

Diffusion of new technology – The case of multiple generations

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Abstract: We model adoption decisions by competitive firms when successive generations of a new technology become available over time. Profit-maximizing firms choose which generation to adopt and at which adoption date. The model accounts for leapfrogging and simultaneous adoption of different generations. Leapfrogging occurs if a potential user does not adopt the state of the art technology but adopts the next generation. In the simultaneous adoption case some adopt the new generation while others still adopt an old generation. The two mentioned patterns are shown to be equilibrium outcomes that depend on exogenous parameters. Both overlap and leapfrogging may arise from the same parameters. As a consequence, firms of different sizes may adopt a generation at the same time. The model predicts that leapfroggers, who are the smallest firms in the industry, may well adopt the new generation before medium and large firms and that large firms are likely to adopt both generations. Empirical analysis on the adoption of two generations of machine tools (NC and CNC) by U.S. metalworking plants show that there is indeed substantial leapfrogging: 26% of all plants in the sample had adopted CNC but not NC by 1993. There was also overlap in adoption: 68% of the adopters of CNC adopted during 1981-1993; 53% of the adopters of NC adopted that technology during the same period. We find that the non-adopters of both technologies (NC and CNC) are the smallest, the adopters of NC but not CNC are on average larger, the leapfroggers are still larger and the largest plants, on average, adopt both technologies. Leapfroggers adopt CNC approximately one year earlier than adopters of both technologies. Empirical results are broadly consistent with model predictions.

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1. Introduction

An important feature of many modern technologies is that they come in successive generations. The most clear cut examples are from the area of information technology. Both hard- and software products typically evolve over time. New, superior generations replace the state-of-the-art products. Two interesting features of the diffusion of multiple-generation technologies that have not been substantially analyzed are leapfrogging and an overlap of diffusion curves of different generations. Leapfrogging occurs if a potential user does not adopt the state of the art technology but waits to adopt the next generation. In a multiple generation framework this might imply that potential users adopt only every other generation. An overlap of diffusion curves implies that some users continue to adopt the old generation while others have switched to adopting the new generation.

We use the case of the diffusion of two generations of machine tools to exemplify the importance of both leapfrogging and overlap. Metalworking machine tools are of general interest as an example of a technology that has had wide application in the manufacturing sector and important impact on productivity growth (e.g. Stoneman and Kwon, 1996). Machine tools can be categorized into conventional (hand operated), Numerically Controlled (NC) and Computer Numerically Controlled (CNC.) The NC machine was developed soon after World War II. NC machines use a series of numbers punched on tape or punch cards to control their motion. In the late 1960s the next generation had computers added to give even more flexibility to the process. Such machines became known as CNC machines. NC and CNC machines could precisely repeat sequences over and over, and could produce much more complex pieces than even the most skilled tool operators.

NC and CNC initially spread slowly. The first adoption of NC in our sample was in 1962, while it was in 1971 for CNC. In 1983, the NC penetration was 9% while CNCs was 16%. Subsequently CNC exhibited rapid diffusion and NC use increased as well. By 1993, CNC had been adopted by 47% of the plants, while 26% had adopted NC (Åstebro, 2002).

Reanalysis of the data collected by Åstebro (2002) reveals that as much as 26% of all plants in the sample had leapfrogged and adopted CNC but not NC by 1993. This is a substantial fraction and evidence that leapfrogging should be seriously considered when modeling and studying the adoption and diffusion of new technology. There was also evidence of overlap in adoption: 68% of the adopters of CNC adopted during 1981-1993; 53% of the adopters of NC adopted that technology during the same period. We were surprised at the relatively large proportion of adopters that adopted the old technology even several decades after the new generation had been introduced.

This paper explains the stylized facts, i.e. leapfrogging and simultaneous adoption of different generations, as equilibrium outcomes of the adoption decisions of profit-maximizing and competing firms. The paper's focus is on the demand side of the new technology. As in a large part of the diffusion literature (Reinganum, 1981a, 1981b, Fudenberg and Tirole, 1985) the paper employs a reduced form of the supply side and takes the adoption cost function as given.¹ The paper builds on the single-generation framework developed in Götz (1999) and extends it to

¹ Our approach therefore differs from papers such as Jovanvic and Lach (1989) and Jovanovic and MacDonald (1994) where the focus is on the supply side of the industry. These papers appear to focus on industry evolution, rather than on firms' decision to adopt. Typically, stationary per period demand is assumed, an assumption which appears hard to justify when talking about a durable product such as semiconductors.

a multi-generation framework.² For simplicity we consider only two new generations of the product. A particularly attractive feature of the monopolistic competition framework of Götz (1999) is the straightforward way to introduce firm heterogeneity. As it will turn out heterogeneity is of particular importance when it comes to explaining features such as the simultaneous adoption of different generations. Furthermore, the framework accounts for rivalry and competition among users of the new technology, while at the same time staying tractable due to the absence of strategic interaction among firms. Due to these features the model allows to single out the effects of both competition and firm heterogeneity. Finally, the approach yields diffusion distribution functions as equilibrium outcomes, which can easily be compared with the diffusion curves for various products.³

² See Ederington and McCalman, 2004 and 2005 for approaches that build on Götz (1999) to address questions of industry evolution and international trade.

³ Given the importance of products which come in successive generations for the so-called New Economy, it might be surprising that there is only a small economics literature on this topic. Many treatments are decision-theoretic in the sense that they analyze optimal adoption decisions of a single firm. Typically, there is uncertainty about new generations and the firms face optimal stopping problems (Balcer and Lippman (1984), Farzin, Huisman and Kort (1998), Doraszelski (2004)). While there are papers dealing with a whole industry taking into account the effect of competition and rivalry on the adoption of successive generation, they are typically restricted to the duopoly case (Huisman and Kort (2004) and Riordan and Salant (1994)). These papers are interested in potentially preemptive behavior of firms, but not in the general diffusion patterns described above.

