_1, T_2)$ and $T_2^* = \arg\max_{T_2} V_j(T_2, T_1)$. The equilibrium involves sequential adoption, with higher payoffs for the first mover.

Assuming that information lags are negligible, Fudenberg and Tirole (1985) demonstrate that the first-mover advantage is not supported by subgame perfect equilibrium strategies if firms are unable to precommit to future actions. Under such a so-called *closed-loop* information structure, a potential first-mover advantage will stimulate preemption until payoffs are equalized across firms. To understand this, consider first the maximization problem of the follower.[11] It is easy to verify that the optimal reaction to the leader's adoption at T_1 is adoption at $\max(T_2^*, T_1)$. Taking this reaction into account, the discounted payoffs to the leader and follower can be specified as a function of the leader's adoption date T_1 alone: $L(T_1)$ and $F(T_1)$, respectively. We have $L(T_1^*) - F(T_1^*) > 0$, where $T_1^* = \arg\max_{T_1 \in [0, T_2^*]} L(T_1)$. Suppose T_1^* is the global maximum of $L(T_1)$. Fudenberg and Tirole show for this case that there is a unique subgame perfect equilibrium in which one firm adopts at date $\overline{T}$ and the other follows at T_2^*, where $\overline{T}$ is the smallest $T_1 \geq 0$ such that $L(\overline{T}) = F(\overline{T})$. This equilibrium is in mixed strategies. With identical firms, each firm will be the leader with probability 1/2, and with probability 1/2 the roles of the firms are reversed. While the formal proof necessitates the use of quite technical arguments, the intuition behind it is straightforward (see also Fudenberg and Tirole, 1986). Clearly, no firm can obtain more than $L(T_1^*)$. Hence, each firm would like to be first at T_1^*. But if a firm, say firm *i*, plans to wait until T_1^*, then firm *j* would like to adopt just slightly earlier due to the potential first-mover advantage. However, then firm *i* would do better to preempt firm *j* slightly. By continuing this reasoning backwards, one obtains first adoption at $\overline{T} < T_1^*$ as the only solution of

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[11] It is worth emphasizing that this does not mean that the distribution of the follower and leader roles is given exogenously.

the game. Hence, when firms cannot precommit themselves to adopt at particular dates, timing competition reduces the initial delay in the adoption of new technology.

Riordan (1992) uses the framework of Fudenberg and Tirole (1985) to analyse the impact of price and entry regulations on the timing of adoption. He shows that these regulation schemes may slow adoption by making preemptive strategies less attractive. As shown by Hendricks (1992), uncertainty about the innovative capabilities of the rival firm tends also to slow down the first adoption of a new technology in the Fudenberg and Tirole model. He finds that this type of uncertainty prevents a complete dissipation of the potential first-mover advantage. Riordan and Salant (1994) consider strategic technology adoption when there is ongoing technological progress and adoption costs are constant. Each firm is allowed to adopt repeatedly and thereby improve its technology over time. The authors show that the adoption pattern is characterized by preemption and increasing dominance, i.e. all new technology adoptions are by the same firm if there is Bertrand price competition in the product market. Under Cournot quantity competition, however, other adoption patterns such as action–reaction are possible.

Building on the work by Fudenberg and Tirole, Dutta *et al.* (1995) consider new product adoption under quality-improving technological progress. Their model can be illustrated as follows. Suppose there are two firms. Let $s(t)$ denote the available product quality at date t and assume that $s = t$. Variable costs of production are independent of quality and zero. Assume that each period each consumer buys at most one unit from either firm 1 or firm 2. Consumers differ in a taste parameter θ and get each period a net utility of $U = s_i\theta - p_i$ if they buy a quality s_i at price p_i, and zero otherwise. A consumer of type θ will buy if $U > 0$ for at least one of the offered price–quality combinations, and he will buy from the firm that offers the best price–quality combination for him. Consumers are assumed to be uniformly distributed over the interval $[a, 1]$, where $0 \leq 2a < 1$.

