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COMPETING AFTER RADICAL TECHNOLOGICAL CHANGE: THE SIGNIFICANCE OF PRODUCT LINE MANAGEMENT STRATEGY

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Research on firm performance after the introduction of a radical technological change has primarily concerned itself with differences between incumbents and entrants. This paper explores other factors that may influence firm performance over the longer term after a radical change—specifically, those related to product line management strategy. Following a radical change, a period of incremental technological change typically creates the opportunity for rapid development of new products. In such settings, strategies to manage multiple products, including families of related products that can be derived from a common platform, may be expected to impact competitive performance, especially over the longer term. The data for the study are from the telecommunications switching sector, specifically the private branch exchange (PBX) industry. Fifty-six firms and over 240 new products were analyzed over 22 years. This study shows that incumbent–entrant-based explanations of firm performance are incomplete. In particular, the results demonstrate that product line strategy explains significant additional variation in firm performance. The paper tests hypotheses linking both overall product line strategy and product platform strategy to firm performance. It finds that overall product introduction rates and product longevity can be linked to performance. It also shows that decomposing overall strategy into product platform strategy—rates of platform and derivative introduction, and platform longevity—can further increase explanatory power. In total, the results indicate that strategic prescriptions in the literature that emphasize development speed alone are oversimplified. They also suggest that differences in how relationships among products derived from a common platform are managed can contribute to competitive advantage and demand complex trade-offs.

INTRODUCTION

Since at least the time of Schumpeter, the potential for radical technological changes to transform products, dramatically alter an industry's structure, and marginalize formerly dominant industry incumbents has been recognized (Schumpeter, 1942). There have been numerous industry studies of such episodes of Schumpeterian 'creative destruction.' For example, Utterback (1994) collected a total of 22 such events. Although they are relatively infrequent, radical technological changes are important competitively, because of the extreme shifts in competitive performance with which they are associated and because of the insights they potentially provide into factors at work during less extreme technological changes (Levinthal, 1992).

Radical changes introduce new design components combined in a system whose function relies on different physical principles and hence a different knowledge base than previous products (Henderson and Clark, 1990). Such changes

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are regarded as competence destroying because the existing knowledge base of incumbent firms is of limited relevance at best for the new technology (Tushman and Anderson, 1986). Tushman and Anderson (1986) operationalize the concept of a radical product technological change as a major discontinuity in the price–performance of the product.

Research undertaken to understand relative firm performance after radical competence-destroying technological change has followed Schumpeter in making the often large performance differences between incumbents and entrants the starting point for analysis. It has also emphasized the near term effects of the radical change. In doing so, the existing research has implicitly de-emphasized product development strategies that higher performing firms—whether entrants or incumbents—might have *in common*, especially over the longer term. This paper complements the existing work by investigating one set of strategic factors that can influence the results of competition after a radical technological change, even after controlling for incumbent–entrant explanations—those related to product development.

More specifically, the paper explores the question of whether and how product line management strategy—how sequences of potentially related products are developed, introduced, and retired as a firm competes—influences firm performance over the longer term following a radical technological change. The paper tests the effects of the overall product line management strategy—the rate of product introduction and the length of time an average product remains on the market. It also examines the role of platform families—sequences of products that are related to one another because they are derived from a common platform product (Sasser and Wheelwright, 1989). While the management of product platforms is an important topic in its own right, as recent strategic, managerial, and innovation literature have emphasized (Meyer and Lehnerd, 1997; Uzumeri and Sanderson, 1995; Wheelwright and Clark 1992), empirical investigation is still at an early stage (Nobeoka and Cusumano, 1997). Hypotheses are tested using data from the private branch exchange (PBX) industry, which underwent radical technological change from electromechanical to computer-controlled products beginning in the early 1970s.

The paper is organized into four major sections following this introduction. The next section draws on the existing literature to characterize the medium- and longer-term period of incremental change that typically follows a radical technological change and to develop testable hypotheses concerning product line management strategy. The succeeding section describes the data and PBX industry setting, while also offering a description of the nature of the technological changes and the relationships among platform family members. After that, the analysis and results are presented. The paper closes with a brief discussion of the results and their implications.

DOES PRODUCT LINE MANAGEMENT STRATEGY INFLUENCE PERFORMANCE?

There are three major explanations offered in the literature for performance differences between incumbents and entrants after a radical technological change—each is attentive to a different dimension of contrast between incumbents and entrants. The explanations are complementary assets, timing of new technology introduction, and technological capability. First, Teece (1986) argues that complementary assets—such as manufacturing assets or hardware, reputation, or distribution, sales, and logistics systems—possessed by incumbents prior to the introduction of radical technological change can create advantage for incumbents. He suggests that if the value of complementary assets is preserved after the introduction of the focal technological change, they confer advantage to incumbents relative to entrants, who must develop such assets *de novo*. Mitchell (1991) provides empirical support for this view.

Second, others have proposed that the timing of introduction of new technologies may systematically differ between incumbents and entrants, with earlier introducers outperforming later ones (Christensen and Rosenbloom, 1995; Ghemawat, 1991; Mitchell, 1989, 1991). A variety of mechanisms that might contribute to entry timing differences between incumbents and entrants have been proposed. These include incentives differences, for example, due to self-cannibalization (e.g., Reinganum, 1989), the possession of complementary assets (Teece, 1986), and the effect of the technological change on value networks (Christensen and Rosenbloom, 1995). Finally, still other researchers have proposed that incumbents have systematic capability deficits that are caused by difficulties in adapting knowledge and experience in the older technologies to the realities created by the new technology (Henderson and Clark, 1990). Tripsas (1997) provides support for these findings.

In its emphasis on the incumbent–entrant distinction as a fundamental explanatory concept, the research on firm performance differences after technological change has focused on analysis of a relatively short interval of time around the introduction of the new technology (typically 5 years at most), and on a relatively few early products, typically 3 years or less. Complementary assets explanations rely on the role of pre-existing differences between incumbents and entrants at the time of introduction of the new technology, and hypothesize advantages in initial product imitation (Teece, 1986). Similarly, studies of entry timing emphasize the first product introduced in the new technology (for examples see Ghemawat, 1991; Reinganum, 1989; Christensen and Rosenbloom, 1995). Also, studies emphasizing capability differences have concentrated on early design projects in the new technology. For example, Tripsas (1997) analyzes the earliest three products in a generation.

However, the ultimate consequences of radical changes extend beyond early products and the short term. Over the medium and longer term following a radical technological change, important but more incremental technological changes continue and are embodied in new products (Abernathy and Utterback, 1978). Such technological changes are usually characterized as 'incremental' for two reasons.[1] First, there is substantial continuity in the principles and practices associated with the initiating radical change, as similar techniques are applied successively to similar technological problems (Dosi, 1988; Nelson and Winter, 1982). Second, individual price performance improvements are relatively small (Tushman and Anderson, 1986). Cumulatively however, incremental changes can generate extremely large improvements in price performance, in part because the period of incremental change is protracted compared to periods of radical change (Usher, 1954; Gilfillan, 1935; Sahal, 1985). As a consequence, high rates of firm attrition can be generated during periods of incremental change, demonstrating their potential importance to competition (Utterback and Suarez, 1993).

Incremental technological changes may occur in two distinguishable modes that offer opportunities to firms that are developing competitive product lines after radical change. First, improvements in the price performance of products for existing users may be developed. Price performance increases for existing uses typically follow logically from known design problems. Rosenberg (1969) notes that incremental innovations may follow a 'compulsive sequence' in which the improvement of one key product component spurs subsequent related improvements in interdependent components. Changes within existing customer markets also provide opportunities for incremental technological development as customers gain experience in use with products (Clark, 1985).

A second mode of incremental progress occurs through employment of the basic technology in designs that attract new users. As technologies develop and improve, they often move from specialized settings to which their performance characteristics are particularly well adapted to wider market applications (Foster, 1986; Cooper and Schendel, 1976). Cooper and Schendel (1976) observe that innovations as diverse as the ballpoint pen, the diesel locomotive and the transistor initially were introduced in niches and then gradually refined and adapted to broader markets.