One of the paper's main results is that even for ex-ante identical firms leapfrogging can occur: a certain percentage of firms choose to adopt every generation, while the remaining part leapfrogs the first generation and adopts only the second generation. Despite the difference in behavior, profits of both types are the same. This might well be explained by the fact that leapfrogging firms are the first adopters of the next generation. A crucial parameter is the date of emergence of the second generation. The later the next generation emerges the smaller the fraction of leapfrogging firms will be. If the next generation emerges sufficiently late, all firms will adopt each generation. Note that leapfrogging implies that demand for later generations is larger.

Explaining the overlap of diffusion curves requires the introduction of firm heterogeneity. Of particular relevance is the case in which both leapfrogging and simultaneous adoption of different generations occurs. The model shows that it is the smallest firms which leapfrog, while medium to large size firms adopt both generations and are responsible for the overlap. The implications of this result are twofold. First, we always find cases in which firms of different sizes adopt the same generation at the same time. Second and related, the leapfroggers, who are the smallest firms in the industry, may well adopt the new generation before medium to large

In contrast to the Economics literature, there is a vast literature on the diffusion of successive generations in Marketing (see e.g. Norton and Bass (1987, 1992), Mahajan and Mueller (1996)). These papers typically follow an epidemic approach, which does not start from individual adoption decisions but some law of motion for the change in the proportion of adopters. The epidemic approach can also be found in recent economic studies of successive generations of new technology when it comes to the diffusion of consumer products (Liikanen, Stoneman and Toivanen (2004)).

sized firms. These implications are in contrast to standard results from so-called rank-effects models (see Karshenas and Stoneman, 1995) and also to conventional empirical wisdom (e.g. Åstebro, 2002) on diffusion of single-generation technologies. The explanation is that the profit gain from the new generation is smaller for the later adopters despite of being bigger, because they have a more recent technology implemented than the leapfroggers.

Testing some predictions of the model, we find that non-adopters of both technologies (NC and CNC) are the smallest, that adopters of NC but not CNC are on average larger, that leapfroggers are still larger and that the largest plants, on average, adopt both technologies. Leapfroggers adopt CNC approximately one year earlier than adopters of both technologies, a statistically significant difference. Empirical results are broadly consistent with model predictions. Notable is that these empirical results are not inconsistent with previous empirical analysis which show that adopters of new technology are on average larger than non-adopters (e.g. Åstebro, 2002), but provides new evidence on differences across adopters of new technology.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 discusses diffusion patterns depending on whether firms are ex-ante homogeneous or not, Section 4 provides data on the adoption of multiple generations of machine tools, and Section 5 concludes.

2. The model

The model follows the setup of Götz (1999) closely. It considers the evolution of an industry in continuous time. In this industry, a continuum of firms produces different varieties of a differentiated product. We assume that there is no entry, with fixed n active firms.

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

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

where $x_0(t)$ is the consumption of the numeraire in time t and $C(t)$ is a consumption index of the Dixit-Stiglitz (1977) type with

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

Here $y(j, t)$ is the amount of variety j of the differentiated product which is demanded by a consumer at time t . The parameter $A(j)$ accounts for potential firm heterogeneity. We assume that $A(j) > 0$ for all j , and that $A(j)$ is a continuous and monotonously decreasing function of the firm index j . That is, firms are ranked in terms of the parameter in a such way, that firms with higher consumer valuations have a lower index number. The parameter captures the idea that consumers value some varieties more than others, be that for reasons of product design or other product characteristics.

Because of the quasi-linear instantaneous utility function, the demand function for the differentiated goods does not change over time. Furthermore, demand is independent of the

consumers' income, as long as total discounted income of each consumer is greater than $1/r$. We assume this to be the case. Denote the number of consumers by E . As each consumer's spending on the differentiated product is equal to one, E is equal to the total instantaneous expenditure on the differentiated product. With the above assumptions, one gets the instantaneous aggregate demand function $Y(j, t)$ for variety j at time t :

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

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

The demand function (2) is isoelastic with the price elasticity of demand $\sigma = 1/(1-\alpha)$. Actions of rivals which result in price changes enter the demand function through the integral in the denominator. As is well known (see Dixit and Stiglitz, 1977 and Grossman and Helpman, 1991, Chapter 3), this demand function gives rise to a simple mark-up pricing rule for given marginal costs c . The profit maximizing price p reads

$$p = c / \alpha. \quad (3)$$

Firms produce with constant marginal costs c_0 . In time $t_1 = 0$, the first generation of the new technology becomes available which, once adopted, allows production with lower marginal costs c_1 . In time $t_2 \geq 0$, the second generation of the new technology becomes available which, upon adoption reduces marginal costs further to c_2 . The discounted costs X_i of purchasing generation i and integrating it in the production process depend on the date T_i , at which production should take place at the lower marginal costs. The function $X_i(T_i)$ is assumed to be

decreasing and convex in T_i so that $X_i'(T_i) < 0$ and $X_i''(T_i) > 0$. Furthermore, we assume that $X_i(\infty) = 0$.

With this adoption cost function, earlier adoption is more expensive, and all firms will eventually adopt the second generation technology. Below, we make the simplifying

Assumption 1:
$$X_2(T_2) = e^{rt_2} X_1(T_2 - t_2).$$

This assumption implies that the two generations exhibit the same adoption costs if one abstracts from discounting.

