Dynamic Competition in Technological Investments: An Empirical Examination of the TFT-LCD Panel Industry*

Jeongsik Lee[a], Byung-Cheol Kim[b], and Young-Mo Lim[a, c]**

[a] Georgia Institute of Technology, College of Management
[b] Georgia Institute of Technology, School of Economics
[c] Samsung Economic Research Institute

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Abstract

When are technological laggards more likely to catch up with leaders? We offer empirical evidence on firm-level data of plant investments in TFT-LCD panel industry, where technological competition has been intense and dynamic. We find that followers' likelihood of catching up investments increases with the leader capacity that employs the state-of-the-art technology. We also find that the effect of followers' technological competence exhibits nonmonotonicity, with intermediate followers the most apt to invest in catching up. These results are robust to variations in specification and alternative accounts of effects. We discuss our findings and contributions in light of technology race literature.

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** Corresponding author: Jeongsik.lee@mgt.gatech.edu.

1. INTRODUCTION

How do firms compete in an industry where technological supremacy implies market dominance? Economists have long sought answers to that question because the outcome of such competition can have significant implications, not only on firm innovations and the market structure but more broadly on the economic welfare of the society. Along this avenue, the literature on technology race has offered numerous insights as to how firms in asymmetric technological positions (e.g. leader vs. follower) might optimally exert innovative efforts to gain or retain competitiveness.[1] Though providing an effective framework for exploring the issue, the large body of works also leaves many questions unanswered. Most notably, the literature—being almost exclusively theoretical in nature—lacks robust empirical evidence, perhaps with the exceptions of Lerner (1997) and Czarnitzki and Kraft (2004). Also, on some critical points, the literature remains silent on the followers' heterogeneous catching up behaviors. A dearth of firm-level data on technology investments appears a nonnegligible roadblock to a progress. In this article, we attempt to fill this gap by exploiting the detailed and comprehensive firm level data on production technology investments in the Thin Film Transistor Liquid Crystal Display[2] (TFT-LCD; hereafter, LCD in short) panel industry. In this representative industry that faces dynamic technological leadership competition, we offer the first examination on when the followers are more likely to make catching up investments. Further, we explore firm heterogeneity in investment strategies, which allows us not only to assess the predictions of prior theories but also to uncover what remains for further study.

We examine the drivers of technological followers' catching up behavior through their investments in fabrication plant technology. LCD panels are produced on glass substrates loaded with transistors and then are integrated into display products such as televisions and monitors. In the industry value chain, the panel fabrication process is the most critical part that determines feasible display size and unit panel cost and hence requires constant R&D and innovation efforts. To effectively respond to the market demand for larger size displays, LCD panel firms have focused on increasing the size of glass substrates by developing or adopting next best available substrate technologies.

We characterize the technological competition in LCD panel industry as a perpetual race with a series of incremental innovations in glass substrates. Market shares are significantly affected by the outcome of technology race, which is not a one-shot game of winner-takes-it-all but a repeated race where the players realize payoffs over time. Because firms that occupy technological leadership can enjoy a

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[1] We provide a brief review on this literature in Section 3.

[2] The LCD is a subset of the broader flat panel display (FPD) technology. Within LCD, several alternative technologies exist. Also, the LCD market is segmented according to panel sizes. In this article, we focus on large-sized panels (10.4 inches or larger) that use TFT-LCD technology. Large-sized TFT-LCD panels account for more than 2/3 of the LCD sales, which are over 95% of the FPD market, and are fast growing (Hart, 2008). Hence, we believe our focus on this segment is sufficiently comprehensive.

substantial price premium, the followers have strong incentives to exert substantial R&D efforts to usurp or regain leadership, thereby altering the industry’s competitive ordering. In fact, no leader persistence exists in this industry; every firm often finds itself running as a follower.

We find that the technological followers—firms that lack the leading technology in their plants—are more likely to make catching up investments when the leaders have a greater production capacity with the state-of-the-art technology. This finding confirms the theoretical intuition that the follower under intensive R&D rivalry are strongly motivated to catch up so as not to fall too much behind. When the leader is moving forward, the followers strive to hop on before the window of opportunity closes as the next generation technology evolves, which expectedly shrinks the payoff from status quo.

