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Strategies for Survival in Fast-Changing Industries

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1. Introduction

Scholars have investigated the factors affecting the survival of firms from a range of academic perspectives. One stream of research has focused on firms' abilities to confront technological change as a primary determinant of survival (Cooper & Schendel, 1976; Foster, 1986). Some scholars have seen the roots of firms' rigidities in the face of technological change in the cultures and routines that historically had led to their success (Maidique & Zirger, 1984; Schein, 1988; Leonard-Barton, 1992). Requirements for different technological skills has also been shown to affect survival (Clark, 1985; Tushman & Anderson, 1986; Henderson & Clark, 1990). In particular, some have noted the emergence of a dominant product design as a watershed event that drastically reduces the probabilities of success for subsequent entrants (Utterback & Abernathy, 1975; Utterback and Suárez, 1993; Freeman, 1994; Suárez & Utterback, 1995). A separate stream of research has focused upon forces external to firms that constrain managers' abilities to change competitive and technological strategies in order to survive (Pfeffer & Salancik, 1978; Willard & Cooper, 1985). Some scholars in this tradition have employed the tools of population ecology to identify those forces that most powerfully affect the probabilities of survival (Hannan & Freeman, 1989; Carroll & Hannan, 1989).

While the findings of these researchers have sometimes seemed disjointed and even at odds with one another, some integrative studies have recently emerged suggesting how technological, cultural, managerial, and competitive forces can interact to affect firms' probabilities of survival (Christensen & Rosenbloom, 1995; Christensen & Bower, 1996; Jones, 1996). This paper builds upon this integrative perspective, applying more rigorous techniques than previously have been employed to address the question of what factors most powerfully affect the survival of firms. It analyzes data on the firms that comprised the rigid disk drive industry from 1975 to 1990, and suggests that the factors which seem most closely associated with survival in this industry may affect survival in other fast-paced industries.

The conclusion that emerges most powerfully from this study is that variables related to managerial choice, rather than external factors in the environment that are beyond the control of managers, were the primary factors driving the probability of firm survival in the disk drive industry. This over-all finding is built upon two insights, which we suggest may be applicable to other industries besides the one studied here. The first is that the emergence of a dominant product design indeed marks a significant watershed in the competitive nature of an industry. In disk drives, firms that incorporated in their product line the key elements of what became the dominant product design had a probability of survival that was over *twice* that of firms that ignored the emergence of the dominant design. In addition, there appears to have been a "window of opportunity" in this industry just prior to the emergence of a dominant product design, during which entry was particularly advantageous. Firms that entered many years before, in the stage of the industry's development characterized by broader variety in product architecture and low volume-per-model manufacturing, faced a higher probability of failure -- suggesting that the capabilities and cultures they developed in that competitive environment may not have equipped them well for the competition that characterized the industry after the dominant design emerged.

The analytical techniques employed in this study offer a deeper insight into what constitutes a dominant product design, and into the process by which such product designs emerge, than previously has been available. The dominant design for disk drives was defined by certain *architectural* concepts, which came to be used by all surviving manufacturers. Within this design architecture framework, component-level innovation (much of it radical, or competence-destroying in character) continued at a furious pace long after the dominant architecture became established. Certain of these component technologies became established as standard in all products as well. Use of new components, however, did not significantly affect the probabilities of firms' survival. Hence, we propose that the elements of dominant design that are most salient to a company's survival are architectural in character: they are the concepts that define how the components within the product interact or relate to each other (Henderson, 1988; Henderson & Clark, 1990).

The second insight relates to the risk of betting on new technologies, versus betting on new markets. We found that in the disk drive industry, firms whose entry strategies involved using proven component technologies in products that facilitated the emergence of new market segments, had significantly higher probabilities of survival than did firms that entered established market segments with new component technologies that offered better performance. In other words, our results suggest that entry strategies that entail *market* risk (entering an emerging market with proven component technology) may be less risky than strategies that entail *technological* risk (entering an established market with new, higher-performance component technology).[1]

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1 Christensen (1993), p. 572, employs a very different, less analytically rigorous technique to arrive at a similar conclusion. Using a different measure of success (and using product architecture as a proxy for market strategy), he concludes that the posterior probabilities of success for companies that entered new markets with proven technology was 65%. He found a 38% success rate amongst companies that entered emerging markets using new product technologies; and an

This paper employs a new technique, discrete survival analysis, to reach these conclusions. It does not require the onerous assumptions inherent in the Cox Proportional Hazard model that has most frequently been used in survival analyses (for example Suárez and Utterback, 1995). Discrete survival analysis generates more robust results which can also be presented more intuitively by allowing inclusion among other things of more time-varying covariates.

2. The Rigid Disk Drive Industry

Disk drives are magnetic information storage and retrieval devices used with most types of computers. The principal components of most disk drives are disks, which are substrates coated with magnetic material formatted to store information in concentric tracks; read-write heads, which are tiny electromagnets positioned over the spinning disks which, when energized, orient the polarity of the magnetic material on the disk immediately beneath them; a motor which drives the rotation of the disks; an actuator mechanism which positions the head precisely over the track on which data is to be read or written; and electronic circuitry and software, which control the drive's operation and enable it to communicate with the computer. These components work together within a particular product architecture. (More detail on how disk drives work is provided in Appendix 1.) From the industry's inception there have been significant technological changes both within each component and in the architecture.

Magnetic recording and storage of digital information was pioneered with the earliest commercial computer systems, which used reels of coated mylar tape. IBM introduced the use of rigid rotating disks for information storage in 1956. Although IBM's invention of a drive using flexible (floppy) disks in 1971 was also important for the computing industry, only the industry manufacturing rigid, or hard disk drives, is studied in this paper.

The rigid disk drive industry's history is a remarkable story of rapid growth, market turbulence, and technology-driven "creative destruction". The value of drives produced grew at a 35% annual rate between 1975 and 1989, when the world-wide market size exceeded $13 billion. Of the 17 firms which populated the industry in 1976 -- all of which were relatively large, diversified corporations -- all had failed and exited, or had been acquired by 1990. During this period an additional 124 firms entered the industry, and 100 of those also

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11% success rate for firms that entered established markets, regardless of whether they employed new or proven product technologies.

failed. Some 60% of the producers remaining by 1989 had entered the industry as start-ups since 1976. A host of factors contributed to this turbulence and high mortality rate, as described elsewhere (Christensen, 1993). Key events that powerfully affected the fortunes of the industry's participants, however, were those that comprised the emergence of a dominant design for rigid disk drives.