Each firm decides when to enter the market, given the best available quality to date and whether and when the rival has previously entered the market. The firm that enters first, i.e. the leader, is indexed by 1 and earns a flow of monopoly revenue of $R_M(s_1)$ from the time of its entry s_1 until $\hat{s}_2$, the optimal response by the second firm, i.e. the follower, who is indexed by 2. After $\hat{s}_2$ both firms earn a flow of duopoly Nash equilibrium revenues from price competition with vertically differentiated goods, $R_1(s_1, \hat{s}_2)$ and $R_2(s_1, \hat{s}_2)$, forever after. That is, each firm must balance the advantage of a temporary monopoly position for the first mover with the competitive advantage for the second mover from eventually entering with a better product. Information and reaction lags are assumed to be negligible. There is hence the possibility of preemptive adoption. The leader's and follower's payoffs as functions of the leader's choice are given by

$$L(s_1) = \int_{s_1}^{\hat{s}_2} \exp(-\tau)\, R_{\mathrm{M}}(s_1)\, \mathrm{d}\tau + \int_{\hat{s}_2}^{\infty} \exp(-\tau)\, R_1(s_1, \hat{s}_2)\, \mathrm{d}\tau$$

$$F(s_1) = \int_{\hat{s}_2}^{\infty} \exp(-\tau)\, R_2(s_1, \hat{s}_2)\, \mathrm{d}\tau$$

where the interest rate is $r = 1$. Hoppe and Lehmann-Grube (2001a) demonstrate that this game is always structured as a race to be the pioneer firm if available quality increases costlessly over time. That is, under costless quality-improving technological progress, both firms value the temporary monopoly position more than the strategic advantage from being the high-quality firm. As a consequence, the subgame perfect equilibrium involves preemptive adoption.

3.2 Late-mover Advantages

Quality-improving technological progress may also give rise to late-mover advantages in the strategic timing of new market entry. Consider the model by Dutta *et al.* (1995) illustrated above. Suppose now that each firm's R&D costs per unit of time are λs, with $\lambda \geq 0$. The leader's and follower's payoffs are then

$$L(s_1) = \int_{s_1}^{\hat{s}_2} \exp(-\tau)\, R_{\mathrm{M}}(s_1)\, \mathrm{d}\tau + \int_{\hat{s}_2}^{\infty} \exp(-\tau)\, R_1(s_1, \hat{s}_2)\, \mathrm{d}\tau - \int_0^{s_1} \exp(-\tau)\, \lambda\tau\, \mathrm{d}\tau$$

$$F(s_1) = \int_{\hat{s}_2}^{\infty} \exp(-\tau)\, R_2(s_1, \hat{s}_2)\, \mathrm{d}\tau - \int_0^{\hat{s}_2} \exp(-\tau)\, \lambda\tau\, \mathrm{d}\tau$$

where the interest rate is $r = 1$. Hoppe and Lehmann-Grube (2001a) demonstrate that the nature of the game switches from a preemption game to a waiting game as λ tends to infinity. By applying a numerical algorithm, Hoppe and Lehmann-Grube (2001b) obtain a unique value $\hat{\lambda} > 0$ such that for $\lambda > \hat{\lambda}$ the game takes the form of a waiting game with a second-mover advantage in equilibrium, while for $\lambda \leq \hat{\lambda}$ the game is structured as a preemption game with payoff equalization in equilibrium. That is, with two basic factors of new product adoption, time (causing opportunity costs) and R&D effort (causing R&D expenditure), it is found that if technology competition is mainly time consuming (i.e. λ is low) there is no second-mover advantage. But if technological competition is mainly R&D effort consuming (i.e. λ is high) a second-mover advantage emerges, slowing down the first adoption of the new product.

4 ADOPTION TIMING WITH RIVALRY AND UNCERTAINTY

This section reviews theoretical approaches that deal with both rivalry in the product market and uncertainty. Stenbacka and Tombak (1994) extend the model by Reinganum (1981a) by assuming that the length of time required for successful implementation is uncertain (see also Götz, 2000). They show that changes in a firm's hazard rate of successfully implementing the new technology may affect the firm's adoption time. Jensen (1992a) introduces a two-period adoption game to analyse the effects of strategic adoption timing under uncertainty on the patent licensing behaviour of an inventor. Mamer and McCardle (1987) develop a model in which two rival firms may choose to collect private observations about the unknown value of a new technology by investing in R&D. However, information acquisition is assumed to take place instantaneously, so timing is not an issue. Strategic timing of new product adoption whose value is uncertain to sellers and buyers is explored by Bergemann and Välimäki (1997). Assuming that initially one of two firms has already adopted a new product, the authors investigate the optimal pricing policies when both sides of the market, buyers and sellers, learn the true value of the new product through observing the buyers' experiences. It is shown that the firm may initially have an incentive to set low prices in order to enhance the accumulation of information and thereby speed up adoption by consumers.

