THE CASE FOR DISCONTINUITY IN THE DIFFUSION OF PROCESS INNOVATIONS: THE PROBLEM OF SMALL FIRMS IN MATURING INDUSTRIES

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Introduction

A widely accepted tenet of contemporary analyses of the diffusion of innovations is that certain types of organizations are better positioned than others to instigate and adopt innovations (David, 1969, 1975; David and Olsen, 1984; Davies, 1979; Mansfield, 1968; Mansfield et al., 1977; Nabseth and Ray, 1974; Stoneman, 1980; Utterback, 1988). With respect to new process technologies, the advantages from being an early user of a superior technology seem to derive largely from the accumulation of experience, that is, from gaining a head start in the process of learning-by-doing necessary to successfully implement a new process technology. Yet differences in firms' capacities to experiment, i.e., to indulge in such a learning process, have not been given much attention as a potentially significant obstacle to a technology's diffusion. Instead, subsequent developments of a technology are assumed to allow late adopters to leap-frog over earlier stages in the learning process. The failure to adopt a well-known technology is not presumed to reflect any weakness in a firm's capacity to innovate, but only a strategic assessment of the costs and benefits associated with deferring the decision to adopt in the light of its particular business strategy and market niche.

In general, diffusion models assume that lead users are not fundamentally different from non-adopters. That is, the same parameters influencing those that have already adopted a new technology are expected to apply to the remaining non-adopters. No discontinuities in innovative capacity or in the set of factors influencing the decision to adopt a new process technology are assumed to differentiate those economic organizations likely to adopt a process innovation from those that are unlikely to do so. Rather, with few exceptions, attempts to explain patterns of diffusion have been predicated on an "epidemic" model of the diffusion process, in which all firms that could possibly derive economic advantage from the use of a superior new technology are assumed to eventually do so.

In this paper, we are concerned with explaining the apparent unwillingness of a distinct class of economic organization to adopt well-known technology improvements. That problem has of course been the underlying concern of all studies of diffusion: "to rationalize why, if a new technology is superior, it is not taken up by all potential adopters" (Stoneman, 1983; p. 65). In a departure from previous theorizing on this question, we hypothesize that there exists a discontinuity in the adaptive capacity of organizations related to their size, particularly in mature industries with mature process technologies, which accounts for the persistence of a failure to adopt a new technology. Only when external economies supplement the limited resources of such organizations and thereby underwrite the risk of innovation would we expect small firms to have a high chance of making the shift to a new technological regime. Moreover, barriers to exit for existing small firms and the low attractiveness of these markets for new entrants result in enclaves of technological backwardness within national economies. We thus hypothesize further that shifts in the locus of technology leadership among nations associated with the emergence of new techno-economic paradigms, such as seems to be occurring between the U.S. and Japan, may reflect as much (if not more) on the inadequacy of national institutions to expedite the adjustment of technologically backward firms as on the superiority of a nation's "system of innovation" in fostering the vanguard (Freeman, 1988).

Learning By Doing: A Paradox for Diffusion of New Process Technologies

Productivity increases arise both from the shift to a new, more efficient technology, and from continued improvement in the way in which an existing technology is utilized. Indeed, for some period of time when both emerging and mature process technologies coexist, additional improvements in the mature techniques also occur and frequently accelerate (Harley, 1973). Whether emerging or mature, every technology has its own associated learning curve. Incremental learning about how best to use a particular configuration of equipment is the basis for productivity improvements which proceed under the same technological regime. The knowledge derived from such marginal adaptations accumulates over time, becoming part of the informal or "tacit" know-how -- the craft "art" recognized by many observers as a key ingredient that distinguishes high from low productivity operations employing the same technology (Bohn and Jaikumar, 1986; Kusterer, 1978; Pavitt and Patel, 1988; Skinner, 1986).

New process technologies always involve a change in the ways in which products are made -- a change in the allocation of tasks, a change in machinery, a change in work methods which may imply retraining, or a change in organization. There is always some uncertainty about how much new knowledge will be necessary and how drastic a change the new configuration of equipment and people will entail (Bohn 1987; Rogers, 1983). If these changes require substantially new skills and expertise, then a displacement of the learning curve results, i.e., a discontinuity arises between the organizational learning accumulated under the previous production regime and that which is needed for the new technology. This could even result in a short-term decline in productivity until a certain portion of the new learning curve has been traversed as the organization develops the additional expertise needed to more fully exploit the potential advantages inherent in the new technological trajectory.

When a process innovation signals a paradigmatic shift in technology, as seems to be occurring with the application of information technology in manufacturing, the highly specific know-how from the old technological regime is not transferable to the new paradigm.[1] In order to make such a shift successfully, firms have to buy, borrow, or somehow internally develop a new expertise which is matched to the emerging system. The costs that such a shift in learning curves would entail are difficult to estimate in advance, but the greatest difficulty is likely to be experienced by firms in which current survival and profitability depends most on the accumulated tacit knowledge associated with older techniques. The more isolated the firm is from potential sources of expertise, such as other firms with experience in advanced technology, the higher these costs are likely to be.

In economic models of diffusion that attempt to incorporate learning by doing (Stoneman, 1980), no explanation is offered for how one firm acquires the knowledge accumulated within other firms from their experience in utilizing the new technology. Late adopters are presumed to learn about the experience of early adopters through osmosis, that is, through informal contact and exchange of know-how among managers and engineers employed in different firms. Yet there is considerable anecdotal evidence to suggest that such an exchange does not occur easily or "naturally."