Figure 1 shows the dynamics of the industry. Note from the figure that the total number of firms active in the industry increased steadily between 1976 and 1983, reaching more than 50 active firms in 1983. From there on, a "shake-out" began: during the 1983-1989 period, there was a steady decrease in the number of firms in the industry, leaving the population in 1989 in about half of what it was in 1983 (Utterback, 1994). This can be confirmed by looking at the entry and exit curves in the figure; note that the entry curve lies above the exit curve for all but one year up to 1983, and that this situation is reversed for the years following 1983. As we will see below, 1983 can also be considered the year when most of the elements of a dominant design in disk drives fit in place and, as theory predicts, thus represents a major milestone in the competitive dynamics of the industry.

[insert Fig. 1 here]

3. The Evolution of a Dominant Design in Rigid Disk Drives

The data-rich technological history of the rigid disk drive industry (Christensen, 1992; 1993) enables a more fine-grained examination of the emergence of a dominant design than was possible in many earlier studies. (Utterback and Abernathy, 1975; Utterback and Suárez, 1994; Anderson and Tushman, 1990). The dominant disk drive design took about 30 years to develop. As Abernathy predicted, the dominant disk drive design was not the result of IBM's initial radical innovation that created the world's first disk drive in 1956. Rather, it resulted from "the weight of many innovations that tilt(ed) the economic balance in favor of one design approach." (Abernathy, 1978).

There were, specifically, four innovations that occurred between 1973 and 1986 behind which the entire industry aligned in defining the dominant disk drive design. Two of these, the Winchester architecture and intelligent interfaces, were *architectural* in character, involving a significant re-arrangement of the ways in which the components interacted within the design (Henderson & Clark, 1990). The other two were *components* -- a rotary voice coil actuator motor and a direct-drive pancake motor positioned at the bottom of the spindle -- that became a standard part of every drive. The analyses reported below show that although all four had become standard elements of 98% of all drives by 1990, the architectural technologies were those that had the strongest impact on survival probabilities.

3.1. The Winchester Architecture

The first step toward a dominant design occurred in 1973, when IBM introduced its first drive employing the Winchester design architecture. Prior drives generally had employed removable stacks of disks mounted on a single spindle -- a design that had originally been developed to increase effective capacity of drives. When the disks were full, the disk pack could be removed and a new stack inserted. IBM's Winchester architecture sealed the entire disk drive -- heads, disks, motors, bearings, and everything else -- inside a dust-free housing. This enabled the heads to fly over a thousand times closer to the surface of the disk than was possible in the removable disk pack design. The resultant improvement in the recording density in Winchester drives made it immediately popular. As Table 1 shows, the percentage of all drives introduced each year that were of the Winchester design increased from 1% in 1975 to 12% in 1980 and 88% by 1985.

[insert Table 1 here]

3.2 The Under-Spindle Pancake Motor

For about 10 years after the initial appearance of the Winchester architecture, the transmission mechanism for spinning the disks was a fan belt that linked an AC motor positioned in the corner of the drive's housing, with a pulley positioned at the base of the spindle. When Seagate Technology introduced its first "microdrive" with 5.25-inch-diameter disks in 1980, there was no room physically within the housing for such a large motor and pulley mechanism. Seagate's solution was to place a flat "pancake" direct-drive motor under the base of the spindle, eliminating the belt and pulleys. This design quickly gained currency. Table 1 shows that 43% of all drives introduced in 1982 employed pancake motors positioned beneath the spindle. This increased to 98% by 1990.

3.3 Rotary Voice Coil Actuator Motors

Disk drives require two motors: the spin motor described above that drives the rotation of the disks; and an actuator motor that moves the heads into position over the proper track on the disk. Most early drives employed a *voice coil* actuator motor that works on the same principle used in sound diaphragms of telephone handsets. As the strength of an electromagnet varies with the amount of current flowing through it, an iron bar is moved in and out, in a very precise, continuous motion. When Shugart Associates introduced its first drive in 1978 it replaced the voice-coil actuator with a less expensive stepper motor -- a motor that rotated in small, discrete steps that corresponded exactly to the spacing of tracks on the disk's surface. Other manufacturers of the period experimented with other technologies as well, such as torque motors and rack & pinion gearing, in an effort to achieve the precision needed to position heads exactly over the right track on the disk, as inexpensively as possible.

By 1986 it had become clear that there were limits to the recording density achievable with stepper and torque motor actuators. The reason was that they moved the head across the disk surface in pre-determined steps. The drive, in essence, had to "assume" that a new track of data would be exactly beneath the head when it took a step. Because disks could expand or contract when they changed temperature, however, this track-per-step alignment became impossible to achieve unless tracks of data on the disk were spaced sufficiently far apart. The industry ultimately had to abandon alternative motors, and standardized on voice coil actuators, which could move in continuous increments. This permitted drive makers to build closed-loop feedback systems into the drives, so that heads could be continuously and precisely repositioned above the correct tracks, as the drives expanded and contracted with temperature; were bounced and jostled; and so on. Table 1 shows that although 42% of all new drives introduced in 1982 used stepper motors, by 1987 the vast majority had reverted back to the voice coil motor. In virtually every case, drives with voice coil motors by 1987 also employed one of two methods for closed-loop feedback, that enabled the continuous repositioning of heads over desired tracks. The standardization on voice coil technology with closed-loop continuous adjustment systems contributed strongly to the industry's ability to move from 450 concentric tracks of data per inch of disk radius achievable with stepper motors in 1983, to 4,500 tracks per inch in 1994.

A dominant mechanical design of the actuator mechanism also emerged over this period. Until 1978 the heads were inserted and withdrawn in a straight line along the radius of the disk in what was called a linear actuator design. Designers' desire to shrink the physical size of drives made this design infeasible, however, and by 1985 a rotary design -- where the heads swung across the disk's surface like the arm of a phonograph, with one end of the arm fixed -- became standard. Table 1 shows that the linear design had essentially disappeared by 1986.

3.4 Embedded Intelligent Interface Electronics

Until 1983, the interface between most drives and their host computers was governed by a separate circuit card, often supplied to the computer manufacturer or disk drive maker by a third party. This was the year in which Quantum Corp. announced the first drive with an intelligent SCSI (Small Computer Standard Interface) control circuit, all integrated onto a single silicon chip that was embedded within the drive. Intelligent drive electronics (IDE) such as SCSI enabled an array of performance enhancements, such that no drive could be performance-competitive without them. These features included:

1. The rate at which data could be transferred to and from the computer no longer was constrained by the speed of rotation of the disks;

2. Codes could be incorporated into the drive that could detect and correct errors;

3. The location of any defects on the surface of the disk could be mapped, and the drive could then be self-programmed not to store data on any defective location; and

4. The density of data could be made more consistent across the disk's surface. Before IDE, drives wrote data at a constant clock rate. On the rotating disk, however, the outer tracks moved beneath the heads at a much faster speed than the tracks closest to the disk's center. As a consequence, data was written much more sparsely on the outer tracks than the inner ones. IDE permitted drives to vary the rate at which they wrote data, to account for differences in the speed at which tracks of varying distances from the center of the disk passed beneath the head. As Table 1 shows, virtually all drives in the industry introduced after 1987 employed embedded intelligent controllers.