Product development rates and product life

The ongoing importance of incremental change suggests that both entrants and the incumbents that introduce a radical technology change must continue to compete on the basis of incremental improvements long after the initial radical technological change. The two modes of incremental technological change create multiple development options and complicate choices for firms managing their product lines. For example, a firm must decide on an overall budget for product development and then allocate resources within that budget as effectively as possible. Also, for a given

[1] Henderson and Clark (1990) develop a valuable typology of technological changes based on whether core components are preserved and whether the way components interact remains the same. In this paper, for brevity, the term 'incremental' is used in the sense of non-radical and encompasses Henderson and Clark's types of architectural, modular, and incremental technological changes.

development project, firms must decide whether the product will replace an existing model and how much of an improvement should be attempted. The overall result of these choices and many others constitutes a firm's product line management strategy, which can be characterized by the speed of product development, and by the length of time each product is offered for sale (Uzumeri and Sanderson, 1995). Together these factors reflect the rate at which products are replaced or renewed and the rate at which product lines are expanded. This section develops simple hypotheses linking these product line management strategy elements to overall firm performance.

The hypotheses draw on the broad literature that has examined the performance of *individual* product development projects in isolation from one another. Most of these studies do not attempt to assess the competitive effect of development project performance in aggregate over time (Nobeoka and Cusumano, 1997) or the impact of relationships among products. However, findings from the overall body of work can be used to develop working hypotheses as to the impact of product management strategy on overall firm performance.

Several papers have argued that relative speed in product development is a source of competitive advantage, with firms faster in product development having the option to expand lines more rapidly or renew products more quickly (Abegglen and Stalk, 1985; Womack *et al.*, 1990; Bower and Hout, 1988). Also, a number of studies set in technologically dynamic industries have found substantial differences in the time required to complete development projects (Eisenhardt and Tabrizi, 1995; Iansiti, 1995; Clark and Fujimoto, 1991; Clark, Chew, and Fujimoto, 1987). Faster product development potentially offers advantages in earlier introduction of improved components, even if all firms eventually employ the same ones, and in more rapid response to evolving user needs. Two papers offer more direct empirical evidence that increased firm-level performance may be associated with faster product introduction rates. First, Nobeoka and Cusumano (1997) show that greater numbers of products introduced (compared with a base period) in a 3-year period were associated with higher sales growth by firms. Second, a paper by Hendricks and Singhal (1997) shows that announced *delays* in product introductions are associated with significant drops in the share price of firms.

In contrast, other work points to increasing costs to firm performance as product development speed increases. Sales of one product can cannibalize the sales of other products in the line, seriously limiting the returns to high product introduction rates (Wilson and Norton, 1989; Ghemawat, 1991; Reinganum, 1989; von Braun, 1991). This problem is most acute when new products do not expand the market, as when one product perfectly substitutes for another; however, even products focused on different segments can compete among themselves for marginal buyers. Extremely high rates of product introduction can therefore exaggerate development expenses and risks, and damage prospects for survival. A second potential issue at very high rates of product introduction is that the products that can be most rapidly introduced may be the result of design projects that are extremely limited in scope. Small improvements in design quality that leave much of a product unchanged may be less effective in generating advantage unless development costs and risks are lowered relatively more (Crawford, 1992).

A third potential factor lowering the effectiveness of high rates of product development is that high rates may be the result of 'crash' (accelerated) development projects. Projects may be accelerated by increasing the level of resources devoted to them (Mansfield, 1968), but the returns may not justify the additional expense incurred. Finally, very rapid introduction of products may increase complexity costs as components proliferate, potentially more than offsetting any increase in revenues or other benefits (Garg and Tang, 1997).

Overall, the literature suggests that firms must balance the benefits of high product development rates against numerous potentially increasing diseconomies associated with very high levels of product introduction. If firms had perfect information, the ability to analyze the relevant trade-offs, and similar capabilities and incentives, it might be argued that they would choose similar rates of product development. However, as a practical matter, considerable variation is expected. Firms with the highest rates of product introduction can be expected to be those with greater cannibalization, with more accelerated projects, the more limited average design scope, or more overall complexity, or some combination of these factors. Consequently, the performance of these firms can be expected to be lower than that of firms with somewhat lower overall rates, who gain benefits of relatively high levels of product introduction rate, but incur fewer of the cost and other disadvantages. Thus:

Hypothesis 1a: The rate at which new product introductions are made after a radical technological change will have a curvilinear relationship with firm performance. Higher rates of product introduction will be associated with higher firm performance; however, beyond some level higher product introduction rates will be associated with lower performance.

There is rather less research on the effect of product life on firm performance. If firms did not vary the size of their product lines, product life would merely be the inverse of product introduction rates. However, firms in general do vary the number of products in their line. For example, in the computer desktop market, product introduction rates have been greater then retirement rates (Bayus, 1998). Uzumeri and Sanderson (1995) suggest product life is crucial to understanding Sony's dominance of the portable tape player (Walkman) market and that longer lives have been a neglected factor in understanding product line strategy.

There are a number of reasons to believe that extended product lives may be associated with enhanced firm performance. For example, at a given budget size for product development, firms with longer product lives may devote a greater proportion of their effort to expand the size of the product line and gain advantage, as Sony reportedly did in the Walkman market. Or, longer-lived products might allow firms to limit expenditure on development and thereby enhance survival chances through minimizing risk (Pierz, 1995). Still another possibility is that firms with longer product lives are able to devote extra resources to complete more ambitious and successful development projects. For all these reasons firms with longer product lives might be expected to have greater success.

However, there may also be increasing diseconomies associated with increasing product life. The length of time a product may effectively compete depends on the probability that customers will prefer it to competitive products. When technological change is rapid, the likelihood that a given customer will not prefer a product should increase on average with the age of the product's design. At some length of life, the benefits of longer lives will be exceeded by the loss of sales to more competitive products. Therefore, firms that choose the longest product lives—to reduce development budgets, or to devote more resources to expanding product lines—will exhibit inferior performance relative to firms that replace products somewhat more frequently. So, as a practical matter, firms that choose the longest product lives for their products are likely to have decreased performance relative to those firms with more moderate average levels and:

Hypothesis 1b: The average product life of a firm will have a curvilinear relationship with firm performance. Longer product lives will be associated with higher firm performance; however, beyond some level longer lives will be associated with lower performance.

Product families and product platforms

If radical technological changes break with past techniques and practice, incremental changes build on them (Nelson and Winter, 1982). As Dosi (1988) has emphasized, a new technology is both physical and conceptual. It consists not only of the actual components and their associated testing and production tools, but also of a set of accumulated knowledge, techniques, and skills that set the agenda for further problem-solving and product refinement.

The relative stability in product design, techniques, and knowledge that develops during a period of incremental change creates conditions that allow the designers of new products to build upon previous products. Such a reliance of new products upon older products creates 'kinship' relations of various types among products. New products may leverage older products directly—for example, by reusing some physical components—or indirectly through cumulative learning. Rothwell and Gardiner (1988) detail and categorize a list of some 12 potential physical relationships among design variants. The potential relationship between products can span a broad range—from deliberately planned modular relationships among major components of a product line such as the different sizes of the Boeing 767 series, to unplanned *ad hoc* use of components from previously designed products.

Wheelwright and Clark (1992) present a three-category typology of development projects that characterizes their relationship to earlier projects.

It is based upon a project's level of (primarily physical) continuity with existing products and processes. First, they suggest that derivative projects share most with previous products and that their development requires only minor changes to existing products and/or processes. Derivative products may be hybrids of components from other products, cost-reduced versions of existing products, or minor enhancements to existing products. Second, radical projects involve a major change in product and process, often establishing a new product category for a firm, and represent a significant break with the past.[2] Finally, platform projects, as an intermediate category, represent significant change in product or process, or more rarely, both. A platform is a base product that can be leveraged, perhaps successively, over a significant time period to produce a family of related derivative products.[3]

The competitive significance of the management of related products and product relationships has been emphasized in recent strategic, managerial, and innovation literature (Meyer and Lehnerd, 1997; Uzumeri and Sanderson, 1995; Wheelwright and Clark, 1992). Also, important differences in how related products are managed have been the focus of study in such diverse industries as stereo components (Langlois and Robertson, 1992), automobiles (Nobeoka and Cusumano, 1997), portable tape players (Uzumeri and Sanderson, 1995), hovercraft (Rothwell and Gardiner, 1988), and vacuum cleaners (Sasser and Wheelwright, 1989). However, empirical investigation of the competitive significance of such differences is still at an early stage (Nobeoka and Cusumano, 1997).