We also find that the followers who have a moderate technological gap from the industry frontier—measured by the relative size of firm best substrate compared to industry best—are more likely to invest in catching up technologies. This finding corroborates the prediction from theoretical works that the followers with a sufficiently large lag lose their motivation to catch up with the leader. This finding, however, goes a step further to uncover a deficiency in technology race literature. To the best of our knowledge, no theoretical framework explains the situation in which the followers with an intermediate lag continues to keep up with the leader whereas those with a small lag choose to maintain status quo or even opt for rationalizing size by consolidating or liquidating existing production lines. Our result resonates with Lerner’s (1997) finding that the disk drive manufacturers with a moderate level of technological gap innovate the most. We submit that something far more than a coincidence must lie behind such common findings, which merit further exploration.

The remainder of this article is structured as the following. In Section 2, we provide a brief description of LCD panel industry to help understand theoretical issues and empirical context we propose in this study. Section 3 reviews prior works on technology race and suggests main empirical issues. We describe our dataset and empirical strategy in Section 4. Section 5 presents specification results along with robustness checks. Finally, in Section 6, we discuss our findings and contributions in light of the literature on technology race.

2. INDUSTRY BACKGROUND

Born in 1968, the LCD panel industry has since grown rapidly, particularly after its wide adoption in notebook computers in the early 1990s. The market size has grown to $73 billion in 2007 (DisplaySearch, 2009), which is more than 400 times that in 1990. This phenomenal growth owes to the technological shift in the late 1980s from the passive matrix method, which has been in use since 1970s, to the active matrix (i.e. TFT) method that effectively combines the optical and semiconductor technologies. The arrival of this novel display technology has given rise to numerous product innovations that enrich the multimedia environment, which calls for continuous improvements in the resolution, size, and response speed of display. Though first commercialized by Radio Corporation America (RCA), LCD panels are now almost exclusively produced by Asian manufacturers. Within the relatively short tenure, the industry has witnessed drastic changes in the composition of players as well as their market positions, first dominated by Japanese firms such as Sharp and Toshiba, then overtaken by the Korean firms such as Samsung and LG Philips, and recently challenged by Taiwanese firms such as AU Optronics and Chi Mei Optoelectronics. Table 1 indicates the rankings by market shares and the changes in market positions of major LCD manufacturers in some representative years.

LCD panel manufacturers supply their products to other companies (or different divisions if integrated), who then integrate these customized panels into consumer electronics products such as TV sets, notebooks, monitors and mobile phones. Since the industry's inception, LCD firms have faced challenges from two fronts. On the one hand, they had to respond timely to the market demand for larger size displays. For instance, the popular size of notebooks, the first application of TFT-LCD technology, has been growing in every one to two years (Murtha et al., 2001) and the same trend applies to TVs, a more recent application of the technology. On the other hand, LCD firms had to reduce cost continuously to attain competitiveness against competing display technologies such as Cathode Ray Tubes (CRT) and Plasma Display Panels (PDP). LCD firms have responded to these challenges, which essentially conflict with each other, by expanding the size of glass substrates (a.k.a. mother glasses) used for panel production.[3] The larger the substrate size, the more panels of a given size or a given number of larger size panels can be produced for given throughput time. Hence, firms using larger glass substrates can supply larger panels at lower costs, thereby strengthening their competitive market positions. It is thus not surprising that LCD firms have competitively invested in fabrication plants ("fabs") that are equipped with larger size glass substrates. Driven by the rivalry in capacity investments, the state-of-the-art glass substrates have undergone multiple generations of technological development, with the standard size expanding almost 60 times over the industry's life (see Table 2 for the size of glass substrate by generation from one (1G) through eight (8G)).