The emergence of a dominant design in the disk drive industry was a process that spanned a decade -- it was not a discrete event. The evolution toward the dominant design, however, rapidly gained momentum in 1980, and by 1983 the first model incorporating all features of today's dominant design had been announced. Although the four innovations comprising the dominant design were contributed by four different firms -- IBM, Shugart, Seagate and Quantum -- the first model in the industry to embody all elements of the dominant disk drive design in a single model was announced in 1983 by yet a different firm, Maxtor, that had just entered the industry. Table 1 shows how the rest of the industry's design efforts coalesced around that paradigm within the few years thereafter.

Of course, innovations in disk drive technology continue at a furious pace. The architecture has shrunk dramatically, from disks that were 14 inches in diameter in 1973 to 1.8 inches today. The speed of the pancake motors has increased from 3600 revolutions per minute (RPMs) in 1980 to 7200 RPMs today. The technologies employed in the design and manufacture of recording heads have changed, and continue to change, dramatically. And the intelligence programmed into the drives' controller chips has increased their reliability and speed dramatically. All of these improvements, however, are achieved at the component level, within the fundamental design parameters that now constitute a dominant disk drive design.[2]

4. Hypotheses

Our previous work marks the starting point of the hypotheses we test in this paper. Utterback and Abernathy (1975) and Suárez and Utterback (1995) propose and give support to the idea that the survival of firms is affected by the technological evolution of the industry. In particular, they propose that the emergence of a dominant design will mark a clear milestone in the competitive landscape of an industry. The period after a dominant design would be a period of rapid decrease in the number of firms in the industry in which many firms will have to leave the business because the dominant design allows for the exploitation of economies of scale and other entry barriers and competitive hurdles (see Utterback and Suárez 1993). Consistent with this argument, Suárez and Utterback found statistical support for their hypothesis that the hazard profile of pre-dominant design entrants was lower than that of post-dominant design entrants.

Indeed, the nature of competition in the disk drive industry changed dramatically after the dominant design began to coalesce in the mid-1980s. Prior to its emergence, industry volumes were less than 2 million units in 1984. By 1990 annual volumes over 25 million units had become typical. Product design cycles that averaged about 30 months prior to the advent of the dominant design got compressed to twelve months. Average cost per megabyte fell in constant

[2] In defining this dominant disk drive design in this way, we do not claim that this is a *permanent dominant design*. New technologies, combined with the demands of new markets, could in the future render the current design obsolete and lead to the emergence of another, more effective technology. In such a case, we would expect the patterns of survival and failure to repeat themselves, in the manner described below.

dollars from about $22 in 1984 to $3.30 in 1990. And most significantly, prior to appearance of the dominant design, a host of competitors with very different manufacturing cost capabilities were able to coexist, because the lack of standardization in product features created substantial variety in market segmentation -- creating niches where high-cost competitors could be relatively protected. In 1984, for example, the difference in the cost of making a 20MB drive differed by as much as 40% between the largest and 5th largest producer. In 1990, after the dominant design had coalesced, differences between the manufacturing costs of the largest and fifth largest producers had narrowed to less than 5%. Product standardization lowered boundaries to mobility across market segments. As a consequence, price- and time-based competition had become severe (Christensen, 1995).

Several authors have raised concerns about the validity of the dominant design model, particularly for new, fast-changing industries, such as the disk drive industry (Teece, 1986). The data available for this industry allows us to directly test the dominant design hypotheses--together with many others--as we can trace firm by firm and year by year the models produced and the technologies employed in each model. In the previous section we identified four elements of the dominant design in this industry, and we assembled data on the use of each of these four components, year by year and firm by firm. Following the logic of the dominant design framework, we hypothesize that firms which incorporated these elements of dominant design in their new products will have experienced a lower probability of failure that those which did not even in a fast changing industry such as disk drives.

We also hypothesize that here might be entry timing issues that may be unique to fast-changing industries. Scholars who have examined the relation between entry timing and survival have generally found that early entrants have an advantage (Foster, 1986; Rosenbloom & Cusumano, 1987). Previous work by Suárez and Utterback (1995) tended to support this idea, dividing data into pre- and post-dominant design entrants. This study of the fast-paced disk drive industry, however, points to a different set of propositions. We hypothesize the existence of a "window of opportunity" to enter the industry, during the period just prior to the emergence of a dominant product design. Firms that entered the industry during this short window tended to have a lower probability of failure.

The reason is that in fast-paced industries, learning -- more precisely, the timing of learning -- becomes critical. As the technology changes rapidly, knowledge, and capabilities obsolesce more rapidly than in other industries. This implies that capabilities and knowledge gained at earlier stages in an industry's development may not be useful -- in fact may become liabilities -- in the competitive environment triggered by the emergence of a dominant design. In the disk drive industry, there appears to have been a critical period just prior to the emergence of the dominant design. Firms that entered during this period, and established the capabilities for rapid product development and volume manufacturing that came to characterize the industry, seem to have had a higher probability of survival than firms whose capabilities were defined in a different competitive environment.

Having described a window of opportunity to enter the market, our proposition is that entering earlier or later with respect to this window will be riskier, as it is implied by the discussion above. Firms entering too early will miss the most attractive value network and spend resources in acquiring knowledge which may become obsolete. Firms entering too late will have to face the steep entry barriers that dominant-design producers have been able to raise, in the form of economies of scale, brand name, manufacturing experience, and so on. Our window of opportunity proposition could be seen as a departure from common wisdom on entry timing, which claims that earlier entrants have an advantage. However, we like to think of it as a "fine-tuning" of the entry timing hypothesis which fits better the reality of fast-changing industries such as hard disk drives.

Christensen (1993) has proposed that the technological choices made by a firm when it enters the market also affects its posterior success or failure. In particular, and building on Henderson and Clark (1990), he shows that firms entering the disk drive industry based on an architectural innovation tended to perform much better than those which entered the market based on component innovation. He then notices that most of the architectural innovators in the disk drive industry make their entry into new markets instead of established ones. Entry into new markets allows them to avoid direct competition with established firms and make progress in the new market segment until they are strong enough to defy the established firms in the established markets.

Building on Christensen's work, here we test the hypothesis that the technological and market strategy of a new entrant are highly interrelated, and that their joint effect plays an important role on a firm's probability of survival. In particular, we propose that firms which target new market segments with an architectural innovation will tend to be more successful than those which target existing markets or innovate in component technology, even after controlling for all the competing predictors of survival.