The potential for products to be related to each other complicates strategic choices for product lines during periods of incremental change. Introduction rates and product lives for both platforms and derivative products must be chosen. In a technologically dynamic environment, firms must choose when to leverage existing platforms with derivative products and when to develop new platforms and/or replace existing platforms and their related derivatives. These choices must be reconciled with other choices that attempt to balance absolute improvements in product performance for a particular segment with tailoring of products to other specific market segments, and with product costs (Kekre and Srinivasan, 1990). Since a platform project is likely to represent a major design effort and to constrain the scope of future development while also providing opportunities to develop a whole family of derivatives, it represents a larger and longer-term commitment for a firm. Typically, platform projects also introduce larger price–performance improvements. In contrast, derivative products are minor, take less time to complete, and individually represent much lower levels of effort, risk, and commitment.

As with the overall rate of product introduction, on balance, firms that introduce platforms more rapidly should be expected to outperform those that introduce most slowly. However, the same factors that can reduce the performance of firms with the highest overall product introduction rates—cannibalization, scope limitations, crash development projects, and increased complexity—also strongly suggest reduced performance for firms with the highest rates of platform introduction because of the greater commitments required. Moreover, firms that produce fewer derivatives from their platform product introductions may be forced to introduce costly platforms at a more rapid rate. Also, the greater resources, longer times, and greater uncertainty associated with platform products may make it more difficult for firms to assess optimal levels for their introduction. As a result, *ceterus paribus*, it can be expected that firms with the highest rates of platform introduction will on average exhibit lower performance than firms with more moderate rates of platform introduction. Therefore:

> *Hypothesis 2a: There will be a curvilinear relationship between firm performance and the rate of platforms introduced. Higher rates of platform introduction will be associated with higher firm performance; however, beyond some level, higher rates of platform introduction will be associated with lower performance.*

The life of a platform family of products may be significantly longer than the life of each of the product derivatives individually. If a single product is continuously upgraded, like Lincoln's

[2] The meaning of the word 'radical' as used in this work is subtly different from its use in Tushman and Anderson (1986) and Henderson and Clark (1990), whose meanings are noted in the Introduction. I use 'radical' throughout the paper in the sense of Tushman and Anderson and Henderson and Clark, except as noted.

[3] Other classification schemes share similar distinctions among products based on how past development efforts are leveraged (Uzumeri and Sanderson, 1995; Meyer and Utterback, 1993; Sasser and Wheelwright, 1989).

ax,[4] the family life, defined as the time from the introduction of the platform until the retirement of the last derivative product, may be appreciably longer. The longer a family life is compared with the lives of individual product family members, the more likely it is to provide the same advantages as longer product lives. However, since products can be continuously renewed, disadvantages associated with longer product lives are likely to be removed or greatly attenuated. Therefore:

Hypothesis 2b: The difference between average family life and average product life will be positively associated with firm performance.

The effects of high rates of derivative product introduction from platforms have been even less thoroughly researched then those of high overall rates of product introduction. However, some have argued that very high rates of derivative introduction achieved through planned platform design can increase overall firm success (Sanchez and Mahoney, 1996; Sanderson, 1991; Uzumeri and Sanderson, 1990). This work tends to assume that firms can design platforms that are highly leverageable at little extra cost. To the extent that firms can, in fact, choose platform designs that allow derivatives to be generated quickly and cheaply, those with higher derivative introduction rates can gain advantage through development flexibility and greater accuracy in responding to changing conditions (Sanchez and Mahoney, 1996). They may also benefit from being able to delay new platform developments. Moreover, platforms designed to boost derivative generation rates can remove or reduce potential sources of disadvantage associated with high product introduction rates—by eliminating the need for crash projects, by reducing overall product line complexity (through higher levels of parts reuse, for example), and by lowering the development costs associated with small changes. While high derivative rates may create higher cannibalization, a more than offsetting advantage may result from pre-emption of competitive products. Therefore, the highest derivative rates may be associated with higher success overall. Hence:

[4] A possibly apocryphal story attributed to Lincoln is that his ax never wore out—occasionally he replaced the handle and occasionally he replaced the head—'same old ax.'

Hypothesis 2c: Larger numbers of derivatives per year of platform family life will be associated with higher firm performance.

TECHNOLOGICAL CHANGE AND PRODUCT LINE MANAGEMENT STRATEGIES IN THE PBX INDUSTRY

To assess the hypothesized competitive effects of product line management strategies, this study uses data drawn from the PBX industry. In this section, the basic technological changes that transformed the PBX industry are described, including both radical and incremental changes. Major relationships among product platforms and their derivatives are also delineated. The subsequent section describes the basic data, presents the methods used, and specifically tests the hypotheses.

Technological change and product development in the PBX industry

PBXs are small telephone switches that provide a private, internal telephone service and connect to the larger public network. PBXs have two major functional components: a means of forming connections and transmitting communications between connected lines (switching), and a means of identifying and controlling which specific lines are to be connected and disconnected (control). The first automatic telephone switch, introduced in 1897, had employed electromechanical components for both functions. Until 1972, PBXs continued to employ similar techniques, albeit with vastly improved components and systems.

Radical and incremental technological change in PBX products

In 1972, a single-site PBX that performed both control and switching functions using subsystems based on semiconductors was first introduced. Semiconductor components, most notably the transistor, brought multiple advantages. Among the most important were their ability to switch electrical currents on and off at incredible speed, their small (and rapidly decreasing) size, and low cost. For example, in 1976, semiconductor switches cost around $0.05 per element, while the latest generation of electromechanical cross-bar equipment cost about $1 per connecting point (Pitroda, 1976). To exploit the particular advantages of semiconductors, new technical concepts were employed in the design of both switching and control subsystems.

Although switching could employ semiconductors using a semiconductor analog-to-electromechanical technique, a different approach, termed time division, ultimately dominated. Time division techniques exploited the high switching rate of semiconductors. In time division, all lines were permanently connected to a common pathway (essentially a computer bus) and two lines were put in communication by synchronizing the brief periods of time in which they were both 'on' (given access to the bus). This arrangement decreased the number of required switching components, especially for large systems, because switching components could be more effectively shared among lines.

Control had been hardwired in previous PBX designs and modifications to the control logic required physical changes in components. However, semiconductor designs allowed control to be performed by comparatively easy-to-modify software programs running on general-purpose computers, microprocessors, or specialized processing chip sets.

Changes in one functional system in general induced changes in the other. For example, control of time division systems differed substantially from the control of electromechanical systems in that new arrangements to transmit high ringing voltages and dialed pulses had to be developed. Also, circuitry previously used to detect which switching elements were in use was eliminated because stored program control could record and read the connections as needed.[5] Since manufacturing and testing methods for semiconductor electronic components also differed considerably from those needed for electromechanical systems (Sciberras and Payne, 1986), the applicability of the knowledge base associated with electromechanical techniques was considerably reduced in designing and building the new systems.

The new semiconductor systems were a radical change in the sense that they were based on new technological principles at the component level and at the subsystem and system level and they required different interactions among functional system components (Henderson and Clark, 1990). As such, they raised new technological problems and trade-offs in design. The changes were also radical in a second sense: the price–performance ratio increased very rapidly with the introduction of the new semiconductor systems (Tushman and Anderson, 1986). Compared with electromechanical systems, these new systems were as much as 80 percent smaller, needed as little as 40 percent of the maintenance effort, and soon performed a greatly increased number of functions (Dittberner Associates, 1980). Savings from one early software feature, the ability to automatically select the lowest-cost route for long-distance calls, often justified the cost of a new system on its own (Bernstein Research, 1983). The new systems facilitated a sharp increase in entry by competing firms. Fifty-six firms entered in total over the period of study.