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[1] Certain changes in technology involve such a radical shift <u>away</u> from existing techniques that traditional competencies and skills are made obsolete (Abernathy and Clark, 1985; Tushman and Anderson, 1986).

When the number of firms is small but all are relatively large in size and rivals are identifiable, improvements in the utilization of new process technologies are a source of competitive advantage.[2] To protect itself, the firm will try to prevent "leakage" of its accumulated, proprietary or tacit knowledge to potential competitors. Case study evidence suggests that, under such circumstances, management will attempt to (and is often successful at) keeping that knowledge secret (Von Hippel, 1988). Moreover, whatever information is transmitted between rivals about their methods of operation is likely to be distorted, tending to exaggerate success and to minimize mistakes. Hence, such arms-length, non-collaborative exchanges are not very reliable sources of practical knowledge about how to handle various implementation problems.

When there are many small firms, none of which obviously enjoy a particular competitive advantage over any other, then it becomes extremely difficult for the firm to evaluate the information gained from an exchange with others about their experience of new technology. Even if the firms are not direct competitors, the simple exchange of information may not be a very good mechanism for transferring expertise. When the process innovation em-

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[2] Galbraith (1956) provides a rationale for the preference of large firms for this type of competitive strategy: "technical development is a 'safe' rather than a reciprocally destructive method by which any one firm can advance itself against its few powerful rivals" (p. 88).

bodies a radical departure from existing techniques and is generic to a wide range of product markets -- as occurs when there is a shift in techno-economic paradigm -- there will be a greater tendency to mistrust the applicability of others' experience and to discount any expertise acquired outside the firm (because other firms are not presumed to engage in making exactly the same mix of products or utilizing their process technology in exactly the same way).

For firms to learn from the experience of others, there must be a trustworthy agency which facilitates the exchange of useful information, helps filter out erroneous or irrelevant news, and promotes the accumulation of tacit expertise within the firm. Though highly valued because of their specificity to problem situations, certain kinds of information, i.e., so-called "tricks of the trade," which ease the adaptation from the old to the new process, are less likely to be in general circulation. For example, marketing communications aimed at spreading general knowledge about the potential capabilities of a new technology do not address these information needs. Meetings of professional associations and industry trade shows where equipment manufacturers display their wares may be an effective means of learning about the general attributes of a new technology but are not vehicles especially well-suited for learning about how to apply a process innovation in a particular firm with a particular market niche or product mix.

Through their service activities, capital equipment manufacturers or distributors can be an agency through which praxis in how best to deploy a new technology is "taught" (Ettlie and Rubinstein, 1980; Leonard-Barton, 1988).[3] Equipment manufacturers will sometimes customize the design of new systems for lead users, adapting the innovation to the customer's specific production requirements, and providing intensive follow-up support services during the initial implementation phase (Collis, 1988; Von Hippel, 1988). They do so in anticipation of winning a large, loyal customer or as part of an experimental developmental effort which will result in improvements in the design of future generations of the technology. When the user dedicates some of its own organizational resources toward that collaborative effort, then it is also likely to engender organizational expertise within the user-firm as a result of close interactions of key personnel involved in such working relationships.

Such arrangements are known to occur particularly in the early phases of the development of a new technology, are sometimes reserved for customers that purchase expensive systems, or are made available to large users from which the equipment maker expects a hefty order. But there is little economic incentive

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3 See Guile (1986), for a discussion of the importance of the role of equipment manufacturers and distributors in disseminating such knowledge and the possibility of market failure when the conditions for appropriating returns from such marketing activity are very weak.

for manufacturers to provide similarly individualized tutoring services to the myriad of small, traditional firms that individually are likely to make only a small investment in the new technology. The expected sales from such a costly marketing effort would be too low to justify the expense. The network of collaborative relationships among equipment manufacturers, distributors and potential users of a process innovation is a relatively exclusive one, leaving out many firms. Thus, customer services provided by equipment manufacturers are a very imperfect mechanism for easing the adjustment problems of large numbers of small firms as compared with large firms.

There is the possibility that by concentrating on the application problems and needs of large, lead users, as Von Hippel suggests, equipment manufacturers can anticipate the problems of non-adopters and build solutions into subsequent generations of the technology which can be expected to eventually reduce the break-in period and hence permit more rapid learning-by-doing among later adopters. To be sure, these improvements in the initial innovation will accelerate movement along the new learning curve <u>once the shift to the new technology has been made</u>. But they will not necessarily diminish the disjuncture in expertise associated with the shift from the traditional to the new knowledge base.

One mechanism for the circulation of specific know-how which is not dependent on any special interchange among economic organizations occurs through inter-firm mobility of key personnel. The kind of "job-hopping" of talented managers and engineers which helps circulate new knowledge tends to happen within fast-growing sectors in which firms are developing emerging technologies, as in computer software. When growth opportunities are poor and cost-cutting strategies common, as is often the case among small firms in industries with mature process technologies, the "bidding" for highly-skilled personnel which encourages job-hopping is much less likely to occur. Under such circumstances, personnel turnover is a weaker mechanism upon which to depend for the circulation of new knowledge.