We stress the fact that all our technology strategy hypotheses described above should complement, not replace, other alternative explanations of survival, such as the population ecology and standard economic or management approaches; indeed, as we will see below, we test for many of these alternative approaches in this paper. The relative importance of each approach to firm survival will change depending on the industry under study. Although we lack enough data from different industries to prove it, we are inclined to believe that in modern, fast-changing industries, technology strategy variables tend to predominate when it comes to explain firm survival. As we will see, the hard disk drive industry is a case in point.

5. Data

The data used in this study were taken from *Disk/Trend Report*, a market research publication that has covered the disk drive industry since 1975. It contains information on the dates of entry and exit for every firm worldwide that announced its intention to introduce a disk drive model, whether it actually produced one or not. It provides the technological and performance specifications of each disk drive model that was ever announced by each of these companies, together with the date on which the model was first shipped, if it was in fact put into production. The data set also measures the revenues and unit sales of each manufacturer, by market segment. It is a remarkably complete data set for the industry -- not a sample of firms and products, but a complete census. A comprehensive search of the trade publications covering the industry, as well as personal interviews with over 90 industry executives, yielded information on only one company that had not been included in the *Disk/Trend* database -- a company that incorporated, but never was able to design and announce a product (Christensen, 1993). Although *Disk/Trend* publishes data on the markets for floppy and rigid or hard disk drives, only the rigid disk drive industry was considered in the present study.

6. Method

Survival analysis, a set of statistical techniques developed in the biological sciences to address the problem of censored data, have gained increasing acceptance in the management literature. The cornerstone of survival analysis is the hazard function, which gives the probability that a company will experience an event in a small time interval--exit from the industry in any given year, in our case. We have omitted basic descriptions of survival statistics in this paper: Suárez and Utterback (1995) present the basics of this technique in a related application; more technical references may be found in Cox and Oakes (1984).

In a previous paper, Suárez and Utterback (1995) used a Cox Proportional Hazard model to test whether firms that entered before the dominant design had different hazard profile from those that entered after the dominant design. Even though Cox models are a widely-used tool in survival analysis, they have several important limitations, the chief of them being the validity of the proportional hazards assumption. Singer and Willett, both statisticians expert in survival analysis, state "we have found that violations of the proportional hazard assumption are the rule, not the exception" (Singer and Willett, 1991). In addition, Cox survival models do not lend themselves easily to include time-variant covariates.

In this paper we use a newer and more robust technique--known as discrete survival analysis-- to calculate the hazard or probability of exiting the industry. Discrete survival analysis does not require the proportional hazard assumption and, as we will see, it allows a more intuitive presentation of the results, and the inclusion of time-variant covariates (Willett and Singer, forthcoming). The general model used in this paper can be written:

$$\log_e (h_j/1-h_j) = [\partial_1 D_1 + \partial_2 D_2 + \ldots.\partial_j D_j] + [ß_1 X_1 + ß_2 X_2 \ldots\ldots. BpXp] \qquad (1)$$

where:

h_j	is the hazard at time j
D_1 to D_j	are dummy variables to denote the period that the record references. There are as many dummies as there are time periods in our data set.
X_1 to X_p	are covariates or predictors, which can vary over time
∂ and ß	are parameters to be estimated

the previous equation is identical to:

$$hj = 1/\ 1+ e^{-\{[\partial 1D1 + \partial 2D2 + \ldots.\partial jDj] + [ß1X1 + ß2X2 \ldots\ldots. BpXp]\}} \qquad (2)$$

which can then be fitted using standard logistic regression procedures (see Willett and Singer, forthcoming, for details). In this way, we are able to retrieve the hazard function without the use of dedicated software.

The disk drive industry data set is very comprehensive and thus allows for the inclusion of many variables. Building on our previous work and the literature on firm entry and survival, Table 2 contains a summary of the variables we included or tested in our models:

[insert Table 2 here]

We tested the significance of each variable listed here adding them one by one--with no other covariates aside--to the most basic model, one which contains only the time dummies. Table 3 shows a summary of such exercise: variables that turned out non significant were dropped at this stage.

[insert Table 3 here]

Next, we formed a model with all variables that passed the first significance test. From this model, we continued applying the decrement to Chi-Square test, dropping one variable at a time from the model, and adding them again if they turned out to be significant. This procedure allowed us to come to a best-fitted model, where all variables left were significant at the 0.05 level or better (plus one borderline case). This model is displayed in Table 4 and will be discussed below.

7. Implications of the Significance Tests

The result of the careful approach to testing the significance of each parameter, contained in Tables 3 and 4, allows us to make several interesting observations about the usefulness of each stream of literature in explaining the survival of firms in the disk drive industry.

Conventional economic variables. Conventional economic arguments find limited support in our data. Only FIRMSALE, the variable measuring the effect of firm size on survival was significant. The industry sales growth variable does not even pass the first significance test, which means that there is no relationship between the probability of failure of a firm and the industry rate of growth. We also tried other economic variables (not reported in the Table), such as industry concentration measures, and they turned out not to be significant.

Population ecology variables. Population ecology postulates find no support in our data. Both (DENSITY) and (INDSALES) variables fail to pass the significance test. In other words, the probability of exiting the disk drive industry does not depend on the number of active firms in the industry, nor on the size of the industry in any given year.

Technology Variables. Two of the five variables included in the final model can be considered technology strategy variables. WINCHARC (Winchester architecture) and INTERFAC (intelligent interface) are the key *architectural* elements of the dominant product design. The two elements of the dominant design which were component technologies -- PANCAKE and ACTUATOR -- proved not to have statistically significant explanatory power in the survival equation. These results suggest that the dominant design is defined by the *architecture* of the product, rather than the individual components used as modules within it. This is consistent with the findings of Henderson and Clark (1990), Christensen (1992) and Iansiti (1995) that established firms have a strong track record in continually improving component technologies -- even radically new ones -- within the framework of a dominant product architecture. Taken together, these findings suggest a modification to the dominant design framework proposed originally by Utterback and Abernathy (1975). Whereas they saw a shift in the focus of technology development from product design to process improvement after a dominant design emerged, these findings suggest that once a dominant architecture is in place, considerable technology development may continue at the component level, as well as in manufacturing processes.

Strategic Variables. The other two variables which proved to have significant explanatory power are related to strategies the firms pursued. ARCHNMKT, the variable describing how the entrants targeted their initial product toward the market, emerged as a highly significant factor. Those entrants whose entry product was architecturally innovative, and who deployed that product in an emerging rather than established market segment, enjoyed a much higher probability of survival. This supports the frameworks presented in Christensen and Rosenbloom (1995) and Christensen and Bower (1996), that a firm's choice of which customers to serve has a powerful impact on the capabilities it develops and the strategies it can pursue.