The major segmentation of markets was by line size. Designs had to be carefully tailored to different line size segments, particularly in the early generations, because systems of different sizes posed different design problems and required different attribute trade-offs.[6] For example, larger systems tended to have increased needs for more complete feature sets and higher reliability.

As in other industries based on semiconductor components such as personal computers, advances in semiconductor components were a key source of incremental improvements to designs. Improvements in the scale of integration, for example, contributed to rapid reductions in system cost and physical size as soon as new designs to take advantage of the new components could be completed. Such changes were incremental in the sense that the new components and techniques employed to perform the basic functions of control and switching which were introduced during the radical phase of change were retained (Henderson and Clark, 1990; Clark, 1985). They were also incremental in the sense that price performance improvements from generation to generation did not exhibit major discontinuities (Tushman and Anderson, 1986).

Price–performance increases in memory and microprocessors also supported rapid introduction of incremental software feature enhancements. The total number of features for a typical PBX system grew from less than 50 to roughly five times

[5] For a more complete description of changes to switching and control subsystems see Joel (1982: especially Chapters 9 and 13) and Goeller (1977: Chapter 1).

[6] For a discussion of this issue see, for example, Dittberner Associates (1980) or Charles, Monk, and Sciberras (1989), and Sciberras and Payne (1986).

that number within 10 years (Jones, 1996). Some of the more important features were data switching, networking of multiple PBXs, voice mail, and automatic call distribution (for a discussion of new features see Matros, 1984). The introduction of superior components and new features was accompanied by incremental design changes in system architecture. System architecture concepts incorporating multiple system processors and spanning greater line size ranges were introduced. Such systems were designed to facilitate incremental upgrades.

Relationships among products

The combination of rapid incremental change and different line size segments created the potential for sharing design work among multiple products. At least four potential levels of sharing existed: product and process designs, components and raw materials, subassemblies and manufactured parts, and high-level assemblies such as software (Charles, Monk, and Sciberras, 1989; Sciberras and Payne, 1986). In practice, firms made different choices that affected which aspects of an initial design platform could be most effectively leveraged with later derivatives.

Frequently, initial designs were opportunistically modified to produce a family consisting of derivatives that extended the basic design into other market segments or replaced the design with an improved version. However, the ease and effectiveness with which this could be done depended upon the architecture employed in the initial design.

Although different line sizes had different requirements, there was considerable and increasing scope for sharing components and subsystems across market segments of different line sizes, provided that initial architectural decisions enabled reuse. For example, an important cost element of the switch—line cards, which were responsible for translating voice or data signals from transmission lines so that the switch could understand them—could be made common across multiple derivatives. In addition, the same microprocessors could be used in multiple models, and if the programs had been written with sufficient generality, and structured so that certain functional modules were sufficiently independent of one another, so could much of the software code. In general, the highest levels of reuse of design elements could be achieved by products that had been conceived as an integrated family, as the following quote from Dittberner Associates illustrates:

> The most important conclusion relating to architecture and system technology is the current trend to provide an integrated product line covering a wide range of system size classes. (Dittberner Associates, 1980: 17)

Differences also existed in the ease with which a given product could be improved through renewal. For example, many enhancements, such as new software features, required greater memory and processing capacity. If the initial software had been written in a higher level language, new features could often be implemented without having to rewrite the existing software. However, as the most efficient use of processor capacity was attained using lower-level (assembly) coding, many incremental redesigns had to have software rewritten from scratch. Firms that employed higher-level languages in their initial designs usually chose to do so because they had envisioned an integrated line of products that would share software. The software redesign task could be eased further if programs had been written in independent and well-documented modules. Derivative products had limits, however, and most firms in the industry eventually designed new families of products from a zero base to escape the constraints imposed by earlier architectural choices.

Sample and data

The overall sample includes all semiconductor-stored program control (SPC) products introduced between 1972 and 1994: 246 total products in 99 separate families. The sample includes all 56 firms that entered the U.S. PBX industry with SPC semiconductor systems in the 1972–94 period. A variety of firm types introduced the new products. Some, such as ATT and GTE, had long been incumbents in the U.S. electromechanical PBX market. Others, such as Northern Telecomm, NEC, and Ericsson, had experience developing and managing electromechanical equipment in their home markets, and had only recently entered the U.S. market for electromechanical equipment, when the new semiconductor products began to be introduced. Later, other firms such as Thomson-CSF, with electromechanical experience in their home markets, also entered. Still other firms were *de* *novo* start-ups, founded with the development of new semiconductor SPC-controlled products. These included ROLM, Mitel, and many others.

To understand industry technology changes and to gather more specific information on product development, some 120 interviews with industry participants, consultants, and observers were conducted. Where necessary a wide variety of other sources were used to corroborate information, including reports from industry observer groups such as Probe, Dittberner Associates, the Stanford Research Institute, the North American Telecommunications Association (NATA), the Yankee Group, Frost & Sullivan, and Data Decisions. In some cases, specific filings with the Federal Communications Commission and the Department of Commerce were also used. Industry journals such as *Business Communications Review, Communication News, Telephone Engineer and Management*, and *Telecommunications* also were consulted for supplemental information.

The principal source used to identify product introductions and retirements was the Marketing Programs and Systems Group (MPSG) report. The MPSG report was widely used by purchasers—for example, many branches of state and federal government used the report to identify qualified PBX models and suppliers for government purchases. MPSG's report was the only source that was continuously available over the time span under study, beginning in 1974. The MPSG reports also constitute the single most comprehensive source for product introductions and retirements as vendors submitted new technical specifications to MPSG for inclusion in their listing, and MPSG technical experts verified and evaluated claims as to changes in the product. After gathering data from the manufacturer, MPSG refused to include products as new when changes were deemed marginal or superficial. MPSG also removed products from the list when active selling efforts had ceased. The data sample ends with the discontinuation of these reports by MPSG. The study also used two other leading industry reports as important supplemental sources of archival of information: Northern Business Information and DataPro. These reports were not continuously available and did not cover the entire industry; however, in some cases they recorded product introductions by smaller firms that had not been captured by the primary source.

An entry by a firm was recorded only when a firm introduced its first all-semiconductor SPC product. A product platform was defined as a product whose design was 'zero-based;' that is, a product whose design did not initially rely on existing architectures or components. Such products could sometimes reuse elements of existing systems, such as software or line cards. Identification of such products was relatively easy in practice because the industry sources cited above tracked the release of both major new products and derivatives. Companies used new names to signal the introduction of new families based on new platform designs because they wanted to signal the improved technology of their products. They used similar names for related products (e.g., Dimension 400; Dimension 600) to convey the breadth of a product family because, for example, expanding or multi-site customers considered being able to provide a variety of different products with common features and operating characteristics valuable. Platform design projects were also distinguishable, in practice, in that they usually took place on a cycle of 3 or more years rather than the 1–2 years that characterized derivative projects. A 'family' was defined as consisting of the platform and all its derivative designs.

Variables

The dependent variable for the study is the length of time a firm in the industry offered products for sale up to 1994 or, in the event of a merger, the length of time products introduced by the acquired firm were offered for sale. If an exit was not recorded during the study period, the observation was coded as being right censored. Event-history methods used here incorporate the information that an observation is censored and weight it appropriately. Twenty-nine firms of the total of 56 that entered remained in the industry in 1994.

This study uses survival time as the measure of firm performance for two major reasons. The first is data availability. As is often the case, the preferred measure of success—cumulative profits earned—cannot be obtained. Typical substitute measures, such as dollar market share or physical sales, are also not available for many smaller firms in the industry. However, even if they were available, these might not be superior indicators of underlying firm profitability. Indeed, such measures may be biased indicators of firm performance considering that tests using market share are more likely to find first-mover advantages than survival or profitability measures (VanderWerf and Mahon, 1997).