In sum, learning by doing is a necessary, but costly, first step in the implementation of any new process technology. For the small firm used to relying on traditional techniques, the costs of adjustment do not necessarily diminish over time even though advances in the technology may make it more transparent and hence easier to use. Moreover, existing mechanisms for circulating information and know-how, which are presumed to ease the transition and accelerate the learning process, often leave out such firms, further diminishing the likelihood of adoption.

Fundamental Differences in Strategic Perspectives of Small and Large Firms

Previous research showing large firms to be leaders in the adoption of process innovations have been explained in terms of the scale of the technology or scale thresholds related to the high initial cost of the innovation. Scale effects were first thought to be important only in some industries, but not others (Mansfield, 1968). Hence, where the scale of investment necessary for a new process technology is very large, it can only be undertaken by large firms; small firms simply lack the financial resources or size of revenue stream to make such an investment. On the other hand, when the cost of the innovation is not very high, diffusion should occur rapidly among small firms. In a variant of this idea, David (1969, 1975) argues that, although large firms may indeed be leaders in the adoption of an innovation because they can most easily afford the initial purchase price of a new technology, subsequent improvements in the technology can be expected to reduce its cost. Over time, the price of making the investment in new technology is expected to fall relative to the price of labor (which is presumed to rise over time), hence making the adoption of the innovation more attractive to smaller firms. However, even if the investment becomes less costly, Davies (1979) predicts that large firms, in general, would still be more likely to adopt a new technology because the payoff period (and hence the risk) for larger firms is invariably shorter (smaller). In mature industries, the accumulated organizational learning embedded in tacit know-how constitutes a competitive asset that is relatively more risky to sacrifice for the small firm than it is for the large firm because the consequences of underestimating the displacement of the learning curve are much more serious for the small firm than it is for the large firm. Hence, these findings suggest that there may be a fundamental discontinuity in the strategic considerations underlying firms' investment behavior which is related to their size and to the kind of competitive environments in which they function. Were that the case, a very slow and uneven pattern of diffusion of new process technologies would invariably occur in sectors with modest opportunities for growth and where large numbers of small firms abound.

When it comes to the risks associated with a new technology, the financial and economic resources of large firms clearly give them an advantage over small firms.[4] Resource-rich organizations have a greater capacity to absorb costly mistakes incurred during the shift from the old to the new learning curve and the initial learning process. As a result of their size, large firms are less vulnerable to the consequences of a strategic error in deploying any single piece of new equipment that does not achieve its expected savings. Moreover, because of its potential purchasing power as a consumer of process technology, a large size firm often has privileged access to special services by equipment manufacturers who have a big stake in the success of their equipment. These services further augment the internal resource advantage of large firms over small firms in implementing a new

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4 Utterback (1988) is an exception to this view, arguing that for both new process technologies and product innovations, the "most innovative" firms are likely to be the small, new firms in newly emerging industries. A weakness of his framework, in our view, is that for so-called "mature" industries or sectors, neither small nor large firms are expected to be innovators.

technology. Yet the differences in the resource base of different size firms give an insufficient account of why, when both small and large firms could benefit from the adoption of a new process technology, we would still expect to find a size-related difference in the pattern of diffusion. Differences in the competitive environment and the strategic approaches of small firms and large firms need to be considered.

The concept of corporate strategy is predicated on the assumption that firms operate in a world of imperfect competition, in which the possibilities for gaining temporary advantages over potential rivals abound. The strategic concerns of large firms, of course, vary with the kinds of markets in which they operate. But to a degree, technology development for new products or the adaptation of new process technologies nearly always play some role. As part of a strategy to attain or maintain leadership in one market, the large firm may seek to develop proprietary technology which provides a unique cost or quality advantage over its competitors. When a firm operates in a number of markets for which there is a shared technical basis, there is the possibility of achieving a greater synergy from exploiting advances in process technology. Being relatively quick to use new production techniques can provide such a firm multiple cost or quality advantages over its competitors in several markets at once. A third possibility is that the large, diversified firm can exploit new technology through vertical integration, by being both a manufacturer and a user of a process innovation.

By contrast, the small firm has a more limited set of alternatives and resources to bring to bear on its strategic choices. The closer the market conditions approximate atomistic competition, the more difficult it is for the small firm to engage in any long-term planning and to develop a long-term technology strategy of any kind. Consider, for example, the situation of the small manufacturing firm with expertise in a mature technology operating in a maturing industry where the prospects for sales growth are poor, i.e. sales trends are flat or only growing at a slow rate, and profit margins are slim. These circumstances sharply limit the firm's planning horizon. For the short run, the firm's aspirations are modest, being concerned simply with survival. The manager/owner may be willing to accept lower revenues and even profits in order to be more certain of staying in business.

In such circumstances, we would expect the small business owner/manager to consider a shift to a new process technology to be outside the realm of rational strategic choices.[5] In the short run, that option exposes the enterprise to greater risk and uncertainty. Hence, management will consider technology to be fixed. Instead, management is likely to focus its attention on familiar problems, attempting to adapt by gaining greater control

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5 The economic environment conditions these choices, or as Simon (1957) put it, "nature and perceptions of its environment limit sharply [the firm's] planning horizon."

over variable production costs in order to make more efficient use of existing equipment and labor (March and Simon, 1958). Management may forestall wage increases or actually reduce wages. Equipment may be operated more continuously, sacrificing downtime for preventative maintenance and further depleting the useful life of the capital stock.