As is known from Götzt (1999), in the monopolistic competition framework the adoption cost function $X(T)$ allows for an interpretation of the adoption process as both a ‘time-consuming activity’ and as the simple purchase of a new capital-embodied technology. Contrary to the oligopoly case, under monopolistic competition there is no difference between the closed – and the open-loop equilibrium since firms are ‘small’ agents and cannot act strategically.

The operating profits π of a single firm can be determined as a function of its own and of its rivals’ behavior. Operating profits are the difference between revenue and variable costs. The adoption decision determines the level of marginal cost. The actions of rivals enter the firm’s profit function via the expression in the denominator of the demand function (2).

Given an arbitrary adoption pattern of the rivals and employing the pricing rule (3), operating profits $\pi_i(j, t)$ of firm j at time t with marginal costs c_i and $i = 0, 1, 2$ are

$$\pi_i(j, t) = \frac{(1 - \alpha) A(j)^{\alpha/(1-\alpha)} c_i^{\alpha/(\alpha-1)} E}{\int_0^n c(z, t)^{\alpha/(\alpha-1)} A(z)^{\alpha/(1-\alpha)} dz}. \quad (4)$$

In the above expression $c(z,t)$ denotes the marginal costs of firm z at time t , which may be c_0 , c_1 , or c_2 . Given the above derivations and assumptions total discounted profits can be derived for two cases; when firm j adopts both generations and when firm j leapfrogs. Denote the profit function in the former case as $\Pi^{2G}(j,T_1,T_2)$, where T_1 and T_2 are the adoption dates of the first and second generation, respectively. In the leapfrogging case the profit function is denoted as $\Pi^{LR}(j,T_2)$. The profit functions read

$$\Pi^{2G}(j,T_1,T_2) = \int_0^{T_1} e^{-rt} \pi_0(j,t) dt + \int_{T_1}^{T_2} e^{-rt} \pi_1(j,t) dt + \int_{T_2}^{\infty} e^{-rt} \pi_2(j,t) dt - X_1(T_1) - X_2(T_2), \quad (5)$$

and

$$\Pi^{LR}(j,T_2) = \int_0^{T_2} e^{-rt} \pi_0(j,t) dt + \int_{T_2}^{\infty} e^{-rt} \pi_2(j,t) dt - X_2(T_2). \quad (6)$$

The maximum discounted profits $\Pi^*(j)$ of firm j derive from the following problem:

$$\Pi^*(j) = \max \left\{ \max_{T_1, T_2} \Pi^{2G}(j, T_1, T_2), \max_{T_2} \Pi^{LR}(j, T_2) \right\}. \quad (7)$$

3. Equilibrium diffusion patterns

Due to the many possibilities described in the introductory section, different equilibrium outcomes need to be distinguished. Which of the potential outcomes is realized depends on the parameters of the model. In what follows I focus on two different (sets of) parameters, t_2 , the emergence date of the second generation, and the function $A(j)$, which measures the degree of heterogeneity among firms.

3.1 Stationary diffusion curves

A straightforward diffusion pattern is the stationary one. In this case the diffusion curves of all generations have the same shape; neither an overlap nor leapfrogging arises. This outcome emerges as a simple extension of the single generation framework if the second generation emerges ‘late’⁴. Furthermore, one needs to assume that adoption costs are identical (up to discounting) and that the percentage decrease in marginal cost due to adoption is also the same. To see this we derive the first order conditions for the adoption of the two generations for firm j from equation (5).

$$\frac{\partial \Pi^{2G}(j, T_1, T_2)}{\partial T_i} = e^{-rT_i} (\pi_{i-1}(j, t) - \pi_i(j, t)) - X_i'(T_i) = 0 \quad \text{for } i = 1, 2. \quad (8)$$

Dividing numerator and denominator of the operating profit $\pi_i(j, t)$ and $\pi_{i-1}(j, t)$ (see (4)) in the first order conditions (8) by $c_{i-1}^{\alpha/(\alpha-1)}$, reveals that $\pi_i(j, t) - \pi_{i-1}(j, t)$, the gain from a adopting a generation, depends only on the percentage change in marginal costs. To see this, note that

$$\pi_i(j, t) - \pi_{i-1}(j, t) = \frac{(1-\alpha)A(j)^{\alpha/(1-\alpha)}E}{\int_0^n (c(z, t)/c_{i-1})^{\alpha/(\alpha-1)} A(z)^{\alpha/(1-\alpha)} dz} \left(\left(\frac{c_i}{c_{i-1}} \right)^{\alpha/(\alpha-1)} - 1 \right). \quad (9)$$

This holds as long as all rivals choose the same (properly adjusted) adoption dates for both generations. In this case the integral in the denominator of (9) is the same for the two generations.

Employing Assumption 1 the first order condition w.r.t. T_2 becomes

⁴ What ‘late’ exactly means is made clear in the next Subsection.

$$\frac{\partial \Pi^{2G}(j, T_1, T_2)}{\partial T_2} = e^{-r(T_2 - t_2)} e^{rt_2} (\pi_1(j, t) - \pi_2(j, t)) - e^{rt_2} X_1'(T_2 - t_2) = 0. \quad (10)$$

Comparison with the first order condition w.r.t. T_1 (see (8)), taking into account that the gains from adoption are the same for the two generations, shows that the same time interval between the emergence of a generation and the adoption solves both first order conditions. We obtain for firm j :

$$T_1^* = T_2^* - t_2 \quad (11)$$

Given that all rivals choose the same adoption pattern for the two generations, it is optimal for firm j to do the same. Since firm j is an arbitrary firm, we know that if we have an equilibrium diffusion curve for the first generation, properly adjusted, i.e. shifted by t_2 , this is also the equilibrium diffusion curve for the second generation.