Though upgrading the production facility to the best available generation technology is regarded critical—perhaps more than anything else—for securing a competitive edge, it is also a dual-edged sword because investing in new technologies is particularly risky and challenging in this industry. First of all,

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[3] Glass substrates have transistors in the surface that drive liquid crystal (LC) to be evenly spread across a large sheet of panel. This LC-loaded panel sheet is cut into multiple panels tailored to the client firms' specifications to be integrated into final consumer products.

the lead time between the start of plant construction and the ramp-up of production adds to the uncertainty in market demand at plant launch, thereby leading to difficulty in deciding the correct timing of investment. In fact, the industry has been fraught with the “crystal cycle,” characterized by booms and busts in demand and supply, witnessing the cycle repeating in every two to three years (Matthews, 2005). Also, firms setting up a new generation plant may face numerous problems, many of which are often unanticipated, before they are able to stabilize the process and ramp up production to an efficiency level (Asakawa, 2007). Furthermore, the plant investment requires an astronomical amount of capital[4], but the prospect of recouping the investment can be obscured by the relatively short-lived technological lead and the frequent oversupply. Despite these potential downsides, however, LCD firms do strive to make technological strides, betting on the upsides of such investments. Indeed, firms that succeed in making opportune movements get to enjoy much higher per-area profits due to a lower unit production cost and higher panel prices, go down the learning curve faster than late adopters, and expect an additional cost reduction due to an earlier ending of plant depreciation.

The uncertainties embedded in technology investments, coupled with large capital requirements, gave rise to several distinctive characteristics of the industry. First, there has been a continuous, highly dynamic leadership competition among the players. Market leaders keep investing in new technologies to maintain their leadership, with some turning out to be strategic failures, whereas the followers take risks to catch up with the leaders, often resulting in technological leapfrogging.[5] A consequence of this technological competition is the frequent changes in market leadership. Between 1989 and 2007, the market leader—based on the annual dollar sales—changed six times.[6] This implies that the average tenure as market leader is less than five years, which is extremely short compared to other industries.[7]

Second, the exponential increase in capital necessary for a new fab construction with a higher generation technology has made entries difficult and widened the gap between leading firms and cash-constrained trailers. The burden of capital requirement, along with technological complexity, has contributed to the industry’s oligopolistic market structure. Table 3 shows the number of active firms, market concentration indices—the Herfindahl-Hirschman Index and the four-firm concentration

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[4] It costs about U$3.3 billion to build an eighth generation (8G) fabrication plant, an amount six times that required for a 3G plant construction.

[5] Macroeconomic downturns, which had asymmetric adverse impacts to market leaders, may have provided “windows of opportunity” for potential entrants. Hart (2008) argues that, in the mid-1990s, the Korean firms entered the market taking advantage of sluggish investments of then-leading Japanese firms since the beginning of the “lost decade”, and that the Taiwanese firms entered the market while the leading Korean firms were suffering from the Asian financial crisis in the late 1990s.

[6] Among the historical market leaders are Sharp (1989-1994), DTI (1995-1998), Samsung (1999-2002, 2004, 2006-2007) and LG Philips (2003, 2005).

[7] Baldwin (1995) and Geroski and Toker (1996) find that, across industries, the number one firm retains its leading market position between 17 and 28 years.

ratio—evaluated at the end of each year. Begun with only two firms in 1989, the industry has since seen more firms enter the market and hence become less concentrated until the early 2000s. More recently, however, the industry is regaining concentration with leading firms taking larger shares, as mergers and exits occur primarily among Japanese manufacturers.

Third, though in general technological upgrades have been a major driver of the advancements in market position, considerable heterogeneity exists among followers in the adopted investment strategies. For instance, firms at the top tend to put higher stakes at bringing out the biggest display panels before their rivals do, not only because such action is expected to yield a higher payoff but also because it could signal technological supremacy. But some followers choose to increase their sizes by consolidating non-best technology capacities, whereas still others opt for selling their fabs to other players. Many firm-level characteristics, such as technological gaps from the industry frontier, firm size, market position, and even nationality, contribute to such heterogeneity in technological investments.