With respect to the PBX industry in particular, there is reason to suspect sales are not an ideal indicator of firm performance. As suggested by the high rates of firm attrition in the industry, profit rates in the PBX industry were extremely low, particularly throughout the 1980s. Press reports suggested that several larger firms were not profitable in their PBX operations during some periods. However, some smaller firms were, indicating that size and profitability may not have been tightly linked in the industry.

The second reason survival time was chosen as a performance measure is to avoid introduction of sample bias. Some 37 of the 56 firms entering the industry exited by the end of the study period. Limiting the sample to firms that survive to the end of the sample period, or to the larger firms for whom data are available, risks biasing conclusions to distinctions that apply only to the surviving subset of firms and to larger firms. For example, smaller firms may have adopted effective niche strategies that were more profitable than broader line strategies when the investments and risk of failure are taken into account. Use of survival data as a performance measure has the advantage of capturing the potential success of such niche strategies and avoiding survivor bias.[7]

Acquisitions played a relatively minor role in this industry. However, with respect to firm performance, acquisitions introduce uncertainty as to how both the acquired firm and the acquiring firm would have performed in the absence of the acquisition. Recording a firm exit on the date of the acquisition would almost certainly bias analysis by systematically underestimating the performance of an acquired firm, since it is unlikely that each acquired firm would have failed (withdrawn products from sale) on the day of the acquisition, had the acquisition not occurred. To minimize clear bias that would be introduced by assuming acquired firms failed at the time of acquisition, two types of acquisition were distinguished: entry acquisitions and intra-industry acquisitions. Entry acquisitions were those acquisitions in which firms from outside the industry acquired a firm that had developed its own products, while intra-industry acquisitions were those in which one PBX supplier acquired or merged with another.

During the 22 years of the sample period, of the 56 firms that entered the industry through original product development, firms from outside the industry acquired nine. To avoid clear downward bias in the performance estimate of these firms, entry acquisitions were treated as if the acquired firm had simply continued operation. This assumption is preferable in that it is not obviously downward biased as an estimate that assumed an exit on the date of the acquisition would be, and it has the added benefit of avoiding double counting the already existing products of the acquired firm as product introductions by the acquiring firm. The assumption is reasonable because such acquiring firms in general brought no specific industry expertise and often left existing firm management in place after the acquisition. Moreover, outside acquisition might as well decrease an acquired firm's performance relative to what it might otherwise have been (through less expert decision-making, for example) as increase it (perhaps for example, through easier access to funds). Consequently, it is not *a priori* a biased estimate. The survival time of the acquired firm was therefore operationalized as the length of time from the entry of the firm to the all-semiconductor SPC PBX market until the retirement (by the acquiring firm) of the last product that had been introduced by the acquired firm. In other words, I assume that the fact of an acquisition by a firm from outside the industry on average had no effect.

In a few cases (six firms out of 56), mergers within the industry occurred. Such acquisitions were usually a more established firm acquiring a start-up. In each acquisition, product lines remained separate; i.e., components from the acquiring company's product lines were not used in combination with components from an acquired line to create new products. Again, to avoid the obvious bias introduced by assuming a firm exit on the date of the acquisition, a plausible assumption, and the one employed here, is that on average the life of the products already on sale by the acquired firm is neither extended nor shortened by the acquisition. That is, the acquired firm would have survived at least to the date of their last product's retirement even if the acquisition

[7] However, to ensure that the results of the tests shown in this paper are not inconsistent with results that would follow from an analysis of firm size, the available size data were also examined. The natural logarithm of average line sales from 1987 to 1989, the latest size data that were available, had a correlation of 0.769 with survival time for the 29 firms still surviving in the industry.

had not taken place. Therefore, for intra-industry acquisitions, acquired firms were assumed to have survived from the time of the introduction of their first product until the time the last of their pre-acquisition products were retired.

In effect, this assumption says that the time of survival of the acquired firm's products beyond the acquisition date represents an estimate (perhaps lower bound) of the remaining life of the acquired firm had the acquisition had not taken place. This assumption is reasonable because the average future life of the acquired firm's products is likely to be strongly associated with the characteristics of the products themselves, their evaluation by customers, and the overall forces of market competition, even if there is an additional effect related to the acquisition.[8] Tests for bias introduced by the assumptions concerning acquisitions made here are reported and discussed in the Analysis and Results section.

Control variables

Independent variables and their definitions are shown in Table 1. The control variables reflect the three different mechanisms by which the literature suggests incumbent–entrant distinctions are expected to account for firm performance differences after radical technological change: entry timing, complementary assets, and capability. The Entry Time Index measure tracks the year a firm's first all-semiconductor SPC PBX was introduced. The measure of specialized complementary assets is based on sales of electromechanical products in the U.S. market. The average of sales from 1971 to 1973 is used since the first of the incumbent firms did not introduce an SPC all-semiconductor PBX until 1974. The natural log was taken to make the distribution of this variable, Sales in ElectroMech Mkt, approximate normality. A dummy variable, Technology Incumbent, is used to represent expected capability in the new technology since the literature suggests experience in electromechanical technology will bias capability in the new technology. The dummy is set equal to one for a firm that had electromechanical design and production experience somewhere in the world before introducing an SPC semiconductor PBX in the U.S. market.

Independent variables

To test hypotheses relating to overall product line management strategy, the average life of products and the average rate of product introduction are measured for each firm. These are normalized to minimize correlation with their squares, which are introduced to test the hypothesis that curvilinear relationships should be observed. To test hypotheses concerning strategy for managing product platforms and their derivatives, the rate of introduction of product platforms is calculated. In addition, for each firm, the rate at which derivatives were generated from a platform and the time by which platform life exceeded the life of the average of individual platform family members is calculated.

ANALYSIS AND RESULTS

A Weibull model was chosen for survival analysis. This model allows a time-variant underlying hazard rate (Hannan and Freeman, 1989) and accommodates different entry times and right-censored data. A plot of the log of the elapsed time from entry of a firm vs. the log of log survival time is approximately linear, as required by the Weibull assumptions. Table 2 shows correlations, means, and standard deviations for the variables.

The results of the tests of hypotheses are displayed in Table 3. The models predict log survival time, making coefficients associated with shorter survival times negative. Model 1 presents the results for the incumbency control variables. The overall model has significant explanatory power; however, only the intercept and the entry timing variable are individually significant. This may be due to the relatively high correlation between the measure of complementary assets

[8] This measure may also be biased on average, but is expected to be less so than the alternative of registering an exit at the time of acquisition. This is because in individual cases the life of the firm may be estimated to be somewhat greater or less then that which would have been measured in the absence of the acquisition. For example, interviews suggested some firms were acquired to gain complementary assets such as distribution networks. To the extent that the products acquired along with these assets were less valuable to the acquiring firm than they would have been to the firm as an independent entity, product lives and hence the estimate of firm life might be too low. In other cases, for example where firms were acquired to add complementary products, overall estimated firm life might be extended. However, the net result may be estimates of firm life that are unbiased.

Table 1. Basic measures and definitions

	Variable	Measure	Definition
	Performance	Survival Time	The length of time in years that SPC semiconductor products designed by this firm survived in the U.S. PBX market
Controls	Entry Timing	Entry Time Index	An index of the year in which a firm entered the U.S. market with an SPC semiconductor product. 1972 = 1
	Complementary Assets	Sales in ElectroMech Mkt	The natural logarithm of the average physical line sales of a firm in the U.S. market from 1971 to 1973
	Capability	Technology Incumbent	A dummy variable set equal to 1 if the firm entering had designed and produced electromechanical systems anywhere in the world previous to entering the U.S. market with an SPC semiconductor PBX product
Independent variables	Overall Product Line Management	Average Product Life	The average life of all products introduced by the firm from 1972 to 1994, normalized to a mean of zero
	Strategy	Product Introduction Rate	The total number of products introduced to the U.S. market by a firm minus one divided by the total number of years the firm survived in the market, normalized to a mean of zero
		Product Life Squared	The square of Average Product Life
		Product Introduction Rate Squared	The square of Product Introduction Rate
	Platform Management Strategy	Platform Introduction Rate	The total number of platforms introduced to the U.S. market by a firm minus one divided by the total number of years the firm survived in the market, normalized to a mean of zero
		Derivative Introduction Rate	The average over all a firm's platforms of the number of derivatives introduced from each platform, divided by the number of years the platform was offered for sale
		Family Life in Excess of Product Life	The average life of a product platform family, defined as the length of time from the introduction of the first platform product until the retirement of the last platform product, minus the average life of a product
		Platform Introduction Rate Squared	The square of Platform Introduction Rate

and the measure for previous experience in electromechanical technology. When tested individually, each is significant and has a positive sign; however, both are included to fully control for the potential influence of variance in each measure which is *not* common.[9] While this has the somewhat undesirable effect of inflating coefficient variance estimates, it ensures full control for incumbent–entrant explanations throughout the analysis.