We might plausibly assume further that there are barriers to exit, i.e. the small firms in such industries may have the choice of going out of business but not the choice of entering new business because there are no known better alternatives to which the organization's skills and expertise (and the owner's capital) can be put. Moreover, because of its poor growth prospects, new, more technologically advanced firms do not find these markets attractive for entry. With both barriers to exit and weak attractiveness of entry, small, technologically-backward, firms are likely to survive in maturing industries for a protracted period of time, retarding the diffusion of technology and contributing to stagnation in productivity growth.[6]

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[6] Insofar as large firms that may themselves be quite sophisticated in their use of advanced manufacturing technologies continue to rely on suppliers with these characteristics, their ability to compete against firms with a technologically advanced supplier chain is also diminished.

An Illustration: A Comparison of Adopters and Non-adopters of Programmable Automation

Much has been written about how information technology -- i.e., applications of advances in computers and telecommunications -- is altering economic life. Programmable automation (PA), in the form of numerically controlled (NC) and computerized numerically controlled (CNC) machine tools and the more complex flexible manufacturing systems (FMS), is a particularly noteworthy IT application because it is the first flexible form of automation which can reduce the costs of manufacturing goods made in small size lots to customer order. Prior to the development of this technology, automatic machines had a fixed sequence of steps built-in to the machine that could not be altered. Hence, automation was presumed to be economically advantageous only for large-scale, high volume operations, such as occurs in the manufacture of bottles and automobile engine blocks. Because instructions controlling the operation of machines are incorporated in software, not the hardware, programmable machines are adaptable to both small and large-volume production in a wide variety of industries. The widespread adoption of programmable automation is believed by many writers (Freeman and Perez, 1986; Hirschhorn, 1984; Kaplinsky, 1984; Perez, 1986; Piore and Sabel, 1984) to signal a shift to a new techno-economic paradigm in which economies of scale are much reduced. But in order for the full advantages of the technology to be realized and to lead to a new wave of growth, organizational and institutional changes are thought to be necessary.

To date, the main application of programmable automation has been to the precision metal-cutting operations of turning, milling, grinding, and boring. By 1982, the combined output from six of the major machine-tool producing countries (U.S., Japan, F.R.G., France, Italy, and the U.K.) indicated that programmable machines had become the dominant technology, the annual production of NC/CNC machines having reached two-thirds of the total value of production of metal-cutting machines.[7]

At first glance, the attributes of this technology would suggest that it is a generic process innovation of wide applicability for both large and small firms operating in a variety of different product markets. First, there is no inherent technological scale required for its use -- that is, single machines can be installed one at a time and used alongside conventional (non-programmable) machines. Second, the technology is applicable to a process (metal-cutting), which is important in the manufacturing of many different products, from coffee grinders to jet engines. Third, since the mid-1970's, improvements in the technology have made it easier to use, even more productive than

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[7] Source: Table 3.3 in Edquist and Jacobsson (1988: p. 26).

conventional machinery, and progressively less costly to purchase (Edquist and Jacobsson, 1988).

If one assumes that the programmable technology is a very close substitute for conventional machine technology in a wide range of applications, then more than 25 years after its initial introduction, one might expect the technology to be widely adopted in the United States. Yet as of 1987, the technology is still at a rather low to intermediate stage in its diffusion. The results of our comprehensive examination of the extent of the diffusion of programmable machine tools among U.S. manufacturing establishments show that only 11 percent of the stock of machine tools in use are programmable (Kelley and Brooks, 1988). We also find a highly uneven pattern of diffusion. Fifty-seven percent of all plants that use machine tools had not yet installed even one programmable machine.

There are, of course, a number of economic factors, such as the relative cost of labor and the degree of dependence on workers in skilled machining occupations which explain, at least in part, why some enterprises (and not others) are more likely to have adopted the technology.[8] However, after controlling for these and other differences in production characteristics, and the types of information networks on which management depends to

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[8] For details on the models and a description of the variables, see Kelley (1988).

learn about new technological developments, our analysis shows that large U.S. plants of large multi-plant enterprises are far more likely than small, single-plant enterprises to have adopted any programmable machines. Among large establishments employing an average of 1,300 workers in large, multi-plant corporations, averaging more than 100,000 employees, one is nearly certain to find at least some programmable machines in use; the chances in favor of having adopted the technology in such organizations are nearly 19:1.[9] For small plants employing less than 50 workers in small firms with a maximum of 85 employees company-wide, the chances that even one programmable machine would have been installed in 1987 were at best 50:50.

[INSERT FIGURE 1 ABOUT HERE]

More than three-fourths of the sample establishments in the 21 industries[10] we surveyed are engaged in market-mediated transactions for the output from their machining technology. These

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[9] These probabilities are estimated from the results of a logistic regression model. Holding all other variables in the model constant at the sample means, these estimates for firms of different sizes and degree of organizational complexity were computed from values of a composite factor scale variable that takes into account the co-variation of firm (i.e., company or corporation) and establishment size, whether or not the plant is part of a multi-plant enterprise and whether the output of the machining process is an integral part of a chain of production activities taking place elsewhere in the firm.

[10] The industries are: nonferrous foundries (SIC 336), cutlery, hand tools and hardware (SIC 342), heating equipment and plumbing fixtures (SIC 343), screw machine products (SIC 345), metal forgings and stampings (SIC 346), ordnance and accessories, not else-

firms are typically small single-plant enterprises that make parts, specialty equipment, or tools for sale to other manufacturers. On average, less than half of such small supplier-firms have any programmable machines.