3. LITERATURE REVIEW AND RESEARCH QUESTIONS

Economists have extensively studied which of the leader and the follower innovates more. Arrow (1962) shows that an incumbent monopolist has a lower incentive to invest in cost reducing process innovation compared to a challenger for both a drastic and a non-drastic innovation. His result is due to the *replacement effect*: the monopolist replaces himself through innovation and thus gains no additional profit whereas the challenger always increases her profits. In contrast to Arrow who considers a situation where a firm's innovation is protected by a patent with unlimited duration, Gilbert and Newbery (1982) consider a monopolist who is concerned about the possibility of substitution by the challenger. Gilbert and Newbery assume a deterministic R&D technology in which the party spending the most gets rewarded without uncertainty just as in a first-price auction. With such a setup, they find an opposite result to Arrow due to the *efficiency effect*: total industry profits dissipate as more firms enter. For instance, the sum of duopoly profits is smaller than or equal to the monopoly profit. This monopoly persistence is challenged by Reinganum (1983) who maintains that the entrant is more likely to innovate than the monopolist if R&D outcome is stochastic. She considers a drastic innovation in a simple model of patent race between an incumbent monopolist and an entrant where the timing of a successful innovation is exponentially distributed. With R&D uncertainty, she finds Arrow's replacement effect working against the monopolist. That is because the monopolist has no additional profit gain by hastening the discovery time whereas the entrant does.

Distinct from this single stage race, economists have studied technology race in a multistage setup—firms must go through multiple stages of R&D to win the race. With this setup, Fudenberg, Gilbert, Stiglitz and Tirole (1983) find "ε-preemption": a slightest lead causes the follower to drop out of race. Harris and Vickers (1985) independently obtain the same result. This not-so-appealing result is earned in deterministic multistage race models. This assumption is later relaxed by Harris and Vickers (1987), Grossman and Shapiro (1987) and Lippman and McCardle (1987), who allow probabilistic stage-to-stage transitions. In these models, the leader devotes more resources to R&D than the follower and thus the leader's advantage increases. Research competition is most intense when firms are neck-to-neck. Remarkably, in these models of multistage patent race, the R&D process has a "memoryless property": each firm's current R&D effort is independent of its past R&D effort. In contrast, Doraszelski (2003) develops a more general model of R&D race that allows knowledge to accumulate and shows that, with knowledge accumulation, the follower invests more in R&D than the leader. This result owes to the *pure knowledge effect* that a firm is inclined to scale back R&D investments as its knowledge stock increases and thus the follower eventually works harder than the leader. He also finds that R&D competition is not necessarily fiercest when firms are neck to neck. This contrasts with the prediction by Fudenberg et al. (1983), Harris and Vickers (1987), and Lippman and McCardle (1987).

The early models of R&D race have another limitation that races have exogenous finishing lines and awards. However, most research-intensive industries such as electronics, pharmaceutical, and LCDs are characterized by a series of incremental innovations and endogenous deadlines and awards. Such a limitation has motivated a strand of literature studying perpetual R&D races in an infinite horizon framework (Aoki, 1991; Harris, 1991; Budd, Harris and Vickers, 1993; Giovannetti, 2001; Hörner, 2004). Budd et al. (1993) examine whether asymmetries between firms increase or decrease in a multistage race. They find the answer hinges on the *joint payoffs*—joint product-market profits less joint effort costs. If joint product-market profits become higher as the gap between firms enlarges, the leader tends to exert more effort than the follower. Otherwise, the follower does more R&D. In deterministic models, there is a threshold gap above which the follower stops investing. In a stochastic R&D technology with leapfrogging, Aoki (1991) finds that the follower's R&D investment may not be monotonic in its technological lag. Building upon Aoki, Hörner (2004) confirms that such nonmonotonicity occurs as one possible Markov Perfect Equilibrium (MPE). Modeling a dynamic race in which the state of competition stochastically evolves depending on firms' relative effort levels, he shows the presupposition that 'high effort is exerted if and only if the lead is sufficiently small' is not generally true, but is only one possibility. Another MPE he characterizes is that both firms exert high efforts when the follower's lag is sufficiently large. The intuition is that the leader wants to outstrip its rival and secure a durable leadership, whereas the follower tries to avoid such an outcome. Giovannetti (2001) considers a duopoly industry facing a sequence of cost reducing innovations. He examines MPEs when an *increasing asymmetry* (or an *increasing dominance*) arises in equilibria and when *alternating adoptions* (or *perpetual leapfrogging*) are equilibrium strategies. The result indicates that, if the price elasticity of demand is greater than or equal to one and adoption is profitable at a given date, alternating adoptions is an MPE but increasing asymmetry is never an MPE.