It is straightforward to extend the stationary framework to the case of k generations. However, we want to turn to more interesting extensions: leapfrogging and overlap.

3.2 Diffusion with ex-ante identical firms

In this Subsection, we examine potential diffusion patterns for the case of homogeneous firms. For simplicity, we assume $A(j) = 1$ for all j . We focus on the effect t_2 , the date of emergence of the second generation, has on the diffusion pattern. As will be shown below, for large values of t_2 the stationary case applies. If one reduces t_2 , eventually some firms will start to leapfrog the first generation. Further reductions eventually make the first generation obsolete in the sense that it is not adopted by any potential user.

Denote the value of the emergence of the second generation, which separates the leapfrogging and the stationary diffusion curve case as t_2^{2G} . Furthermore, denote the value which

separates the leapfrogging case and the case where the first generation is irrelevant as t_2^{LR} . Leapfrogging occurs in the interval $[t_2^{LR}, t_2^{2G}]$. In order to determine t_2^{LR} , one needs to examine the incentive for a single firm to adopt both generations if all rival adopt only the second generation. The calculation is straightforward in general, since the ‘equilibrium’ distribution function for the case in which all firms adopt only the second generation derives directly from the single generation framework of Götz (1999, see Proposition 1). Due to the rather complicated expressions an analytic solution is not available. We will present numerical results below. The determination of t_2^{2G} works analogously. Given the equilibrium distributions in the stationary case, we need to derive the value of t_2 for which $\Pi^{2G}(j, T_1^*, T_2^*) = \Pi^{LR}(j, T_2^*)$.

In order to provide more insight into this case, we present a simulation next. The functional forms and parameters used are $X_1(T_1) = fe^{-(r+\beta)T_1}$, $c_0 = 4$, $c_1 = 2$, $c_2 = 1$, $\alpha = 1/2$, $E = 10$, $r = 0.1$, $n = 10$, $\beta = 0.1$, $f = 10$. The parameter β is a positive constant capturing the decrease in cost induced by technical progress (see Fudenberg and Tirole, 1985). The next generation decreases costs by 50%. For these parameters we obtain: $t_2^{LR} = 11.39$, $t_2^{2G} = 16.09$. Taking an intermediate value of t_2 such as $t_2 = 13$ yields the following diffusion pattern:

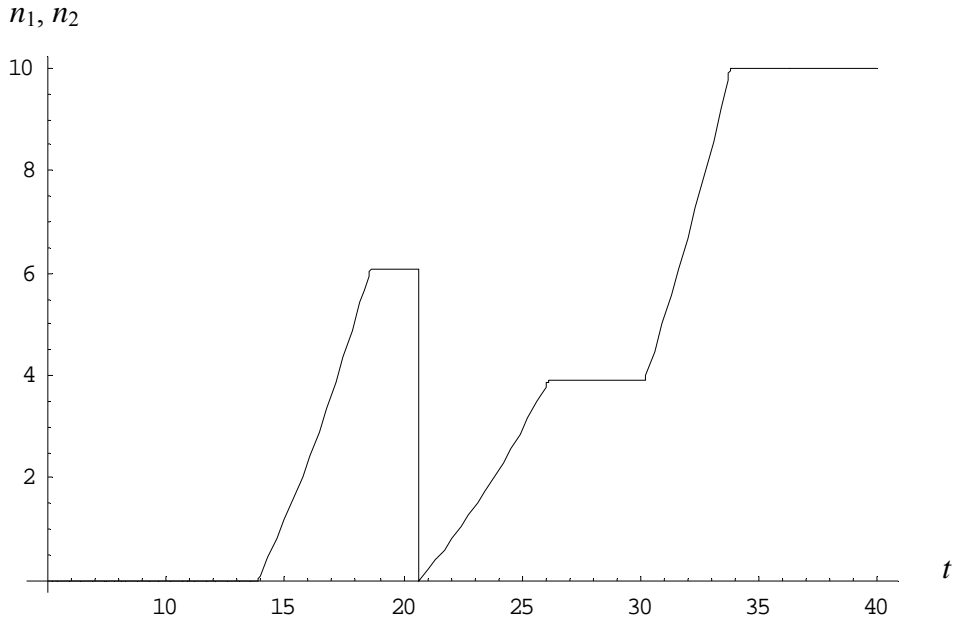


Figure 1: Diffusion pattern with leapfrogging; homogeneous firms

The variables n_1 and n_2 denote the (cumulative) number of adopters of generation 1 and 2, respectively. The diffusion of the first generation starts at 13.9 and about 60% of all firms adopt the first generation. The 40% leapfroggers start adoption of the second generation at about 20.5. About five periods after the leapfroggers have finished adoption ($t \approx 31$), adopters of both generations start adopting the second generation.

The simulation highlights a number of properties of the model. First, even with ex-ante homogeneous firms we obtain cases in which some firms adopt both generations, while others adopt only the more advanced technology. Second and related, profits of all firms are equalized. This holds by construction of the equilibrium diffusion curves. Third, there are time gaps between both the diffusion of the first and the second generation as well as within the diffusion of the second generation.

Leapfrogging speeds up the diffusion of the second generation, while it implies that not all potential users adopt the first generation. However leapfrogging leaves these parts of the diffusion curves unaffected, which capture the actions of adopters of both generations.