Among parts-supplier firms, it is the relationship with their customers, rather than access to any other type of information network, that is most important in increasing the likelihood of PA adoption.[11] However, transaction ties are rarely so strong

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(continued)

where classified (SIC 348), miscellaneous fabricated metal products (SIC 349), engines and turbines (SIC 351), farm and garden machinery and equipment (SIC 352), construction and related machinery (SIC 353), metalworking machinery and equipment (SIC 354), special industrial machinery (excluding metalworking (SIC 355), general industrial machinery and equipment (SIC 356), miscellaneous machinery, excluding electrical (SIC 359), electrical industrial apparatus (SIC 362), motor vehicles and equipment (SIC 371), aircraft and parts (SIC 372), guided missiles and space vehicles (SIC 376), engineering and scientific instruments (SIC 381), measuring and controlling instruments (SIC 382), jewelry, silverware, and plateware (SIC 391).

[11] With respect to the role of equipment manufacturers and distributors, in general, we find that about one-third of all production managers in the plants surveyed rely on direct contact with sales representatives who visit the facility for information about new technological developments. However, such contact does not translate into a special relationship of particular importance and significance for PA adoption, except when the output from the plant's machine tool technology is exclusively "consumed" or totally "integrated" into the production of some other final good the firm manufactures. The plants (and parent firms) that use machine tool technology solely in this way tend to be larger, more complex organizations than those that sell at least part of their machining output to some customer external to the firm.

between U.S. firms that a customer will provide financial support to its suppliers for investment in new equipment. Only 3 percent of plants that sell their machining output to other firms report that their customers provide such financial assistance. Involvement of a customer in the decision to adopt a new technology is also relatively rare. Just 9 per cent of U.S. plants with direct customers for their machining output report that these customers require or request the use of programmable machine technology. The most common type of close linkage between U.S. supplier firms and their customers occurs through the exchange of technical personnel. Nearly one-fourth of production managers in supplier-plants report having engineering and programming staff "on loan" from a customer to assist them in improving their manufacturing operations.

This type of collaboration between supplier and customer firms does not generate the kind of external economies which promote the transfer of technical know-how important to the adoption of programmable automation independent of the type of industry in which the supplier operates; it is a practice that is closely related to industries in which the share of total sales purchased directly or indirectly by the U.S. Department of Defense (DOD) is relatively high. For example, fifteen percent of all supplier-plants are in industries that have a very low dependence on DOD as a customer, amounting to only 4 percent or less of total sales. With all other characteristics assumed to reflect the average firm, when the small single-plant enterprise (employing no more than 85 individuals company-wide and with a plant workforce of fewer than 50 employees) operates in these industries the chance of PA adoption are at best 1.3:1, even with the benefit of customer-provided engineering assistance.[12]

Nearly one-fourth of the establishments in U.S. metalworking industries are in industries with a moderate degree of dependence on Defense as a customer -- between 10 and 30 percent of total sales. For the small enterprise, which is similar in all other respects to its counterpart in industries with a low dependence on Defense, when the firm's major product is identified with an industry that has just 10 percent of its sales going to Defense and is fortunate enough to benefit from its customers' engineering expertise, the chances of PA adoption are much improved, at 2.5:1. When 30 percent of total industry output is for sales to Defense, the chances of PA adoption for the small firm are quite high, at 5.2:1, assuming customer-provided manufacturing engineering assistance. Among industries with a very high dependence on sales to Defense (70 percent of industry sales, such as occurs in the aircraft industry), the odds favoring adoption of programmable automation by the small firm with close engineering support from their customers are very high, at better than 15:1. For the small firm, it is therefore possible

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12 See Appendix Table for a comparison of the probabilities of PA adoption for small firms with and without engineering assistance from their customers in industries with different degrees of dependence on the U.S. Department of Defense as a final customer.

for the external economies engendered in environments that foster close supplier-customer relationships specifically intended for the purpose of improving manufacturing operations of the supplier-firm (which seems to characterize Defense subcontracting relationships) to closely approximate the internalized economies of scope enjoyed by large, multi-plant firms, which make them better-equipped to adopt a new process technology such as PA.

The supplier firms least likely to adopt PA are very small firms, employing on average about 20 people, producing a more limited variety of products than the average firm, and paying 20 percent below the average wage. In these firms, managers don't use computers for such ordinary functions as production planning and inventory control. Moreover, as hypothesized, firms with the least chance of adopting PA are isolated, relying solely on printed media (e.g., advertisements, mailed catalogues, and published papers) for learning about new technological developments. They do not attend trade shows or have much contact with other manufacturers like themselves, and don't have customers that will provide them any assistance in improving their production operations. Furthermore, when operating in particular industries that have a very low share (4 percent or less) of total sales to the U.S. Department of Defense, such small supplier-firms were found to have only 1:10.5 chance of adopting programmable machine technology.

We find further support for the proposition that those small firms that have failed to adopt programmable automation thus far are unlikely to do so in the near future. That is, their unwillingness to purchase a programmable machine is indicative of a short-sighted survival strategy that is likely to persist over time. Despite improvements in the technology that have made it easier to use and less costly to install, two-thirds of non-adopters perceive the payback period associated with the introduction of PA as being too long to justify any investment.