Though the technology race literature has provided various insights on firm incentives to innovate in leadership competition, it lacks a good balance between theory and empirical corroborations.[8] A few exceptions include Lerner (1997) and Czarnitzki and Kraft (2004).[9] On an empirical study of the innovation propensity of hard disk drive manufacturers, Lerner finds that the followers are more likely to innovate than the leader—a finding that supports Arrow (1962) and Reinganum (1983) rather than Gilbert and Newbery (1982). More specifically, Lerner shows that the followers whose technological position—measured by the relative performance of drive density against the industry best—lies between 25% and 74% of the leader are most likely to innovate. However, from the firms in the lowest technological position (bottom 25%), no significant effect is found. This result suggests that the firms whose technological competence is too low are less likely to innovate. On a survey of about 3500 German firms between 1992 and 1995, Czarnitzki and Kraft find that potential entrants invest more in R&D than the incumbents to enter a new market.

In this article, we examine the technological competition in the LCD panel industry, using a population of firm-level production technology investment data during 1989-2007. Adding to a dearth of empirical studies in R&D race literature, our study also differs from prior studies in that we investigate the technological investment decisions of followers and are particularly interested in the *heterogeneity* of their catching up behavior. We focus on follower behavior for two reasons: first, the heterogeneity within follower group has received little attention in the literature, a gap that we feel need be filled; second, and more important, there is no leader persistence in this market due to such industry characteristics as the crystal cycle and the high speed of technological development, and hence most firms are followers in the technology race.[10] More specifically, we examine *when* the followers are more prone to make a catching up investment. In particular, we focus on two key factors that affect such decision: the accumulated capacity of leading technology and the follower's technological gap from the industry frontier.

We first note that a greater leader capacity with the state-of-the-art technology implies that the followers should expect a smaller profit unless they embrace the leading technology. Hence, the followers will respond aggressively to a greater leader capacity in the "action-reaction" pattern a la Giovannetti (2001). This intuition is also consistent with earlier theoretical models of R&D race (Fudenberg et al.,

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[8] For instance, Reinganum (1984) points out the need for and the difficulty of empirical tests of the theories. Our reading of the literature indicates that the situation has not much changed since.

[9] Khanna (1995) studies the racing behavior in high-end computer industry and reports that the technological leadership competition is best described as a race among a subset of firms in the industry. He finds that laggard firms display a robust tendency to catch up.

[10] This feature precisely fits the perpetual leapfrogging in Giovannetti (2001).

1983; Harris and Vickers, 1987; Lippman and McCardle, 1987; Aghion et al., 1997), whose basic premise is that to remain as effective contenders the followers must not be too much behind. Technology leader and follower are respectively analogous to incumbent and entrant.[11] Thus, the readers of strategic entry deterrence literature might surmise that, with a greater state-of-the-art capacity from the technological leader, the followers would be discouraged against making investments to catch up with the leader. This is because, as Spence (1977) and Dixit (1980) show, the incumbent's capacity decreases the expected profits of potential entrants. In the LCD panel industry, however, such opposing force is not strong enough to reverse the direction. For the capacity investment to be credible, it must be "sunk". But LCD fabrication capacities are industry-specific rather than firm-specific as in the case of airport gates (Gale, 1991).[12] Therefore, we expect that the followers will more likely make catching up investments when there is greater leader capacity with the state-of-the-art technology.