Model 2 jointly tests Hypotheses 1a and 1b. The overall model improves fit and partial support for the hypotheses is found. The sign of the variable

[9] The positive sign for the Technology Incumbent measure suggests that either incumbents did not have capability disadvantages or that other advantages, such as those associated with complementary assets, but not fully captured by the complementary assets measure more than compensated for disadvantages. Perhaps, for example, brand name played a role. This result, while interesting, is outside the scope of this paper and I do not pursue it here.

Table 2. Descriptive data and correlation matrix ($N = 56$)

Variable	Obs.	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11	12
1 Survival Time	56	9.49	6.08	1.000											
2 Entry Time Index	56	9.34	4.46	−0.576	1.000										
3 Sales in ElectroMech. Mkt	56	−11.58	8.36	0.516	−0.481	1.000									
4 Technology Incumbent	56	0.30	0.46	0.449	−0.359	0.664	1.000								
5 Product Introduction Rate	56	0.00	1.00	0.709	−0.558	0.466	0.404	1.000							
6 Product Introduction Rate Squared	56	0.00	1.00	0.593	−0.466	0.454	0.378	0.916	1.000						
7 Average Product Life	56	0.00	1.00	0.646	−0.278	0.197	0.147	0.176	0.032	1.000					
8 Product Life Squared	56	0.00	1.00	−0.109	0.119	−0.079	−0.137	−0.329	−0.260	0.217	1.000				
9 Platform Introduction Rate	56	0.00	1.00	0.627	−0.417	0.594	0.495	0.648	0.505	0.209	−0.329	1.000			
10 Platform Introduction Rate Squared	56	0.00	1.00	0.330	−0.246	0.430	0.343	0.418	0.379	0.066	−0.159	0.720	1.000		
11 Family Life in Excess of Product Life	56	0.00	1.00	0.449	−0.448	0.206	0.104	0.673	0.612	0.098	−0.223	0.139	−0.021	1.000	
12 Derivative Introduction Rate	56	0.00	1.00	0.535	−0.394	0.265	0.272	0.843	0.842	0.134	−0.189	0.190	0.034	0.713	1.000

Table 3. Results

Measure	1	2	3	4	5	6	7	8	9
Entry Time Index	−0.079**	0.014	0.013	−0.001	−0.001	−0.001	0.002	−0.012	−0.004
	(0.031)	(0.012)	(0.010)	(0.009)	(0.009)	(0.008)	(0.007)	(0.010)	(0.01)
Sales in ElectroMech. Mkt	0.014	0.004	−0.008	−0.006	−0.006	−0.007	−0.007	−0.012	−0.024**
	(0.026)	(0.010)	(0.010)	(0.008)	(0.008)	(0.008)	(0.006)	(0.007)	(0.01)
Technology Incumbent	0.433	0.286	0.38**	0.325***	0.324***	0.331***	0.387***	0.5***	0.799***
	(0.427)	(0.179)	(0.153)	(0.113)	(0.118)	(0.115)	(0.106)	(0.130)	(0.22)
Average product Life		0.755***	0.702***	0.635***	0.634***	0.63***	0.6***	0.641***	0.635***
		(0.056)	(0.047)	(0.037)	(0.050)	(0.039)	(0.030)	(0.036)	(0.03)
Average product Life Squared		−0.275***	−0.229***	−0.337***	−0.336***	−0.338***	−0.352***	−0.372***	−0.335***
		(0.057)	(0.049)	(0.040)	(0.045)	(0.040)	(0.033)	(0.043)	(0.04)
Product Introduction Rate		0.406**							
		(0.175)							
Product Introduction Rate Squared		0.051							
		(0.222)							
Platform Introduction Rate			0.354***	0.333***	0.333***	0.32***	0.396***	0.302***	0.315***
			(0.087)	(0.060)	(0.061)	(0.070)	(0.057)	(0.07)	(0.06)
Platform Introduction Rate Squared			−0.08	−0.137***	−0.137***	−0.128**	−0.418***	−0.144***	−0.09**
			(0.078)	(0.043)	(0.043)	(0.051)	(0.081)	(0.05)	(0.05)
Family Life in Excess of Product Life			0.164**	0.739***	0.739***	0.743***	0.825***	0.781***	0.78***
			(0.064)	(0.109)	(0.109)	(0.109)	(0.085)	(0.13)	(0.11)
Family Life in Excess of Product Life Squared				−0.369***	−0.369***	−0.371***	−0.365***	−0.321***	−0.326***
				(0.088)	(0.090)	(0.090)	(0.077)	(0.10)	(0.09)
Derivative Introduction Rate			0.172**	−0.307***	−0.308***	−0.336***	−0.353***	−0.371***	−0.413***
			(0.073)	(0.086)	(0.088)	(0.124)	(0.073)	(0.10)	(0.1)
Derivative Introduction Rate Squared				2.804***	2.81***	2.884***	4.113***	3.483***	3.000***
				(0.97)	(0.99)	(0.99)	(0.88)	(1.22)	(0.89)

(continued overleaf)

Table 3. (*Continued*)

Measure	1	2	3	4	5	6	7	8	9
Family Life*Derivative Introduction Rate				−1.314*** (0.471)	−1.316*** (0.476)	−1.307*** (0.462)	−1.988*** (0.461)	−1.756*** (0.61)	−1.49*** (0.42)
Less Then 5 year Firm Life Dummy					−0.003 (0.105)				
No Derivatives Dummy						−0.053 (0.161)			
ATT Dummy							3.629 (436)		
Firm in Industry Acquired another PBX firm								−0.062 (0.137)	
Acquired by Firm in Industry								−0.336*** (0.125)	
Firm Acquired by Firm Outside Industry								−0.097 (0.127)	
Parent Age									−0.005** (0.002)
Ln Parent Size									0.008* (0.004)
Constant	3.312*** (0.458)	2.035*** (0.217)	1.842*** (0.188)	2.175*** (0.160)	2.177*** (0.173)	2.19*** (0.167)	2.199*** (0.127)	2.273*** (0.19)	2.004*** (0.16)
Log likelihood	−69.881	−23.628	−17.497135	0.7345584	0.7350545	0.792544	6.9880785	4.502917	2.31754
Chi squared	15.96	106.88	119.14	155.6	155.6	155.71	168.11	163.14	150.33
N	56	56	56	56	56	56	56	56	53

* $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$

for product introduction rate is positive and significant, supporting Hypothesis 1a. However, the coefficient of the square of product introduction rate is not significantly different from zero. Support for Hypothesis 1b is stronger: longer product lives are associated with significantly improved survival time. Also, as predicted, the sign of the product life squared variable is negative and significantly different from zero, indicating that the highest values of product life are associated with lower firm performance.

In addition, the coefficient estimate of the Entry Time Index measure is reduced relative to Model 1. One interpretation of this result, suggested by interview data, is that earlier entry facilitated product line expansion into emerging, 'open' market segments and that earlier firms may have also been able to choose longer product lives during the period of 'munificence' expected after the introduction of radical technological changes (Tushman and Anderson, 1986). Conceivably, one of the benefits of early entry is greater opportunity for product line expansion.