That unwillingness to invest in programmable automation is indicative of a general unwillingness (and lack of resources) for making investment in their capital stock. The average investment in new equipment of any kind for firms that had not purchased any PA at the time of our survey was less than one-third the amount invested per employee by PA users in the same year.[13] Over the previous five year period (from 1982-1986) during which time more than half of all programmable machine tool installations presently in use in the United States were purchased, two-thirds of enterprises that made no such purchases never even considered that alternative. Moreover, less than ten percent of those that have

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13 In 1986, an average of $6,265.51 per employee was invested for new equipment among establishments with programmable machines, compared to the $1,972.40 per employee invested in establishments that were found to have no PA technology.

failed to invest in PA to date report that they have any plans for purchasing the new technology in the next couple of years.

Non-adopters most commonly cite instability or uncertainty in the demand for their products and lack of financial resources as obstacles to investment. In the maturing industries in which they operate, market conditions are likely to remain unstable. Hence, future earnings streams are insufficiently predictable for such firms to undertake a changeover to the new technology. The external economies derived from close ties to customers are not commonly available in American industry, but seem to be specific to particular manufacturing sectors, such as in industries heavily dependent on sales to the U.S. Department of Defense in which there is a tradition of fostering innovation from the major contractors throughout the supplier chain.

Our research suggests that the more isolated and "independent" the small firm is from other firms and the network of technical and economic supports which flow from such ties, the less likely it is to adopt any new process technology. Although the "resistance" of such firms to the changeover to a new techno-economic paradigm is not irrational, it is nevertheless unlikely to be overcome by further changes in relative prices. The very isolation and set of market conditions that characterize these small firms are what constrains them from shifting to the new technology.

Conclusions

Uneven patterns of diffusion of a new process technology such as programmable automation can be explained largely as the failure to adopt the technology by small firms operating in isolation from other organizations and in markets where the kinds of linkages to business customers that help to underwrite the risks from shifting to the new technology are relatively rare. Without new institutional mechanisms for generating external economies among such small firms in the United States, we do not think such firms will eventually adopt programmable automation, no matter how superior it proves itself to be.

In this paper, we have argued that a set of necessary conditions must be met in order for a firm to make the shift to a new techno-economic paradigm. Small firms lack the internal resources and operate at too small a scale to generate the kind of internal synergies across a number of product markets, that is, the economies of scope, enjoyed by large diversified companies, which permit them to undertake the risks of a technological shift. Small firms that do adopt a new process technology such as programmable automation, are distinguishable from organizations of similarly limited internal resources by their external linkages. Without the kinds of connections to other firms that help to underwrite the risks of adopting a new process technology, the isolated small firm that relies wholly on traditional techniques will not be able to attempt the necessary retooling of machines and people. Instead, we would expect such firms to eventually cease to stay in business. However, in the absence of more technologically advanced competitors, their short-term strategy of lower wages and more intensive use of aging capital may permit these firms to exist far longer than might otherwise be the case.

Our research suggests that the persistence of lower than expected overall rates of diffusion and an uneven pattern of diffusion of a new process technology with the potential for widespread application may be largely attributable to discontinuities between small and large firms facing similar market conditions in their strategic considerations and their resources and to the varying propensity (by sector and possibly by nation) of technologically sophisticated firms to assist their suppliers in making the transition to the new technology. Models that take into account these factors should provide more accurate forecasts of the rate and level of a new process technology's diffusion. More importantly, with such models, it will be possible to develop a profile of the firms that could take advantage of a new process technology (because no known technical barriers to its adoption exist) but lack the kind of inter-organizational linkages necessary to make the transition from a mature to an emerging technological paradigm. Firms so identified are possible targets for technology policies designed to accelerate the adjustment process.

There are two ways to consider the implications of these findings for policy. One could argue that the greatest obstacle to diffusion is simply these firms' tenacity, i.e., their stubborn commitment to continuing to do business as usual as long as they can. Hence, a policy designed to more aggressively drive them out of business would presumably hasten the process of diffusion. Alternatively, one could argue that what is notable both for its importance to the small firm and its rarity in American manufacturing is the kind of customer-supplier relationship that facilitates the changeover to a new techno-economic paradigm. In certain other national economies, the most well-known example being that of Japan, these linkages are reported to be far more common, helping to diminish the disparities in the technological sophistication between large and small firms that might otherwise prevail.[14] National economies with institutional arrangements that are generally supportive of such ties among many manufacturing industries, rather than only a select few, may thus be more successful in sustaining their technological leadership in various markets in the transition to a new techno-economic paradigm. Those economies where such close ties rarely occur or where their

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[14] In a recent unpublished report of the U.S. Congressional Office of Technology Assessment, entitled Technology and American Manufacturing, supplier-firms in Japan were described as having customers that are nearly 1.5 times as likely to provide engineering support as we find among U.S. supplier-firms. The higher incidence of such close relationships among Japanese firms may explain the higher rate of adoption of PA technology by very small Japanese subcontractors (to that of U.S. firms of similar size) reported in a recent survey of such firms undertaken by the Shokochukin Bank in 1988.

occurrence is predicated upon special circumstances, such as happens in the U.S. when an industry is highly dependent on government expenditures for military hardware, may be poorly positioned to adjust to major paradigmatic shifts.

REFERENCES

Abernathy, William J. and Kim B. Clark. 1985. "Innovation: Mapping the Winds of Creative Destruction." Research Policy 14: 3-22.