On the issue of technological gap, theories remain inconclusive about the relationship between technological gap and innovative activity. As Aoki (1991) and Hörner (2004) note, the relationship may not be monotonic. Hörner (2004) notes: "… [w]hen the lead is moderate, low effort may be the best choice since there is neither an urgent need for an active defense of the leadership, nor hope to see the laggard quickly let go (p.1066)". The resulting equilibria suggest a U-shaped relationship between the technological gap (on the X-axis) and the innovation (on the Y-axis). Interestingly, however, this theoretical prediction is diametrically opposite to the empirical finding of an "inverted" U-shape in Lerner (1997). Lerner's finding implies that the most arduous innovators are the intermediate followers who are neither too far from nor too close to the technology frontier. Thus, it remains to test empirically whether the relationship is nonmonotonic and, if so, which of the particular pattern (a U-shape or an inverted U-shape) characterizes the relationship.[13]

4. EMPIRICAL DESIGN

Empirical Context

We corroborate our expectations on the data of fabrication plant investments in the TFT-LCD panel industry during 1989-2007. For at least three reasons, we believe that the LCD panel industry is particularly good for examining the research questions posed in this study. First, an intense leadership competition exists among industry participants, with the race resulting in frequent leadership changes.

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[11] In fact, two terms have been used interchangeably in the literature of R&D races.

[12] LCD fabs are often resold to other LCD firms. As Krishnan and Roller (1993) show, entry deterrence is not optimal for the incumbent when capacity is resalable. See Krishnan and Roller and therein references for more examples of resalable capacity.

[13] This study is even more interesting in that the LCD panel industry focuses on the cost-reducing *process* innovation, while Lerner's disk drive industry focuses on *product* innovation.

The constant churning in market ordering puts virtually all players in the position of follower who has strong incentives to invest in catching up technologies. Second, important technological improvements can be clearly defined. For the study of technology races, one should be able to identify and measure technological innovations on an objective standard (Lerner, 1997). In the LCD panel industry, the upgrades in the size or the generation of glass substrates serve as an uncontroversial indicator of technological improvement over the status quo (Murtha et al., 2001).[14] The measurement is also straightforward because the specifics of fabrication plants are fairly standardized for each generation of glass substrate. Third, the relative standing and technological competence of industry players can be precisely identified. Due to an oligopolistic market structure, firm interactions and the outcomes of technological choices are easily observed and can thus be effectively analyzed. The industry consensus on technological standards facilitates the measurement of individual firms' relative standings with respect to the industry frontier.

The Dataset

We construct our data primarily from three sources. First, we obtain the capacity investment data from the *Nikkei Microdevices' Flat-Panel Display Yearbook*, published annually by Nikkei Business Publications, Inc. The yearbook provides detailed information on the worldwide fabrication plants that produce LCD panels. The contents of information include the name of panel manufacturer, plant location, investment amount, generation of technology, size of glass substrate, time of plant launch, and per-month production capacity. From this data source, we compile a comprehensive dataset on firm-plant level panel production capacities that were active during 1989-2007. This dataset not only lists all production capacities that existed at the time of publication but also reports the transfer of ownership changes. Hence, we know from the dataset whether a plant was newly constructed, acquired from other firms, or liquidated. It is important to note that, unlike semiconductor fabrication plants that are essentially scrapped (i.e. become obsolete) when a new generation technology fab begins production, LCD panel fabs do not "exit"; older generation capacities coexist with the newer generation fabs. Coupled with the fact that the industry tenure is relatively short, this reusability of existing plants enables us to identify all the LCD panel fabs that ever existed in this industry. Hence, we believe that our data represent the industry's population of all capacity investments. In a small number of cases in which the information in the yearbook is incomplete (e.g. production capacity is not reported), we resort to an extensive search of news articles, company

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[14] Though technological improvements in the LCD panel industry are primarily process innovations, they represent product innovations as well because the substrate size not only determines the unit production cost but also constrains the size of panels that can be produced from the substrate. As long as these two innovation goals are integrated within the decision making process, any change in innovation target is less likely to have asymmetric implications on the investment benefit-cost ratios across firms.

websites and industry reports to fill in the missing information.[15] As a result, we have a total of 161 capacity investment decisions made by 38 firms during the period.