3.3 Diffusion with heterogeneous firms

In this subsection we examine the effect of firm heterogeneity on the diffusion pattern. In order to have a simple measure of heterogeneity and a tractable specification we assume the following functional form for the parameter $A(j)$:

$$A(j)^{\alpha/(1-\alpha)} = \frac{z+1}{z} - \frac{2}{z} \frac{j}{n} \quad \text{with } z \geq 1. \quad (12)$$

With this specification firm profits are uniformly distributed (see (4)) (among firms which employ the same technology). The ratio of profits $\pi_i(0)/\pi_i(n)$ and the ratio of outputs $Y(0)/Y(n)$, respectively, between the largest ($j = 0$) and the smallest firm ($j = n$) is $(z + 1)/(z - 1)$. It varies between 1 and infinity with z . Therefore, z provides a straightforward measure of the degree of firm heterogeneity.

In what follows, we describe diffusion patterns which result for different combinations of t_2 and z . In order to understand the results, it is helpful to remember the effect of increased heterogeneity in the single generation framework. Heterogeneity expands the diffusion process in the sense that diffusion starts earlier and takes longer than with homogeneous firms. Furthermore and in opposite to the homogeneous firms case, the identities of adopting firms are uniquely determined: larger firms adopt earlier.

Late emergence and strong heterogeneity: Overlap, but no leapfrogging.

We illustrate this case with a simulation employing the parameters of the previous section. Furthermore, we assume $t_2 = 18$ and $z = 3/2$. With this date of emergence no leapfrogging would

arise in the homogeneous firms case. The value of z implies that the largest firm is five times the size of the smallest. The diffusion curves are now of the following shape:

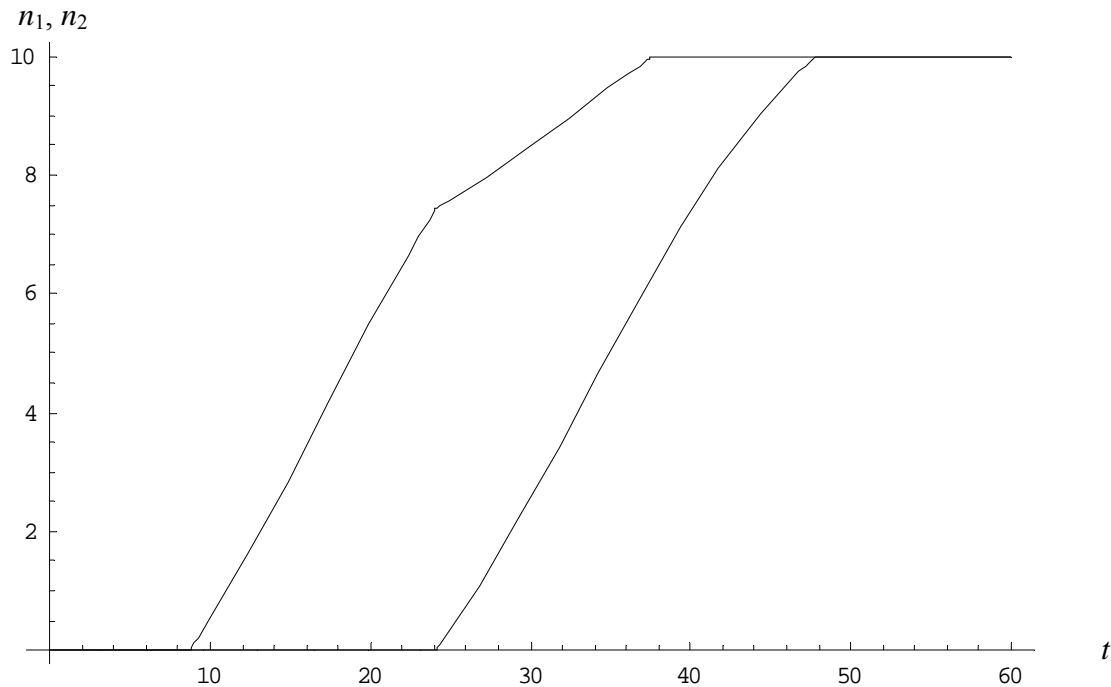


Figure 2: Diffusion pattern with overlap; heterogeneous firms

All potential users adopt both generations, but between periods 24 and 37, both generations are adopted simultaneously. This becomes even more obvious, when looking at the density functions depicted in Figure 3 rather than the cumulative distribution functions. The density functions provide the number of adoptions in a certain time span. In cases in which adoption mainly requires buying a new capital good, the density gives the per-period sales of a generation. Figures 3 and 4 show that the large firms may start adopting the next generation well before all firms in the industry have adopted the first generation. The overlap has various consequences. First, the fact that not all firms have adopted the first generation at the moment

that adoption of the second generation starts speeds up diffusion of the second generation and retards diffusion of the first. The reason is that the adoption gain for the large firms increases while that of the laggards decreases. The start of second generation adoptions reduces the intensity of first generation adoptions as becomes obvious in the downward jump of the density for the first generation.