In the model introduced by Hoppe (2000a), the major approaches described in Sections 2 and 3 are unified by integrating uncertainty regarding the profitability of an innovation, as in Jensen (1982, 1992b), into Fudenberg and Tirole's (1985) extension of the Reinganum (1981a) model. Assume that the value of the innovation is 'good' (i.e. it increases profits) with probability p, and 'bad' (i.e. it does not increase profits) with probability $1 - p$. The probability of success, p, is common knowledge. The nature of the innovation becomes publicly known when the first firm adopts. Thus, a firm's adoption gives rise to an informational spillover. In the extreme case of $p = 1$, i.e. when there is certainty of success, the payoff functions of the leader and follower firm reduce to those of the Fudenberg and Tirole (1985) model. Moreover, under uncertainty, the general properties of the payoff functions remain the same as in the case of $p = 1$. That is, T_2^* is clearly independent of p since the follower decides whether or not to adopt being informed about the true value of the innovation. However, technological uncertainty affects the relative positions of $L(T_1)$ and $F(T_1)$. If the probability of success, p, is sufficiently high, we have $L(T_1^*) - F(T_1^*) > 0$, but $L(T_1^*) - F(T_1^*) < 0$ if p is low enough.

There exists a unique value of p, denoted by $\overline{p}$, such that the unique subgame perfect equilibrium can be characterized as follows (Hoppe, 2000a, Propositions 1 and 2). If $p > \overline{p}$, firm i adopts at the earliest preemption date $\overline{T}$ and firm j ($\neq i$) follows suit at T_2^* if the innovation is 'good'; payoffs are equalized across firms due to the threat of preemption. If $p < \overline{p}$, the first adoption occurs at the global maximum of $L(T_1)$, T_1^* or T_M^*, where $T_M^* = \arg\max_{T_1 \in [T_2^*, \infty)} L(T_1)$, and the second adoption at T_2^* or T_M^*, respectively, if the innovation is 'good'; the equilibrium involves a second-mover advantage because of informational spillovers. It is worth noting that the model predicts that the equilibrium payoffs will typically be discontinuous and non-monotonic in the probability that the new technology is profitable. That is, a small reduction in the probability of success from above $\overline{p}$ to below that value can convert the competition from a preemption game to a waiting game, and thereby cause an *upwards* jump in the equilibrium payoffs of both firms.[12] To see this, note that a preemption contest may result in excessive rent dissipation, i.e. each firm may find in equilibrium that it is worse off than in a situation in which one of them could credibly precommit not to preempt its rival. Note further that a decrease in the probability of success reduces the preemption gains engendered by the new technology. If p is sufficiently low, preemptive motives are outweighed by an incentive to wait and see, so excessive rent dissipation need not occur.

Another approach to the modelling of strategic adoption timing under uncertainty, introduced by Hoppe (2000b), builds on the timing games of quality competition by Chikte and Deshmukh (1993) and Lippman and Mamer (1993) in which R&D activity leads to a stochastic increase in the quality of a new product over time. While these models of quality competition do not admit any late-mover advantages,[13] the adoption model of Hoppe (2000b) takes both potential first-mover and second-mover advantages into account. It is assumed that firms may increase the profitability of adopting a new technology over time by active search for technological and adaptive information, but also by passively observing the other firm's adoption experience, which gives rise to an informational spillover.

In the subgame perfect equilibrium of this game, firms employ reservation level strategies, i.e. they stop R&D and adopt the new technology if and only if the expected profitability of the new technology exceeds a certain level. At the equilibrium reservation level, the opportunity cost to delay (the risk of being preempted plus forgone earnings from the use of the new technology) is equal to the benefits of

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[12] The question of whether firms may benefit from a higher probability of failure when they can choose among technologies that differ in their probability of success is addressed in Hoppe (2001).