Second, the panel manufacturers' market share data come from DisplaySearch, LLC. and *Nikkei Microdevices*. DisplaySearch specializes in flat panel display market research and consulting, and publishes quarterly reports of flat panel display market trend including shipments and sales (in US dollars) by panel manufacturer. Though most widely used in display-related research, the DisplaySearch database only covers the period from the fourth quarter of 1999. To cover the entire industry tenure, we use for the earlier periods the sales data reported in *Nikkei Microdevices*, which was regarded as the most comprehensive data source before the launch of DisplaySearch. As the sales data in *Nikkei Microdevices* use local currencies, we convert the sales into US dollars via the year-end exchange rates for consistency in currency unit. Hence, we believe our dataset contains the best-available data on the time-varying landscape of the industry's competitive structure as indicated by the division of revenues.

Third, we obtain patent data from the United States Patent and Trademarks Office (USPTO). Using the names of panel manufacturers, we search and identify all LCD-related US patents that are applied for by these firms since 1970 and granted by 2007. By this, we intend to identify the panel manufacturers' patented knowledge assets that embody the technologies directly relevant to LCD panel manufacturing. The USPTO assigns each patent to one or more technological classes based on the patent's technological characteristics. We use the US Class 349 (Liquid Crystal Cells, Elements and Systems) to define the scope of the relevant patented knowledge.[16] This search criterion results in 6,172 patents owned by the panel manufacturers in our dataset.

Variables

For the regressions analysis, we construct the variables as the following.

Dependent Variable Our dependent variable represents the choice of production technology. Facing the decision of production technology for the new plant, firms have three categories of choice: 1) catching up with the state-of-the-art technology, including the improvement upon the industry best ("catching up")[17]; 2) choosing a technology that is inferior to the state-of-the-art but superior to the firm's

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[15] In the seven cases for which we cannot find the exact quarter of plant launch, we assign Q2. The results are robust to variations in the assignment method including random assignments.

[16] FTF-LCDs consist of multiple components and involve technologies classified outside Class 349. However, consultations with patent lawyers confirm that Class 349 is sufficiently accurate and comprehensive for capturing patented knowledge related to panel manufacturing. Scholars have also used Class 349 to identify LCD patents (e.g. Stolpe, 2002).

[17] By this, 'catching up' behavior includes both 'front-hugging' and 'leapfrogging.' Front-hugging occurs when the follower reaches the industry frontier by matching the leader technology. Leapfrogging occurs when the follower comes up with a technology that surpasses the state-of-the-art and hence claims the new frontier. We attempted to

internal best ("running on the spot"); and 3) consolidating a capacity with a technology inferior to the internal best or liquidating an existing capacity ("resizing"). To classify investments into one of these categories, we first measure the state of chosen technology by the size of glass substrates that each new plant employs. We define the size of a glass substrate by the "area," which is a product of the length and the width of the substrate. Assuming an equal efficiency in glass cutting, more and/or larger panels can be produced from the substrates with greater aerial spaces. Based on this area, we classify a technology investment (at time t) as catching up if the size of a new substrate is larger than or equal to that of the industry's best as of time t-1. We categorize a technology investment as running on the spot if the substrate size is smaller than the industry best but larger than or equal to that of the firm's internal best. Lastly, a technology investment is resizing if the firm chooses—typically by acquiring other plants—a substrate size smaller than the firm's internal best or the firm liquidates the production facility thereby reducing the internal best. We then define our dependent variable as a category variable indicating the value of '1' if a firm chooses catching up, '2' if it chooses running on the spot, and '3' if it chooses resizing in technology investments. Among a total of 161 firm-quarter investment decisions in the data, 43 (26.7%) are categorized as catching up, 88 (54.7%) running on the spot, and 30 (18.6%) resizing.[18]

Explanatory Variables Over the sample period, the LCD panel industry has seen technological development through multiple generations of technology. As the coveted panel size in downstream applications such as monitor and TV has increased over time, the optimal size of glass substrate has accordingly expanded. As a new size of substrate is announced, industry experts form a consensus on which "generation" the technology belongs to. Minor improvements in size are considered as the same generation technology. Only a significant size improvement (typically, the length of new substrate's shorter side surpasses that of current largest substrate's longer side) merits a generation "upgrade". Thus, there is modest—often substantial—within-generation heterogeneity in substrate size. As of the end of 2007, the eighth generation (8G) facility is the state-of-the-art generation technology. We define *state-of-the-art capacity* at time *t* (quarter) as the following:

$$K_t = \frac{\sum_i sotacap_{it}}{\sum_i totcap_{it}}$$

where $sotacap_{it}$ is as the sum of all the production capacities of plants at time *t* that employ the state-of-the-art generation technology and $totcap_{it}$ is the sum of industry's total capacity at time *t*.[19] Note that it is