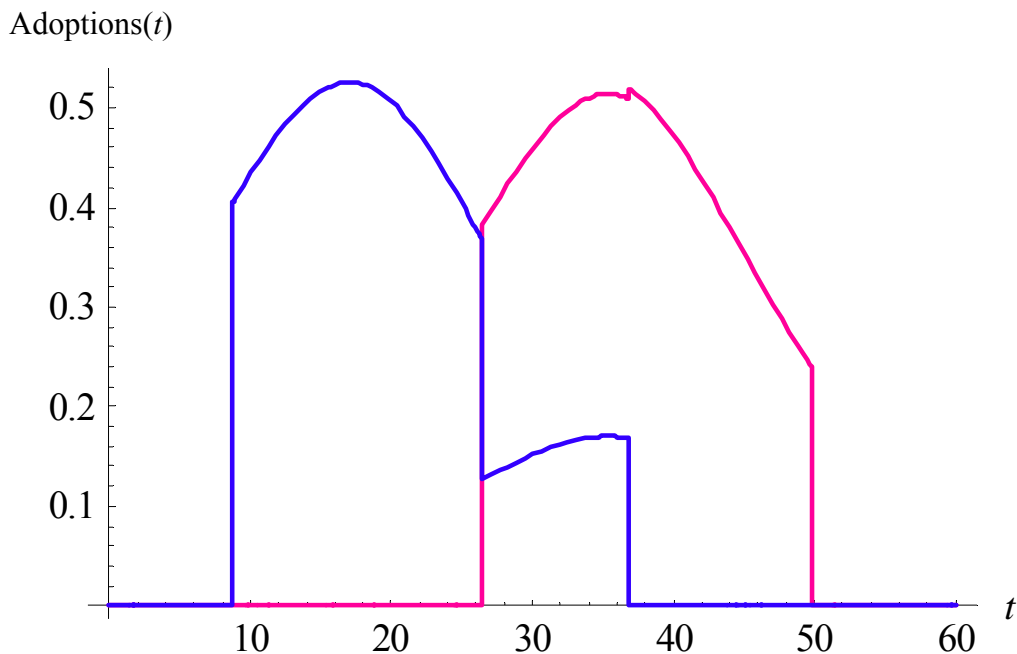


Figure 3: Density function (adoptions per period) with overlap; heterogeneous firms

Intermediate emergence dates and heterogeneity: Overlap and leapfrogging.

If we decrease t_2 compared to the previous case, the profitability of the first generation decreases and some firms might want to leapfrog. In the next simulation we use an intermediate date of emergence, $t_2 = 14$ as well as a moderate level of heterogeneity with $z = 2$, implying a ratio of three between the largest and the smallest firm. Figure 4 shows the resulting diffusion curves clearly exhibiting an overlap and leapfrogging. About 80% of the firms adopt the first

generation. In this case the densities, i.e. the flow of adoptions, is even more telling, as becomes clear from Figure 5.

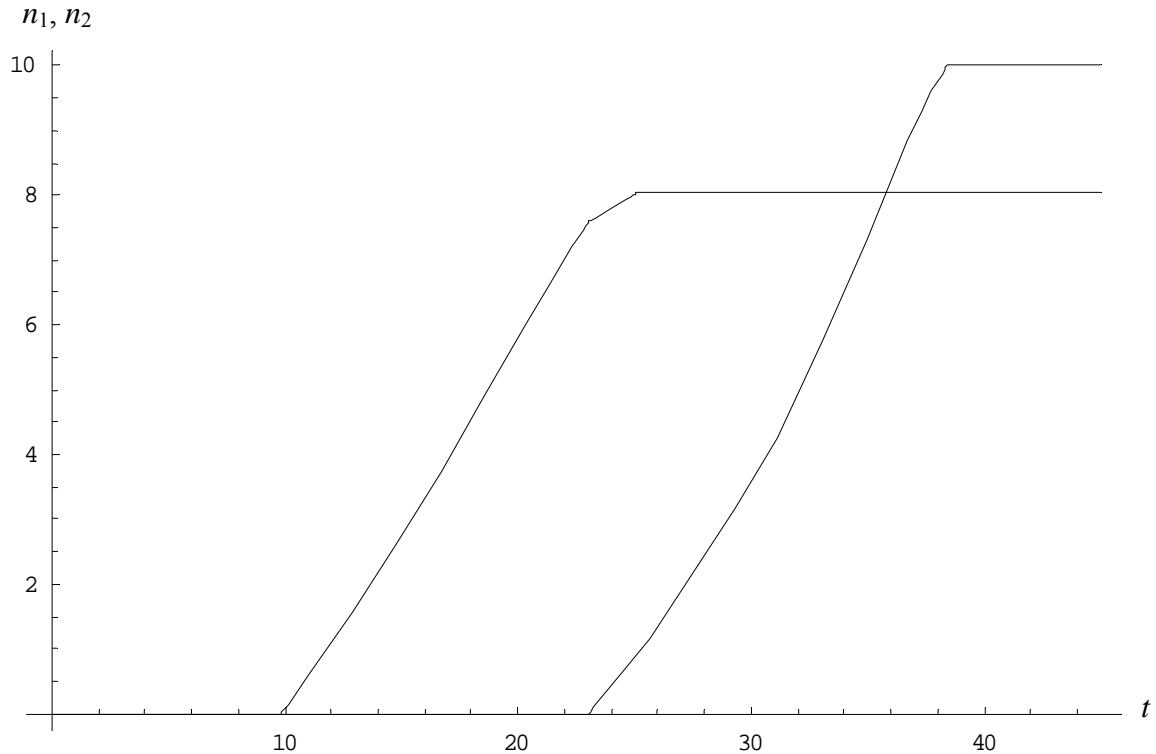


Figure 4: Diffusion pattern with overlap and leapfrogging; heterogeneous firms

As in Figure 3, the density function for the first generation jumps down once the first firms start to adopt the second generation. Analogously, and more visible than in Figure 3, the flow of second generations jumps up (at about $t = 25$), as soon as first generation adoptions stop. Most interesting is the hump starting at about $t = 32$. It is the result of simultaneous adoptions by leapfroggers and by adopters of both generations. From the fact that the leapfroggers are the smallest firms in the industry, an interesting result derives. In the range above $t = 32$, a technology is adopted by firms of different sizes at the same time. This is a contradiction to the usual prediction of rank effects models that larger firms adopt earlier (see Karshenas and Stoneman, 1995). The contradiction becomes even more obvious looking at the final part of the

density function for the second generation (t greater than 37.5). In this range the small leapfrogging firms have already finished adoption, while medium size firms still adopt. Therefore, the model yields a prediction that is contrary to established models and most empirical facts: smaller firms adopt before larger.