Bohn, Roger E. 1987. "Learning Experimentation in Manufacturing." Harvard Business School Working Paper No. 88-001.

Bohn, Roger E. and Ramchandran Jaikumar. 1986. "The Development of Intelligent Systems for Industrial Use: A Conceptual Framework." Pp. 169-211 in Research on Technological Innovation, Management and Policy, vol. 3.

Collis, David J. 1988. "The Machine Tool Industry and Industrial Policy, 1955-82." In International Competitiveness, edited by Michael A. Spence and Heather A. Hazard. Cambridge: Ballinger.

David, Paul A. 1969. "A Contribution to the Theory of Diffusion." Stanford Center for Research in Economic Growth, Memorandum No. 71., Stanford University.

__________. 1975. Technical Choice, Innovation and Economic Growth. Cambridge: Cambridge University Press.

David, Paul A. and Trond E. Olsen. 1984. "Anticipated Automation: A Rational Expectations Model of Technological Diffusion." Technological Innovation Program Working Papers, No. 6, Center for Economic Policy Research, Stanford University.

Davies, S. 1979. The Diffusion of Process Innovations. London: Cambridge University Press.

Edquist, Charles and Staffan Jacobsson. 1988. Flexible Automation: The Global Diffusion of New Technology in the Engineering Industry. Oxford and New York: Basil Blackwell.

Ettlie, J. E. and A. Rubenstein. 1980. "Social Learning Theory and the Implementation of Production Innovations." Decision Sciences 11: 648-668.

Freeman, Christopher. 1988. Technology Policy and Economic Performance. London and New York: Pinter.

Freeman, Christopher and Perez, Carlotta. 1986. "The Diffusion of Technical Innovations and Changes in Techno-economic Paradigm." Science Policy Research Unit, University of Sussex.

Galbraith, John K. 1956. American Capitalism. Boston: Houghton-Mifflin.

Guile, Bruce. 1986. "Investigation of a Transaction-cost Approach to Market Failures in the Development and Diffusion of Manufacturing Technologies," paper presented at the Annual Meeting of the Association for Public Policy Analysis and Management. Austin, TX (October).

Harley, C.K. 1973. "On the Persistence of Old Techniques: The Case of North American Shipbuilding." *Journal of Economic History* 33:372-398.

Kaplinsky, Raphael. 1984. *Automation: The Technology and Society*. Harlow, England: Longman.

Kelley, Maryellen R. 1988. "Technical, Economic, and Organizational Factors Influencing the Propensity to Adopt Programmable Automation Among U.S. Manufacturers." Working Paper No. 88-54, School of Urban and Public Affairs, Carnegie Mellon University.

Kelley, Maryellen R. and Harvey Brooks. 1988. *The State of Computerized Automation in U.S. Manufacturing*. Center for Business and Government, John F. Kennedy School of Government, Harvard University.

Kusterer, Ken. 1978. *Know-How on the Job: The Important Working Knowledge of 'Unskilled' Workers*. Boulder, Colo.: Westview Press.

Mansfield, Edwin. 1968. *Industrial Research and Technological Innovation*. N.Y.: W.W. Norton.

Mansfield, Edwin, John Rapoport, Anthony Romeo, Edmond Villani, Samuel Wagner, and Frank Husic. 1977. *The Production and Application of New Industrial Technology*. New York: W.W. Norton.

March, James G. and Herbert A. Simon. 1958. *Organizations*. New York: Wiley.

Nabseth, L. and G.F. Ray, eds. 1974. *The Diffusion of New Industrial Processes: An International Study*. London: Cambridge University Press.

Nelson, Richard and Sidney Winter. 1977. "In Search of a Useful Theory of Innovation." *Research Policy* 6:36-76.

Pavitt, Keith and Pari Patel. 1988. "The International Distribution and Determinants of Technological Activities." *Oxford Review of Economic Policy* 4:35-55.

Perez, Carlotta. 1986. "The New Technologies: An Integrated View," trans. of "Las Nuevas Tecnologias: Una Vios de Conjunto." In *La Tercera Revolucion Industrial: Impactos Internacionales del Actual Viraje Tecnologico*, edited by C. Ominami. Buenos Aires: Grupo Editor Latinoamericano.

Rogers, Everett M. 1983. Diffusion of Innovations. New York: Free Press.

Schumpeter, Joseph A. 1939. Business Cycles. N.Y.: McGraw Hill.

Simon, Herbert A. 1957. "Rational Choice and the Structure of the Environment." In Models of Man: Social and Rational. N.Y.: Wiley.

Skinner, Wickham. 1986. "The Productivity Paradox." Harvard Business Review (July-August): 55-59.

Stoneman, Paul. 1980. "The Rate of Imitation, Learning, and Profitability." Economic Letters 6: 179-183.

Stoneman, Paul. 1983. The Economic Analysis of Technological Change. London: Oxford University Press.

Tushman, Michael L. and Anderson, Philip. 1986. "Technological Discontinuities and Organizational Environments." Administrative Science Quarterly 31: 439-465.

Utterback, James M. 1988. "Innovation and Industrial Evolution in Manufacturing Industries." In Technology and Global Industry: Companies and Nations in the World Economy, edited by Bruce R. Guile and Harvey Brooks. Washington, D.C.: National Academy Press.

Von Hippel, Eric. 1988. The Sources of Innovation New York and Oxford: Oxford University Press.