Of the variables measuring entry timing, LNRANK -- which was a rank-ordering of the sequence of firms' entry into the *over-all* industry, failed the significance test when added to the final model. In fact, LNRANK had a *negative* sign -- indicating that *later* entrants would have a lower probability of failure. Our alternative hypothesis, that entry too early might be *dis*advantageous in situations where capabilities and knowledge rapidly become obsolete, was supported in the significance of the WIND8083 variable (it showed a better chi-square test).

VARIETY, which measured a firm's ability to produce multiple product models at one time, is another variable that has attracted some attention in the management and population ecology literatures. It also failed the significance test.

8. Interpreting the Results of the Best Fitted Model

The best fitted model is shown in Table 4. As we can see, only five variables passed all the decrement to Chi-Square tests:

WINCHARC, one of the dominant design variables, which takes a value of 1 if a firm used the Winchester architecture in its models, at any given year (0 otherwise).

INTERFAC, another dominant design variable, which takes a value of 1 if a firm used embedded intelligent interface electronics at any given year (0 otherwise)

WIND8083, the window of opportunity for entry variable, takes a value of 1 if a firm entered during the 1980-1983 period (0 otherwise).

ARCHNMKT, the entry strategy variable, takes a value of 1 if a firm entered a new market with an architectural innovation (0 otherwise).

FIRMSALE, the firm size or economies-of-scale variable, measures the sales of a firm per year in millions of dollars. The average annual firm sales for the sample is $64 million.

[insert Table 4 here]

In order to interpret the results, consider first the sign of the five significant predictors of survival. The negative sign for each of them indicates that all are negatively correlated with the probability of failure. That is:

- the probability of failure is reduced if a firm was using each of these two elements of the dominant design: Winchester architecture or embedded intelligent electronics interface. Firms which did not adopt these two design features--i.e. did not adopt the dominant design--have a higher probability of failure.

- the probability of failure is reduced if a firm entered the industry during the period 1980-1983 (inclusive). This supports our hypotheses that in fast-changing industries such as this, there may be a short "window of opportunity" to enter the market. We believe this window to exist during the few years prior to the crystallizing of the dominant design, and these results lend support to our proposition.

- the probability of failure is reduced for firms that enter the industry targeting a new market segment--different from the established market dominated by the existing firms-- with an architectural innovation. Note from Table 3 that is the combined effect of the ARCHINNO and NEWMKT variables (i.e. ARCHNMKT) which has the strongest effect (largest decrease in Chi-Square).

- the probability of failure is reduced for larger firms, when large is measured in terms of sales. For the calculations of the hazard profiles below, a "baseline" (small) firm was found to be one selling $30 million/year, whereas a typical large firm has sales of $150 million/year.

Table 5 below and its companion Figures 2 to 5 help us interpret the results and see the effect of each covariate on the hazard pattern. The table describes five different scenarios or situations for which we calculated the hazard function. The baseline scenario (i) assumes a firm that did not use either of the dominant design, did not enter the industry during the window 1980-1983, did not focus on a new market with an architectural innovation, and had a small size (sales of $30 million/year). Then, in scenarios (ii) to (v), we change the value of one covariate at a time, in order to see the effect of that covariate in the hazard profile (see table). Substituting these numbers in equation (2) results in $h(t)$--the hazard at year t. Figures 2 to 5, graphically show the effect of each predictor on the hazard profile.

[insert Table 5 here]

The Figures are quite eloquent. First, consider only the baseline curve in Figure 2; its shape and level are a striking indication of the consequences of following a wrong strategy. Given the way we have defined the baseline in Table 5, our baseline firm follows a "dumb" strategy: does not adopt the dominant design, does not enter the industry in the advantageous time window and when it enters, it probably does so targeting the established markets --where the incumbent firms are strong-- without the advantage of an architectural innovation. It does not even have the advantage of a large size. A firm with such a strategy is very likely to fail soon, as we see by looking at the baseline curve. Such a firm has almost an 0.9 probability of failure during the first year in the market, and that propensity to fail continues every year for almost all the data period, making it extremely unlikely that a firm with the baseline strategy will survive.

In Figure 2 it is also easy to see that firms which followed the dominant design --i.e. firms that used both Winchester drive architectures and embedded intelligent electronic interfaces--had a clearly lower hazard profile than those firms of the baseline model. Indeed, the positive shift in the hazard profile is larger for these covariates than for any other variable in the model, which suggests that in fast-paced industries such as the hard disk drive, adopting the dominant design features is crucial for survival.

A positive shift (down) in the hazard profile can also be found in Figure 3: firms that entered during the 1980-1983 window present a much lower probability of failure than firms entering in a different time period. For instance, while a firm entering during the 1980-83 window had a probability of 0,67 of leaving the industry during its fifth year of business (see figure), the same probability for a firm that entered in a different period was 0,85.

Figure 4 shows how choosing an appropriate combination of innovation and entry market can significantly reduce a firm's probability of failure. Architectural innovators entering into new markets present a much lower hazard than baseline firms. For example, note from the Figure that the probability of failure for a baseline firm during its sixth year of business is 0.83, whereas it is only 0.64 for a firm which is an architectural innovator entering a new market.

Finally, Figure 5 shows the effect of larger size on survival. Our baseline firm is five times smaller than our "large" firm. This later firm, with sales of $150 million/year has a hazard profile that is significantly more benign than the baseline firm: while the baseline firm had a probability of failure of more than 0.8 during its seventh year of life, the same probability was about 0.4 for a large firm.

[insert Figure 2, Figure 3, Figure 4 and Figure 5 here]

9. Concluding Remarks

Our results have important implications for understanding firm survival and strategy-making in fast-paced industries, and point toward a number of potentially fruitful avenues for further research.. They suggest that in such industries managerial decisions explain a great part of an entrant's later success or failure. Based on the evidence in this research, a firm entering an industry such as the disk drive industry should carefully study its timing decision (relative to the emergence of the dominant design); look for opportunities to participate in the creation of new value networks, rather than enter established markets; and adopt the architectural elements of the dominant design as rapidly as possible, after they begin to coalesce in the industry. Managers that take these actions appropriately will dramatically reduce their companies' probability of failure through the years. Certainly, as other scholars have shown, factors outside the control of the firm can have a significant impact on a company's fortunes; indeed, they may significantly shape the sorts of strategies management can pursue (Christensen & Bower, 1996). Nonetheless, these results suggest that the firm's own decisions and strategy matter greatly.