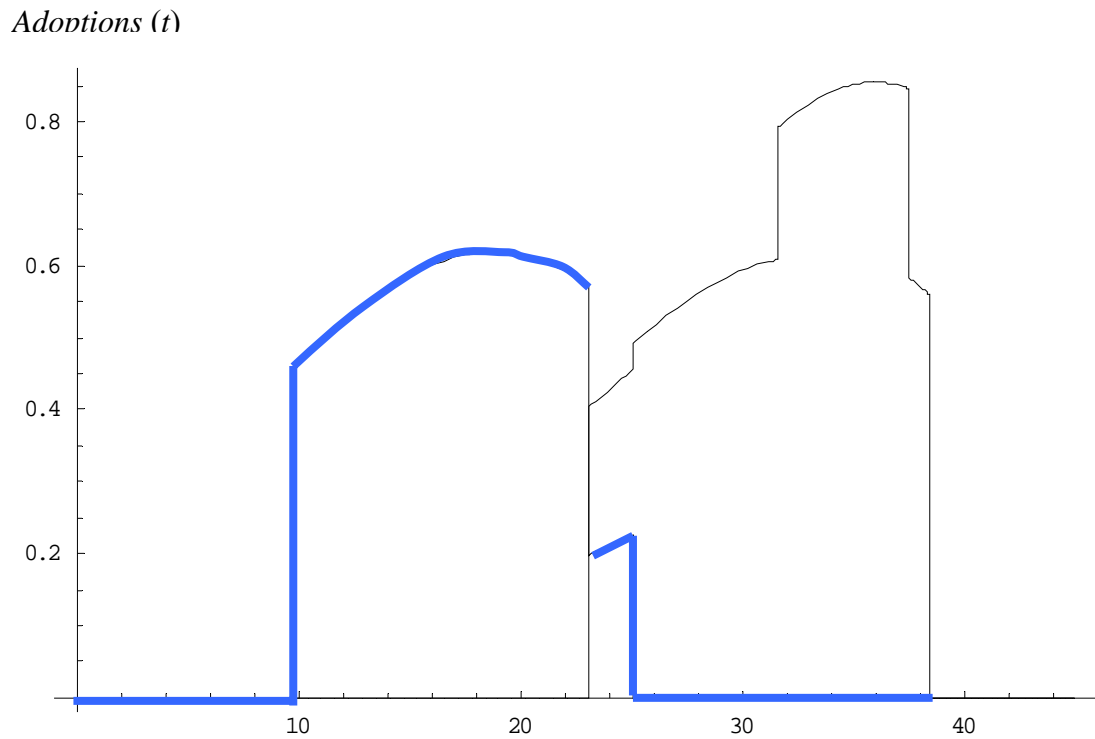


Figure 5: Density function with overlap and leapfrogging; heterogeneous firms

The above simulation assumed a modest level of heterogeneity. Stronger heterogeneity such as $z = 3/2$ section imply that the smallest firms are the last adopters even though they are leapfrogging. However, due to continuity of the $A(j)$ function the result that firms of different size adopt at the same time still holds. A final, rather obvious observation concerns the case with rather early dates of emergence of the second generation. In this case the result resembles the homogeneous firms case, we will find leapfrogging behavior, but no overlap.

4. Empirical Evidence

We have data on NC and CNC use from 318 plants in 23 well-defined U.S. metalworking industries. Detailed information on sampling and survey methodology can be found in Åstebro (2004.) A condition for being included in the sample is that the plant use conventional machine tools and have been conducting metalworking for three years prior to survey date. Our interest lies in testing some of the predictions of the model presented in Section 3 as well as in general indicating the existence and importance of the phenomena of overlap and leapfrogging. We start by addressing the latter point.

The diffusion patterns of the two generations are summarized in Table 1. Apparently the older technology exhibit somewhat of an upswing in its diffusion during the early eighties coinciding with the increased spread of CNC technology. CNC, however, continue to spread also in the late 1980s and into the 1990s while the rate of NC diffusion drops off. The rapid diffusion of CNC in the early 1980s coincide with the introduction of the PC and the concomitant drop in computer prices which also impacted on CNC prices and applications (Battisti, 2000). We, and others, believe that there was some spillover on those price declines to NC technology price declines that spurred the adoption of NC during the 1980s (e.g. Battisti, 2000).⁵

⁵ There could also, potentially, exist complementarities across the two generations so that in some cases the adoption of CNC might spur the adoption of NC machines. For an analysis of

Table 1. Diffusion of two generations of machine tools.

	62-75	76-80	81-85	86-90	91-93	Total*
NC #	11	12	17	12	3	55
%	20.0	21.8	30.9	21.8	5.4	99.9%
CNC #	5	18	40	44	17	124
%	4.0	14.5	32.2	35.5	13.7	99.9%

* Some plants have missing data on first year of adoption while there is still data on whether the plant has adopted the technology or not. This table only use data from plants reporting first year of adoption. Columns do not sum to 100% due to rounding error.

For those plants that had adopted both technologies by 1993 we can establish the sequence of adoption of NC and CNC. There were 41 plants in our sample with full data on this matter. Of those a clear majority, 31 (76%), adopted NC before CNC, 2 adopted CNC before NC and 8 adopted CNC in the same years as NC. This pattern is also broadly consistent with our model.