[13] To be precise, in Chikte and Deshmukh's duopoly model a second-mover advantage is not ruled out *a priori*. However, their analysis reveals that the competition always takes the form of a contest for being first. In Lippman and Mamer's model, however, it is assumed that only one firm can adopt the new technology, i.e. the winner takes all.

waiting (new information gained by active search or observing the adoption experience of other firms). In this model the equilibrium order of adoption is induced by chance due to the stochastic nature of the information acquisition process. Firms that are initially identical will have an equal chance of being first or second in the adoption timing, just as in the preemption game of Fudenberg and Tirole (1985) where adoption costs decrease deterministically over time. Note, however, that the stochastic nature of R&D in Hoppe (2000b) generates an option value of waiting for new information for each firm which reduces the risk of being preempted. As a consequence, the model admits an *ex post* first-mover advantage in equilibrium, in contrast to Fudenberg and Tirole's adoption game in which *ex ante* and *ex post* returns are always equalized in equilibrium by preemptive adoption.

Among the results obtained for this model of adoption timing are that a firm's equilibrium threshold for becoming the first adopter can be higher in a duopoly than in a monopoly. When there is a sufficiently strong second-mover advantage, each firm's benefits from waiting for higher profitability are increased by the possibility that another firm may move first in the meantime. But even in markets with a strong first-mover advantage, a duopolist may choose to wait until it is more profitable to adopt the new technology, where a monopolist would have adopted. The reason is that the opportunity costs of waiting in terms of forgone profits are lower for a duopolist than a monopolist due to strategic interaction in the product market.

5 EMPIRICAL EVIDENCE

The empirical literature offers few explicit links with the theoretical models that deal with uncertainty and learning about the profitability of adoption or with strategic interaction in the product market. Most of the recent empirical studies on new process adoption use probit and logit, linear probability and hazard rate models where the dependent variable is the time of adoption of a new technology by individual firms, while those on new product adoption tend to focus on the measurement of early-mover and later-mover advantages. Recent contributions to each line will be briefly reviewed in turn.[14]

The effect of uncertainty and information acquisition on adoption timing is studied by Weiss (1994), using data on the adoption of a new process technology called surface-mount technology by printed circuit board manufacturers. Estimating a multinomial logit model, he finds

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[14] For a survey over earlier contributions as well as discussion of estimation and measurement problems, see Karshenas and Stoneman (1995), Lieberman and Montgomery (1988, 1998) and Mueller (1997).

empirical evidence that uncertainty about technological progress discourages firms from adopting the currently available invention. His findings also suggest that a greater ability to search, as measured by the level of skills and knowledge of a potential adopter, results in a lowered tendency to adopt early, which supports the theoretical result of Jensen (1988b). In an attempt to test the impact of learning and strategic interaction on the timing of adoption of computer numerically controlled machine tools in the UK, Karshenas and Stoneman (1993) build a general duration model which incorporates price expectations and firm characteristics as well as stock and order effects as envisaged by game-theoretic models. The findings suggest that expectations and firm characteristics, such as firm size, play a significant role in the adoption process, while there is little evidence in support of stock and order effects. Firm size has also been found by Rose and Joskow (1990) to significantly affect adoption timing. Using a hazard rate model, their results suggest that smaller firms are slower in adopting new technologies in the electric utility industry. The reason could be the presence of scale economies associated with the use of the new technology or a lower degree of risk disposure for larger firms. Empirical evidence for preemptive adoption is provided by Genesove (1999). Applying a hazard rate model to data on the adoption of offset presses in the US daily newspaper publishing industry from 1964 to 1967, Genesove finds that, in markets in which one of two firms has exited, the remaining one is less likely to adopt than otherwise.