The fact that we considered several elements of technology strategy in our model, permits us to build upon previous studies that have examined each of these elements separately. For instance, Christensen's earlier work has stressed that the leaders of one generation of disk drives tended not to remain as leaders for the next generation. The interrelationship between this idea and that of a dominant design in the industry may imply that Christensen's findings could be most applicable for the period before the dominant design. In a post-dominant design period it may be possible for a few dominant firms to stay as leaders for several generations. This hypothesis finds support in the disk drive industry after 1983.

Our results also point toward certain improvements or modifications needed in other existing frameworks. In particular, the analysis suggests that "first-mover advantages" and most of the postulates of the entry timing literature may not hold true in fast-changing industries. Entry timing still has something to tell us about the success or failure of firms in these industries, but in a different way. We suggest the existence of a "window of opportunity" may be a more accurate way of conceptualizing the importance of entry timing in fast-paced industries -- rather than simply first-mover advantages.

We also provide a clearer definition of the idea of a dominant design or standard, which may guide future research in this field. By tracing the main technical elements of a dominant design and their evolution over time, we have been able to determine more rigorously what it is and how it emerges -- thus departing from noisier measures, such as the use of model sales or other non-technology constructs. Moreover, according to our propositions here, the dynamics of how a dominant design emerges should directly affect the size, temporal location and duration of the window of opportunity to enter an industry. Further research is needed to shed more light on this important relationship.

APPENDIX 1: A BRIEF PRIMER ON HOW DISK DRIVES WORK

Rigid disk drives are comprised of one or more rotating disks -- polished aluminum platters coated with magnetic material -- mounted on a central spindle. Data is recorded and read on concentric tracks on the surfaces of these disks. Read/write heads -- one each for the top and bottom surfaces of each disk on the spindle, are aerodynamically designed to fly a few millionths of an inch over the surface of the disk. They generally rest on the disk's surface when the drive is at rest; "take off" as the drive begins to spin; and "land" again when the disks stop. The heads are positioned over the proper track on the disk by an actuator motor, which moves the heads across the tracks in a fashion similar to the arm on a phonograph. The head is essentially a tiny electromagnet which, when current flows in one direction, orients the polarity of the magnetic domain on the disk's surface immediately beneath it. When the direction of current through the electromagnet reverses, its polarity changes. This induces an opposite switch of the polarity of the adjacent domain on the disk's surface as the disk spins beneath the head. In this manner, data is written in binary code on the disk. To read data, changes in magnetic field on the disk as it spins beneath the head are used to induce changes in the direction of current--essentially the reverse process of writing. Disk drives also include electronic circuitry enabling computers to control and communicate with the drive.

As in other magnetic recording products, *areal recording density* (measured in megabits per square inch of disk surface area, or mbpsi) was the pervasive measure of product performance in the disk drive industry. Historically, areal density in the industry has increased at a steady 35% annual rate. A drive's total capacity is the product of the available square inches on the top and bottom surfaces of the disks mounted on the spindle of the drive, multiplied by its areal recording density. Historically, the capacity of drives in a given product architecture has increased at about 50% annually. The difference between the 35% increase in areal density and the 50% increase in total capacity has come from mechanical engineering innovations, which enable manufacturers to squeeze additional disks and heads into a given size of drive.

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Table 1: Patterns of Adoption of Technologies that Came to Comprise the Dominant Rigid Disk Drive Design

Element of Dominant Design	Percent of models introduced in these years that incorporated these features																
	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Winchester Architecture	1%	0%	1%	2%	2%	5%	10%	12%	34%	45%	66%	78%	88%	93%	96%	97%	98%
Pancake Motor at Spindle Base	0%	0%	0%	0%	0%	0%	0%	3%	20%	43%	64%	82%	88%	93%	95%	96%	97%
Voice Coil Actuator Motors	100%	100%	100%	100%	100%	89%	85%	81%	73%	58%	52%	71%	87%	91%	96%	98%	100%
Rotary Actuators	15%	18%	14%	18%	23%	30%	33%	48%	66%	82%	91%	98%	100%	100%	100%	100%	100%
Intelligent Drive Electronics	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	3%	6%	45%	78%	92%	97%

Table 2. Variables tested out during the modeling

Variable	Description	Rationale
LEAVE	Takes a value of 1 the year a firm exits the industry. 0 otherwise	the dependent variable
DENSITY	number of firms active in the industry each year	Population ecologists argue that it is directly correlated with probability of failure (e.g. Carroll and Hannan 1989)
WINCHARC	a dummy variable with value =1 if firm was using the winchester drive architecture at any given year	one of the four components of the dominant design
ACTUATOR	a dummy variable with value =1 if firm was using the rotary voice coil actuator motor at any given year	one of the four components of the dominant design
PANCAKE	a dummy variable with value =1 if firm was using the under-spindle pancake motor at any given year	one of the four components of the dominant design
INTERFAC	a dummy variable with value =1 if firm was using embedded intelligent interface electronics at any given year	one of the four components of the dominant design
VARIETY	total number of different models (8, 51/4, 31/2 inches, etc.) produced by each firm per year	higher variety or mix flexibility makes a firm more competitive (e.g. Suárez, Cusumano and Fine 1994)
ARCHINNO	a dummy variable with value = 1 if the firm was an architectural innovator, as defined by Henderson and Clark (1990)	Christensen's work (1993) suggests that architectural innovators tend to be more successful in this industry
NEWMKT	a dummy variable with value = 1 if the firm entered in a new market as opposed to an established one	Christensen's work (1994) suggests that entrants to new markets tend to be more successful.

ARCHNMKT	a dummy variable with value = 1 if a firm was an architectural innovator and entered a new market	interaction between the two previous variables.
INDSALES	sales of the industry per year, in millions of dollars	population ecology think that a larger market can "feed" more firms
FIRMSALE	sales of a firm per year, in millions of dollars	economists suggest the existence of economies of scale - larger firms have lower costs
ISLGROWT	industry sales growth (%) per year	economists suggest that high-growth industries makes it easier for a firm to stay in business
LNRANK	natural logarithm of entry timing. Entry timing starts in 1 for the first entrant, and so on	first mover advantages concept in the management literature: early entrants would have an advantage
WIND8083	a dummy variable with value = 1 if a firm entered the industry during the 1980-1983 time period, inclusive	there may exist a window of opportunity to enter, just before the dominant design gets established

Table 3. Significance of the Variables when Included Individually in the Most Basic Model (only time dummies)

Variable	Decrement to X^2	Significance (P-value)
DENSITY	0,12	not significant
WINCHARC	25,24	0,001
PANCAKE	6,16	0,02
ACTUATOR	0,92	not significant
INTERFAC	11,80	0,001
VARIETY	5,38	0,05
ARCHINNO	25,88	0,001
NEWMKT	36,67	0,001
ARCHNMKT	39,02	0,001
INDSALES	0,50	not significant
FIRMSALE	58,22	0,001
ISLGROWT	0,48	not significant
LNRANK	17,96	0,001
WIND8083	9,44	0,01