Appendix Table: The Probability of PA Adoption Among Small Firms By Industry Dependence on Sales to the U.S. Department of Defense*

Sales to DOD as a Percent of Total Industry Sales	Engineering Support Provided By Customer?	Predicted Probability	Likelihood Ratio
2%	NO	.367	1:1.7
2%	YES	.454	1:1.2
4%	NO	.481	1:1.1
4%	YES	.571	1.3:1
10%	NO	.633	1.7:1
10%	YES	.712	2.5:1
30%	NO	.785	3.6:1
30%	YES	.839	5.2:1
50%	NO	.837	5.1:1
50%	YES	.881	7.4:1
70%	NO	.866	6.5:1
70%	YES	.903	9.3:1

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*These probabilities were estimated for the small supplier firm having a total of 85 employees with a plant workforce of fewer than 50. In addition to the two variables shown in these scenarios and the factor scale measuring organizational size and complexity, the model used to estimate the probability of adoption among supplier-firms included 11 other variables. That set of variables contained measures of economic and technical aspects of production as well as indicators for the kinds of information networks upon which management depends for learning about new technological developments. For each of the scenarios shown above, these 11 additional variables were fixed at their sample means.

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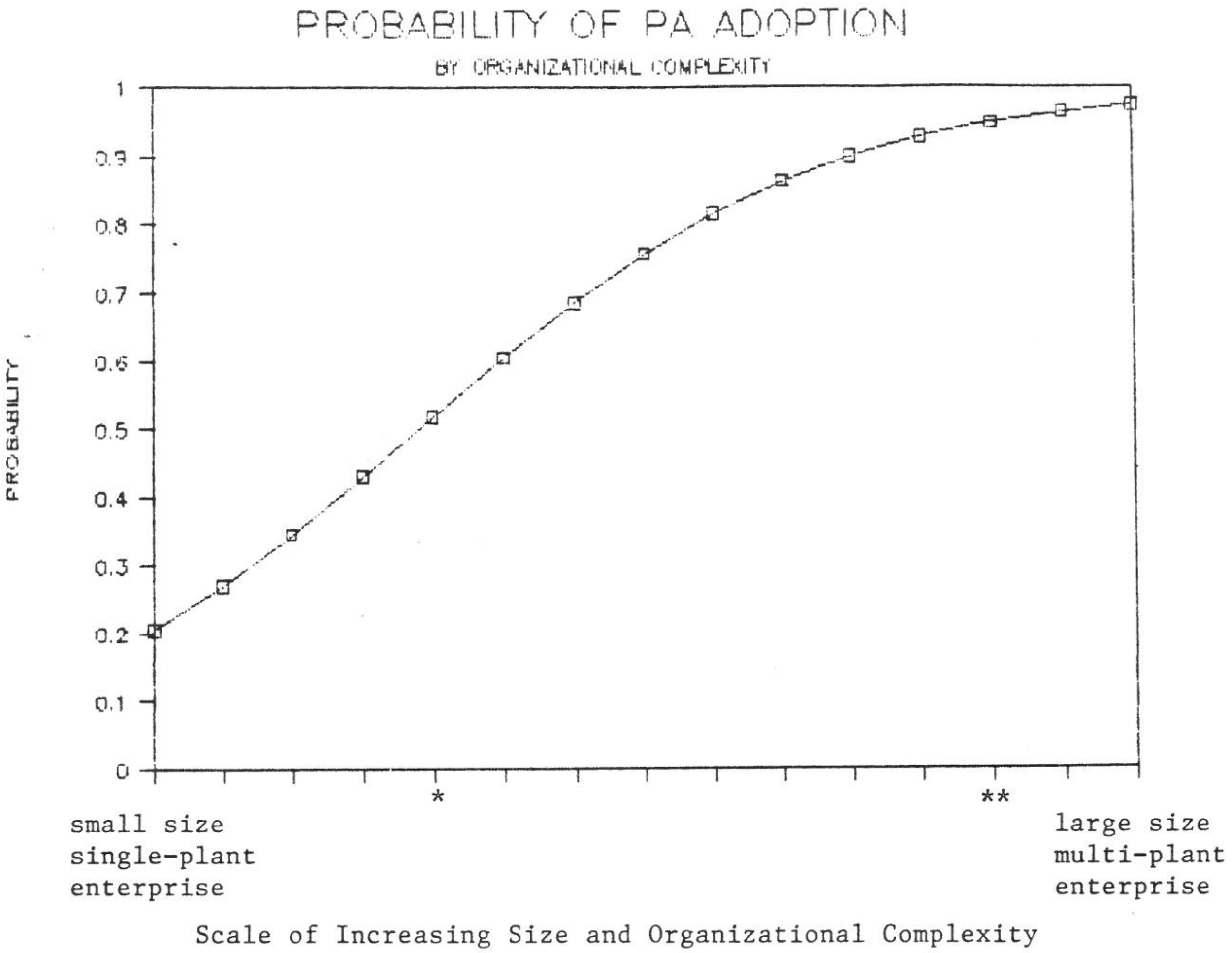
Figure 1:



Notes:

* Establishments to the <u>left</u> of this point on the scale employ fewer than 50 workers and are part of small firms with a maximum of 85 employees company-wide.

** Establishments to the <u>right</u> of this point are large, employing 1,300 workers on average; all of these plants are part of multi-plant corporations averaging over 100,000 employees in the United States.