There is a large empirical literature on the advantage of being first in marketing a new product, exploring the impact of switching costs, network externalities, economies of scale and buyer inertia due to uncertainty over quality.[15] Recently, attention has shifted to late-mover advantages. In their analysis of 50 different markets, Golder and Tellis (1993) and Tellis and Golder (1996) find that, on average, late movers are more successful, which supports the results of Hoppe (2000a). In contrast to earlier studies, the authors include all the pioneer companies and brands that failed in the sample. They discover that the failure rate for pioneers is high: almost half do not survive. There are several recent studies which emphasize the importance of product quality improvements for the relative performance of firms. Shankar *et al.* (1998), for instance, analyse 13 brands in two pharmaceutical product categories and find that second movers can overtake the pioneers through product innovation. Their results suggest that an innovative late entrant will enjoy a market potential, as measured by brand sales, at least as high as the pioneer's. Similarly, Berndt *et al.* (1995) attribute a second-mover advantage in the US anti-ulcer drug

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[15] For further discussion, see Mueller (1997).

market to, amongst other things, better quality. The theoretical finding by Hoppe and Lehmann-Grube (2001a) that an increase in the duration of technological competition tends to reduce a potential second-mover advantage appears to be supported by a study of Lilien and Yoon (1990). Using French data of 112 new industrial products, the authors find evidence that the earlier a follower enters with a new product, i.e. the shorter the duration of technological competition, the better is the performance of that product.

6 Conclusion

The theoretical studies point out a number of factors that influence a firm's decision to adopt a new technology at a certain point in time: under uncertainty, individual information acquisition as well as learning from the adoption experience of others tend to delay the first adoption of a new technology; under strategic interaction in the product market, the nature of adoption timing can be one of either preemption or waiting. The studies have also delineated several circumstances under which the effect of learning on the length of delay tends to be stronger or weaker and when strategic interaction is likely to give rise to early-mover or late-mover advantages to adoption. However, many opportunities for further research along these lines remain.

There are many possible extensions of the theoretical approaches described above. For example, one could combine the models of information acquisition and learning from others by introducing lags between the adoption and the disclosure of its profitability and by making these lags endogenous through information-gathering activities of firms lower in the order of adoption. An important theoretical challenge is to flesh out how the information acquisition behaviour of subsequent adopters influences the timing decision by the first adopter. There may also be opportunities to link more work on social learning and herding (see, for example, Lee, 1993; Vives, 1996) to the context of new technology adoption. In addition it seems worth exploring strategic adoption timing under different, more realistic forms of uncertainty. Boyer *et al.* (1998), Décamps and Mariotti (1999) and Huisman and Kort (2000), for example, have recently started to extend real-options models in which the value of investment can change unpredictably because of aggregate demand shocks (as in McDonald and Siegel, 1986; Dixit and Pindyck, 1994) by allowing for strategic interaction among firms. Boyer *et al.* also consider sequential acquisition of indivisible units of capacity, which is another mainly unexplored line of research. Little attention has been paid to the related question of how the process of intra-firm diffusion is initiated. The work by Stoneman (1981) and Jensen (2001) provides a useful start along this line.

Moreover, the decision to adopt a particular technology at a certain point in time may depend on other strategic choices, such as decisions about related technologies (see Jensen, 1983; Stoneman and Kwon, 1994; Colombo and Mosconi, 1995), R&D investments (see Lee, 1985; Hoppe, 2000b), the internal structure of the firm, and financing decisions. It seems important to bring the existing models of technology adoption closer to reality by putting them in a broader perspective. For example, it would be interesting to know how potential early-mover and late-mover advantages in the timing of adoption are interlinked with preceding decisions about R&D projects or the hiring of skilled workers. In addition the work of Cohen and Levinthal (1989) and Kamien and Zang (2000) on a firm's capacity to realize spillovers from other firms' R&D, i.e. its 'absorptive capacity', could be usefully applied to the context of new technology adoption.

There is also a need for more empirical research that tests specific models, in particular game-theoretic models, and distinguishes among the different factors determining the lag between the time at which a new technology becomes available and its commercial usage (e.g. using the approach by Karshenas and Stoneman, 1993). Finally, far too little attention has been paid to welfare issues and public policies with regard to the timing of new technology adoption (see Stoneman and David, 1986; Stoneman, 1987; Stoneman and Diederen, 1994; Hoppe, 2000a). The circumstances under which policy intervention is desirable need to be further explored, as well as the form that such intervention should take.

In short, while advances have been made in the understanding of the nature and timing of new technology adoption, the opportunities for future research are still extensive.

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