Table 4. Best Fitted Model

Predictor	Estimate	St. error	Significance	Delta X^2 *
D1_76	2,33	0,68		
D2_77	2,36	0,65		
D3_78	2,52	0,60		
D4_79	2,27	0,55		
D5_80	2,03	0,52		
D6_81	1,92	0,54		
D7_82	2,36	0,53		
D8_83	2,39	0,55		
D9_84	2,49	0,56		
D10_85	2,22	0,55		
D11_86	2,12	0,58		
D12_87	2,59	0,66		
D13_88	0,58	0,94		
D14_89	-0,09	1,18		
WINCHARC	-1,16	0,40	0.01	9,21
INTERFAC	-0,85	0,49	0,07	3,07
ARCHNMKT	-0,66	0,25	0,01	6,88
WIND8083	-1,51	0,29	0,001	28,87
FIRMSALE	-0,018	0,003	0,001	48,14
-2LL	440,65			

* when dropped one at a time from full model

Table 5. Four Scenarios to Illustrate the Impact of Covariates on Hazard

SCENARIO	WINCH ARC	INTER FAC	ARCH NMKT	WIND 8083	FIRM SIZE
(i) Baseline	0	0	0	0	30
(ii) Effect of dominant design	1	1	0	0	30
(iii) Effect of entry window	0	0	0	1	30
(iv) Effect of tech/mkt entry strategy	0	0	1	0	30
(v) Effect of Firm Size (Scale)	0	0	0	0	150

Figure 1. U.S. Producers of Winchester Drives, 1976-1989.