Models 3 and 4 decompose the overall product introduction rate term into the three platform strategy components that underlie it: platform introduction rate, the rate of derivative introduction for an average platform, and the length of time by which platforms exceed average product life.[10] Model 3 substitutes these three components for overall product introduction rate and drops the non-significant product introduction rate squared variable, while substituting the platform introduction rate squared variable, to allow an initial test for a curvilinear relationship between platform introduction rate and firm performance (Hypothesis 2a).

The results for Models 3 and 4 support Hypotheses 2a, 2b, and 2c. In Model 3, the rates of platform introduction, derivative introduction, and product platform family life are all significantly associated with higher survival rates, as predicted. Still, part of Hypothesis 2a finds only weak support in Model 3. While the sign of the square of the rate of product platform is negative, as expected, indicating a lowered chance of survival at the highest levels, the coefficient estimate is not significantly different from zero. Moreover, while variables associated with platform management strategy are significant and of the expected signs, their incremental explanatory power is modest in comparison with Model 2. To explore the possibility that the weaker than expected results for the platform strategy variables were the consequence of a more complex curvilinear relationship between firm performance and the platform strategy variables, normalized squared and interaction terms for derivative introduction rate and the excess of family life over product life were introduced in Model 4.[11]

The results for Model 4 show a large increase in explanatory power over Model 3 and provide stronger evidence of an association between the platform management strategy variables and firm performance, albeit in relationships that are more complex than were hypothesized. The coefficients of the platform introduction rate and platform introduction rate squared variables remain of the expected sign and both coefficients are now highly significant, supporting Hypothesis 2a. Further, the amount by which platform life exceeds that of the average product remains significant and of the predicted sign. However, the square of this variable is also significantly negatively associated with firm performance. The signs and significances of these relationships suggest that, all else equal, there are also limits to the useful life of a product platform and that at least some firms have chosen platform lives that exceed them.

Although the association between the longest platform lives and lower firm performance was not hypothesized, it appears understandable. If product platform architectures limit the scope of technological changes that can be undertaken, eventually the benefits of being able to leverage previous development projects in current ones is exceeded by the benefits obtainable by being able to redesign a platform with fewer constraints. This point may be difficult to anticipate, and therefore some firms may choose platform lives that prove too long.

Model 4 contains another interesting result. With the addition of the higher-order platform management strategy variables the sign of the derivatives

[10] The overall product introduction rate is a function of platform life because the overall rate of derivative introduction depends upon both the rate of generation of derivatives from a given platform and the number of platforms on the market at a given time. In turn, the number of platforms in the market at a given time on average reflects both the introduction rate of platforms and the average life of a platform.

[11] Interaction terms for the other component of product introduction rate—platform introduction rate—were also tested, but were not statistically significant at even a 10 percent level of confidence.

per year variable changes from positive to negative and remains significant, while the coefficient of the derivative rate squared variable is positive and significant as well. Together, these coefficients suggest a U-shaped relationship between the rate of derivative introduction from a platform and firm performance. All else equal, the highest levels of platform exploitation through high rates of derivative generation are associated with higher firm performance. Similarly, very low rates of derivative introduction are also associated with relatively high firm performance. More intermediate levels of platform exploitation are associated with lower firm performance. Overall, then, this result suggests that middle-range levels of derivative generation from platforms result in lower firm performance than either higher or lower levels.

Again, while not hypothesized, the result appears understandable. It is consistent with an interpretation that leveraging platforms is both beneficial and risky. Interviews suggest that many firms invested to develop a design that could be modified to serve multiple market segments. Successful strategies, in the sense that designs could be quickly leveraged to provide new derivatives, are associated with higher firm performance. However, such efforts were not always successful. On the other hand, strategies that made lower use of derivatives, by taking advantage of only *ad hoc* opportunities for example, also appear to have been more successful than firms introducing derivatives at moderate rates. This interpretation appears consistent with two alternative modes of success—providing a broad product line or maintaining focus—with the broad line approach requiring more risky investments in platforms designed to facilitate derivative generation.

The relationships among the platform strategy variables in Model 4 also suggest an interpretation to account for the non-significance of the product introduction rate squared variable in Model 2. While one component of product introduction rate—derivative introduction rate per platform—is strongly positively related to firm performance, another—platform introduction rate—is negatively related for high values of the variable (negative sign of squared term). The net result is not significantly different from zero for the higher values of product introduction rate. Underlying relationships can be observed only by decomposing the overall introduction rate into its components.

The interaction term of the derivative generation rate per platform and the excess of platform life over average product life has a negative sign and is also significant. The significance of the interaction variable indicates that the effect on firm performance of a given level of platform life depends on the rate at which derivatives are introduced and vice versa. The result implies that firms that seek to optimize their choices for these platform strategy variables must coordinate their choices, in the sense that the effect of a change in one variable depends upon the choice of the other. Here, the negative sign indicates that a given change in rates of derivative introduction and the change in firm performance that is associated will be reduced (increased) as the chosen platform life increases (decreases). And, for a given change in platform life, the change in firm performance that is associated is reduced (increased) as the chosen derivative rate is increased (decreased).[12] Again, the results appear understandable. For example, these findings are consistent with the effect of high platform derivative rates decreasing in their effectiveness as the platform from which they are derived ages.

Models 5–9 test the robustness of these results. To analyze whether firms that survived only a short period of time drive the results, Model 5 controls for the effects of firms that survived in the market for less then 5 years in the industry, i.e., less then an average platform life.[13] Controlling for these firms does not substantially alter results; i.e., coefficient estimates and significance levels remain stable. Model 6 adds a dummy variable to control for firms that did not generate derivatives from platforms. This model explores whether those firms that did not leverage platforms, perhaps because their initial platforms were of poor quality, drive the results. Again, coefficient estimates and significance tests are essentially unaltered. To test whether ATT, by far the largest incumbent at the

[12] Model 4 also shows that the coefficient estimates of the incumbency variables measuring complementary assets and technological experience in the electromechanical technology are both reduced from their estimates in Model 1. The measure Technology Incumbent is now significant, indicating that experience in the prior technology aids performance, even after controlling for differences in product line management strategy. I do not pursue this interesting issue here, other than to suggest that the reduced coefficient estimate may indicate that some of the incumbent effect is due to more effective choice of product line management strategy by incumbents.

[13] Subsets of greater than 4 years and greater than 6 years were also tested, with essentially the same results.

introduction of the radical technological change in the PBX, skewed the results, an ATT dummy was also tested, again with no alteration to the basic results as shown in Model 7.

Model 8 explores the effects of acquisitions on the results. Three dummy variables are tested: one represents firms in the industry that acquired other PBX firms, a second indicates PBX firms that were acquired by other PBX firms, and the third designates firms that were acquired by firms from outside the industry. The results of Model 8 indicate overall that the relationships among firm performance and product line management strategy variables do not depend upon differences among firms associated with acquisition activity.

The non-significance of the dummy for PBX firms that acquired other firms suggests that these firms perform no better then non-acquiring firms. It therefore also suggests that the acquiring firms did not derive greater performance then expected for a given choice of product line management strategy and consequently that the assumptions made regarding acquisitions introduce no obvious bias with respect to these firms. The dummy variable representing firms that were acquired by firms from outside the industry is also not significant and leaves coefficient estimates essentially unchanged. This indicates that treating such firms as if the firm had simply continued operation also did not obviously bias the results of the product line management strategy variables.

In contrast, the dummy variable for firms that were acquired by other PBX firms is negative and significant. This suggests that such firms had lower performance on average than expected, given their particular product line management strategy. This is consistent with the arguments made earlier concerning the treatment of such acquired firms; i.e., firm performance does not appear to have been biased upward. Instead, the negative sign of the coefficient suggests that the acquired firms systematically underperform. In turn, this suggests that the performance of acquired firms may be biased downwards, perhaps, for example, because firms were acquired to gain assets other than the acquired firm's existing products. The existing products might then plausibly have been retired 'prematurely,' lowering estimates of the acquired firm life and hence performance.