Having established the existence and pervasiveness of both leapfrogging and overlap in diffusion for the case of NC and CNC we move on to examine model prediction for the case in which both leapfrogging and simultaneous adoption occurs. The model predicts that it is the smallest firms which leapfrog, while medium to large size firms adopt both generations and are responsible for the overlap. We examine these predictions first by analyzing differences in average plant sizes across leapfroggers and adopters of both generations. Taking the logarithm of dollar value of plant shipments in 1992 we find a statistically significant difference ($t=-2.67$, $m_1=15.29$, $m_2=16.12$, $n_1=82$, $n_2=67$, unequal variances.) showing that indeed leapfroggers are

complementarities across two different but related technologies and its effect on diffusion see Åstebro, Colombo and Seri, (2005).

on average smaller than plants adopting both generations. The average plant size and standard deviation of the estimate for various groups of firms are displayed in Table 2, which include previously mentioned data.

Table 2. Average plant size for various groups of adopters and non-adopters.*

Group	NC	CNC	\bar{x}	σ	N
1	0	0	13.94	2.28	151
2	1	0	14.34	1.48	17
3	0	1	15.29	1.82	82
4	1	1	16.12	1.95	67

* Means reflect natural logarithm of 1992 dollar value of plant shipments.

It could be argued that plant size in 1992 is endogenous to the adoption decision and that the test is biased if the adopters of both technologies grow faster than those adopting only CNC. As a remedy against this potential problem we examine difference in sizes across plants in 1987 only for plants that adopt CNC on or after 1987 and were established before 1987 (so that size in 1987 is not zero). 49.1% of the adopters adopted CNC in 1987 or later, implying that plant size in 1987 was likely not endogenous for those. In this comparison the difference in 1987 plant size between leapfrogger and adopters of both generations was in the direction expected but not significant ($t=-1.41$, $m_1=12.96$, $m_2=14.38$, $n_1=22$, $n_2=28$, unequal variances.)

Testing the prediction that it is the medium to large firms that are responsible for the overlap in diffusion we examine the size of plants that adopt NC in the later years of CNC diffusion and compare these to leapfroggers. Table 3 reveals that the “footdraggers” that eventually adopt NC and also adopt CNC (group B in Table 3) are indeed significantly larger

than leapfroggers (group 3 in Table 2.), $t=2.58$. Footdraggers are as well somewhat larger than early adopters of NC that also adopt CNC as Table 3 displays. While this difference is not significant it is a difference that is opposite of what is typically expected: received wisdom is that early adopters are larger. From Table 3 it is clear that the major difference in size is between those that adopt one generation or both generations, not between those that adopt a single generation early or late.

Table 3. Average plant size for NC adopters.

Group	Timing of NC adoption	CNC	\bar{x}	Std. Dev.	N
A	After 1980	0	14.50	1.65	13
B	After 1980	1	16.19	2.03	52
C	Before 1980	0	13.82	.61	4
D	Before 1980	1	15.90	1.66	15

Notable is that the empirical results reported above are not inconsistent with previous empirical analysis which shows that adopters of new technology are on average larger than non-adopters (e.g. Åstebro, 2002.) We find that adopters of either CNC or both NC and CNC are all statistically significantly larger than non-adopters. However, we find new evidence indicating that the late adopters of NC technology are primarily the large companies which adopt both technologies. This result is consistent with our model prediction indicating that it is the large companies that are mostly responsible for the overlap.

Our model further predicts that for those adopting both generations, the difference in time of adoption decreases the later the adoption of the 1st generation. We have data on the dates of adoption of NC and CNC for 38 plants adopting both these technologies where CNC is adopted at the same time or after adopting NC (we dropped two observations where CNC was adopted before NC). The average difference in years of adoption is 4.89 years, the minimum was zero and the maximum difference is 21 years. For these 38 plants we ran a Tobit regression with the difference in time of adoption as dependent variable and the time of adoption of NC as predictor, the difference censored at zero. The resulting model has a coefficient of -0.48 for the time of adoption of NC, with a t-statistic of -5.32. The size of the coefficient means that for every year later that the plant adopts NC, the difference in time of adoption between the two generations is reduced by 0.48 years. The prediction is thus well supported by the data.

5. Conclusions

We model adoption decisions by competitive firms when successive generations of a new technology become available over time. Profit-maximizing firms choose which generation to adopt and at which adoption date. The model accounts for leapfrogging and simultaneous adoption of different generations. Leapfrogging occurs if a potential user does not adopt the state of the art technology but adopts the next generation. In the simultaneous adoption case some adopt the new generation while others still adopt an old generation. The two mentioned patterns are shown to be equilibrium outcomes that depend on exogenous parameters. Both overlap and leapfrogging may arise from the same parameters. As a consequence, firms of different sizes may adopt a generation at the same time. The model predicts that leapfroggers, who are the smallest firms in the industry, may well adopt the new generation before medium and large firms and that large firms are likely to adopt both generations. Empirical analysis on the adoption of two

generations of machine tools (NC and CNC) by U.S. metalworking plants show that there is indeed substantial leapfrogging: 26% of all plants in the sample had adopted CNC but not NC by 1993. There was also overlap in adoption: 68% of the adopters of CNC adopted during 1981-1993; 53% of the adopters of NC adopted that technology during the same period. We find that the non-adopters of both technologies (NC and CNC) are the smallest, the adopters of NC but not CNC are on average larger, the leapfroggers are still larger and the largest plants, on average, adopt both technologies. Leapfroggers adopt CNC approximately one year earlier than adopters of both technologies. Empirical results are broadly consistent with model predictions.

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