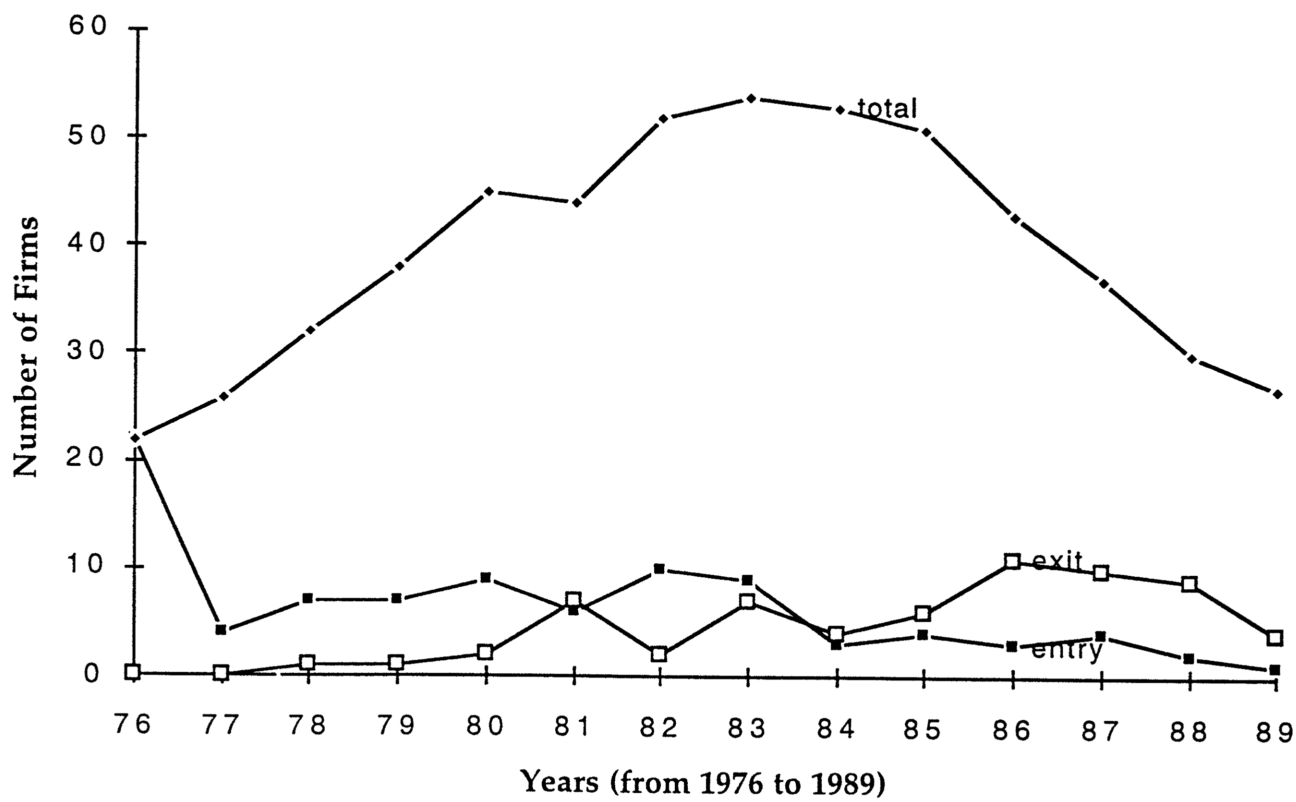

Figure 2. Effect of Dominant Design on Hazard

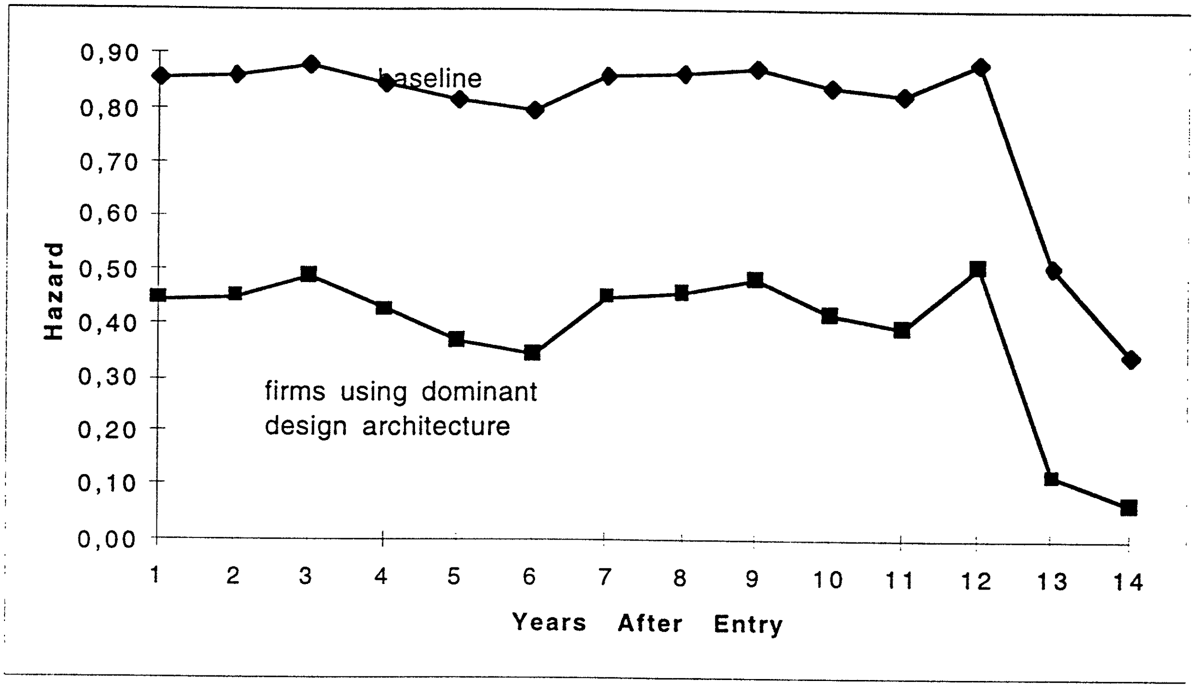

Figure 3. Effect of Entry Window (1980-1983) on Hazard

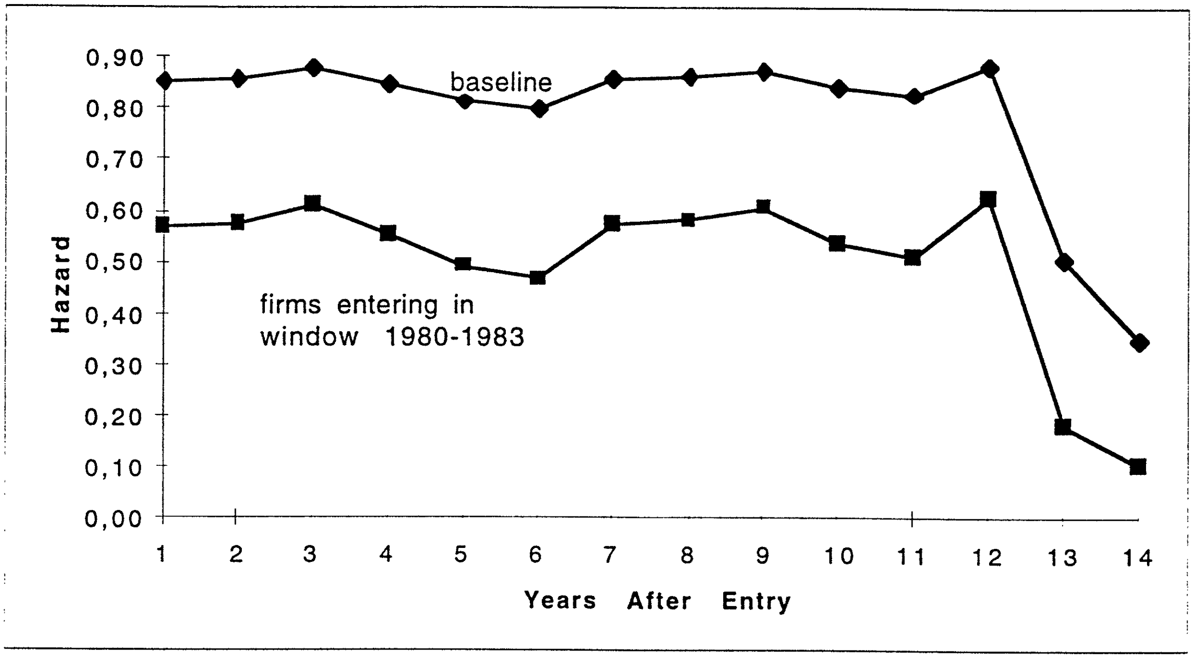

Figure 4. Effect of Technology Entry Strategy on Hazard

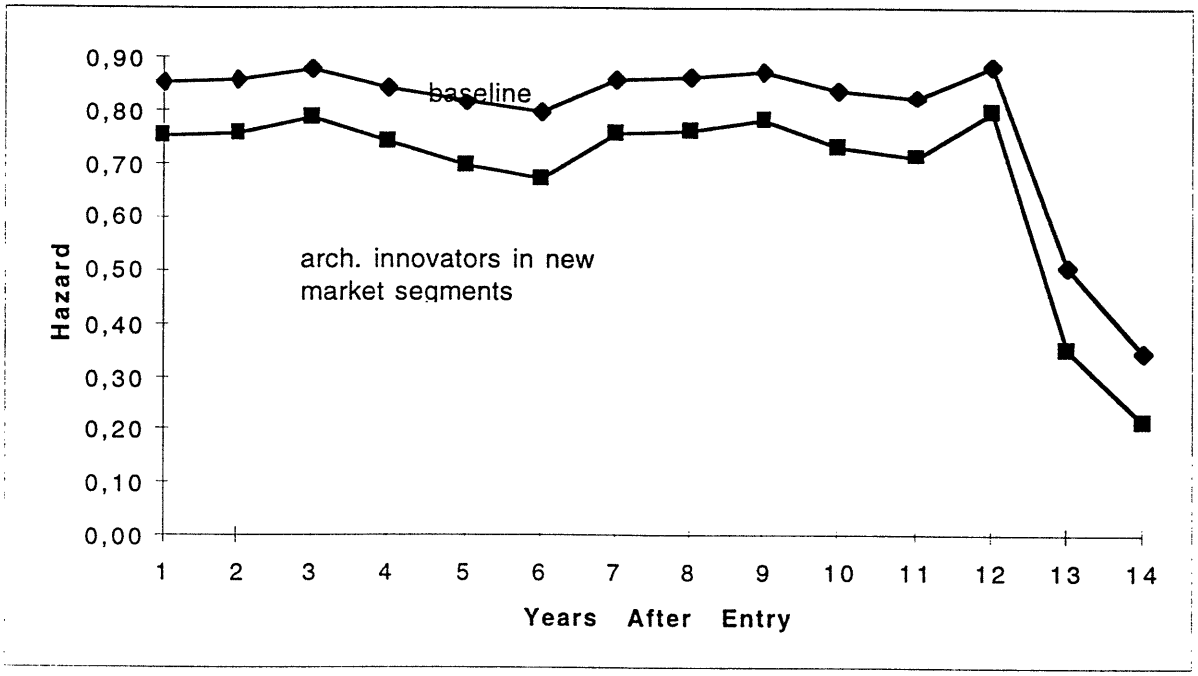

Figure 5. Effect of Firm Size on Hazard