Model 9 tests whether control for the age and size of parent firms influences the results. While the control variables are significant, the signs and significance of product line management strategy variables remain unaltered, suggesting the product line management strategy results are not due to size and experience differences among corporate parents.[14]

DISCUSSION AND CONCLUSION

Following the introduction of a radical technological change, numerous opportunities for related product developments that introduce incremental changes are created. Since incremental technological changes can be cumulatively significant to competition, this paper has argued that how a firm manages a product line development strategy to introduce these changes will impact firm performance, particularly over the longer term. Taken as a whole, the empirical results reported here support the hypotheses and provide empirical results that go beyond them.

The paper makes three principal contributions to the literature. First, the investigation of product line management strategy extends existing research on the competitive implications of radical technological change. The majority of work on this topic has focused on explaining incumbent–entrant performance differences immediately following the radical change. This study complements such work by demonstrating that over the longer term firms with greater performance have certain product line management strategy approaches *in common*, whether they are incumbents or entrants. The paper shows that while initial differences between incumbents and entrants such as capability differences, differences in complementary assets, and differences in incentives may influence overall competitive outcomes, effective product line management strategy holds the potential to amplify or offset such differences, especially over the longer term. Therefore, strategic prescriptions emphasizing the effects of entry order and other factors

[14] *Parent Age* was calculated from parent founding until entry to the PBX market with an SPC semiconductor product (introduction of the radical technological change). Where possible, parent size as measured by sales during the year prior to entry was used to calculate *Ln Parent Size*. Where this was not possible, parent size within 1 year of the entry was used. Data for three firms were unavailable. Where necessary, sales were converted to U.S. dollars using prevailing exchange rates. All sales data were then deflated to 1972 dollars. Models 1–8 were also tested with the addition of these controls, but this created no change to the signs or significance of the product line management strategy variables.

derived from incumbent–entrant differences may be oversimplified. For example, firms may trade off some benefits of an early entry and take more time developing an effective product line management strategy—perhaps by investing in design characteristics such as modularity to more effectively generate derivatives from platforms (Baldwin and Clark, 1997)—and still realize competitive advantage over the longer term.

A second contribution of the paper derives from its analysis of links between overall product line management strategy and firm performance. The characterization of product line development strategy in this paper draws upon the expanding literature on this topic. However, while there has been increased emphasis on product lines in academic and managerial publications, systematic empirical investigation has lagged theoretical work (Nobeoka and Cusumano, 1997). The findings in this paper both support and suggest extensions of some of the central arguments of this literature.

First, the results apparently shed light on debates over the performance consequences of high rates of product introduction, which have been prominent within the literature on product line management and within the literature on the performance of individual projects more generally. While some have extolled the potential of ever greater rates of product introduction (see, for example, Stalk, 1988), others have pointed out potential pitfalls (Crawford, 1992; von Braun, 1991). The overall results here imply that higher rates of product introduction yield higher performance. However, the results for platform strategy variables suggest this result can be understood more fully by distinguishing the rate of derivative introduction from the rate of platform introduction. While derivatives introduced at the highest rates may be associated with higher performance, more moderate platform rates may be most advantageous. Thus, the key factor may be the component mix of platform and derivative rates, not the overall rate per se.

Second, the results here empirically demonstrate the additional explanatory power of product life—a factor Uzumeri and Sanderson (1995) have argued has been neglected in characterizing product line strategies exclusively in terms of product introduction rates. On the basis of the evidence here, product life presents firms with an additional important trade-off. All else equal, longer product lives provide clear benefits—either lower overall risk and expenditure in product development as a result of creating fewer products, or the ability to devote a greater proportion of resources to product line expansion. However, in a technologically dynamic environment, longer product lives are risky as products may become inferior to competitors' products in the later stages of their lives. Hence, the longest-lived products are associated with lower firm performance.

A third contribution of the paper lies in its exploration of the impact of choices concerning relationships among products: product platform strategy. While some papers have championed the importance of how relations among designs are managed (e.g., Meyer and Lehnerd, 1997; Meyer and Utterback, 1993), systematic empirical investigation on this topic has been sparse. Also, empirical and conceptual analysis in the broader literature on the performance of individual development projects has been dominated by the assumption that projects are independent or nearly so. However, during the often prolonged period of incremental change following radical technological change, the potential for one design project to depend upon another, through borrowed parts for example, is much enhanced because technological continuity is greater. Therefore, in general firms may benefit from planned and coordinated family relationships among products—platform strategies—that incrementally renew or extend their product lines.

Taken as a whole, the empirical results here confirm that platform strategies do impact firm performance. They show that complex trade-offs and even interactions among basic parameters such as platform lives, platform introduction rates, and derivative introduction rates exist. In turn, this suggests a rich agenda for future exploration of how product 'kinship' relations impact firm performance as consequential choice dimensions are expanded to include combinations of product, derivative and platform lives, rates of introduction, and, potentially, interactions. For managers, they imply that the goal should be to optimize an interdependent portfolio of projects rather than managing each development project independently.

To manage such a portfolio, it is an open question whether best practice techniques for managing individual projects, such as 'heavyweight' teams (Clark and Fujimoto, 1991), can generate an effective overall portfolios. Presumably, firms can develop additional capabilities to manage trade-offs among multiple related development projects.

Organizational practices associated with the relevant capabilities might span a broad range—from *ad hoc* largely independent development projects making opportunistic use of components to formally planned design coordination of multiple projects whose relationships are planned over time and across segments. Future research might usefully address the needed and effective practices.

One additional implication of the platform strategy findings, those concerning platform life, appear consequential. Since firm performance is highest at moderate platform lives, it seems that the time over which a platform may be usefully leveraged is limited. Presumably then, platform designs place important constraints on the effectiveness with which derivatives can be evolved to renew products or optimize them for new segments. At this point, we know little about which choices in platform design and which environmental factors are responsible for limiting the competitively effective period of derivative generation from platforms. Future work might attempt to identify specific decisions made in product development that alter effective platform lives. The extent to which, for example, even costly investments in modular design result in net benefits at the level of the overall product line would be of considerable interest to those championing increased use of modularity, as might identification of the conditions under which different modular partitions are more effective (see, for example, Baldwin and Clark, 1997; Sanchez and Mahoney, 1996).

Clearly much else remains to be learned in the area of product line management strategy more generally. Firm performance may depend on many factors that, practically speaking, no single study can explicitly control. The primary purpose of the analysis here was not, however, to support claims concerning the ultimate causes of firm performance. Rather, it was to extend our understanding of relevant factors in the chain of causation that results in superior firm performance after radical technological change. Clearly, further research will be needed to verify and extend the findings here.

Specifically, two further avenues of research may merit particular attention. First, different environments should be explored. The results here have been observed in an industry where the potential for sharing among multiple development projects from a single platform is high and where the degree of such sharing can be modified by managerial choices. In industries or over time frames where such sharing is of minimal value, or where sharing levels are not easily influenced by managerial choices, strong product platform effects of the type shown here may not be observed. Similarly, in environments where firms in an industry have less influence over the pace of incremental change, product line strategy effects may be minimized. Perhaps, for example, in industries such as the desktop PC market, where major product changes are paced by suppliers' development of core components such as microprocessors and operating system software, there may be less scope for product line strategy choices to affect different dimensions of product line strategy. However, it is also possible that in such industries small differences in product line strategy are of particular importance, since accurate trade-offs among platform rates, derivative rates, and product and platform lives may be especially important.

A second line of investigation might attempt to understand the role of differences in development capability in the observed product line strategy differences. The data available for this study do not permit a distinction between 'choices' and 'capabilities.' That is, the observed product line management strategy of firms might in part reflect differences in the product development capability of firms, independent of the incumbent–entrant distinction. Such differences have been documented in a number of industries for individual development projects (Iansiti, 1995; Clark *et al.*, 1987). It is therefore conceivable that observed differences in product development strategy may be the result of similar 'intentions' but different abilities to effectively execute plans. For example, rapid platform introductions with low rates of derivative generation might reflect firms whose processes to coordinate trade-offs among multiple related products addressing different market segments are weak. Pursuit of such additional research appears warranted given the potentially extensive strategic and managerial impacts of the product line management variables identified here and in a wider emerging literature.

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