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separate between these two types, but it failed the independence of irrelevant alternatives (IIA) test— i.e. these two investment alternatives are statistically distinguishable. The distinction between choosing lower technology and liquidating capacity also failed the IIA test. Thus, we maintain the reported classification of investment choice.

[18] Catching up investment includes 7 cases of leapfrogging and resizing includes 18 cases of capacity liquidation.

[19] We define the capacity of a plant as the product of area per glass substrate and the monthly production capability.

important to normalize the state-of-the-art generation capacity by the total industry capacity because, as the optimal substrate size increases with generation, the state-of-the-art generation capacity also increases linearly; absent normalization, one would incorrectly confer greater weights to later innovations.

We define *technological competence* as the following ratio:

$$\theta_{it} = \frac{bestsize_{it}}{sotsize_t}$$

where $bestsize_{it}$ is firm *i*'s internal best size at time *t* and $sotasize_t$ is the industry's state-of-the-art size at time *t*. Thus, higher values on this measure imply smaller gaps from the technological frontier. Because the substrate size is an important indicator of technological capability, the best available size for a firm should indicate the firm's technological competency in panel production. To capture the expected nonlinearity effects, we also construct *technological competence squared* by squaring the measure. Notice that, to avoid spurious collinearity between the linear term and the square term, we center the measure by subtracting the sample mean from each observation before squaring the linear term. Hence, in the regression equation, we include the linear and quadratic terms of centered values.

Control Variables We construct several other variables to control for possible confounding effects. *Market concentration* controls for the impact of competitive pressure on firms' efforts or incentives to make technological advancements. For instance, Scherer (1965) argues that firms in a competitive market are more likely to innovate in order to stave off the competitive pressure whereas Schumpeter (1942) claims the converse (higher concentration leads to more innovation). Though equivocal on the sign of the impact of competitive pressure, literature agrees on the existence of influence that the competitive environment exerts on firms' behavior in technological innovation, calling for a control of such influence on the choice of technological investment. We measure *market concentration* by the Herfindahl-Hirschman Index (HHI) of market shares in annual sales. Using the sales data from DisplaySearch and Nikkei Microdevices, we compute the concentration measure in year *j* as:

$$HHI_j = \sum_i^{N_j} s_{ij}^2$$

where N_j is the number of firms in year *j*, and s_{ij} is the firm *i*'s market share in year *j*. We lag this measure by two years to take into account the lead time from the investment decision (i.e. start of plant construction) to actual production at a planned scale (Matthews, 2005).[20]

Time since last investment represents the length of time between the immediate past capacity investment and the current investment, measured by the number of calendar quarters between two investments. All else equal, firms will be more likely to invest in technologies that improve upon their

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[20] Notice that accounting for the lead time we lag HHI and patent stock by two years. Other explanatory variables are considered as reflecting all information available at the time of investment decisions.

internal best technology as more time has elapsed since last investment. There are at least two reasons for this expectation. First of all, LCD fab investments occur relatively infrequently and require significant capital outlays. Thus, firms generally need a reasonable amount of time to elapse before they become financially ready to consider next investment. Also, as the industry's frontier expands over time, the pressure for follow-up investments increases accordingly. The variable is intended to control for this timing effect. For the entrants who make their first capacity investment, we assign zero on this measure.

Patent stock captures the knowledge effect from R&D experience accumulated over time (Doraszelski, 2003; Hall, Jaffe and Trajtenberg, 2005). Reflecting the intensity of technological and market competition in this industry, patents are considered as an effective measure of protecting the profit stream from R&D investments and hence are commonly sought after. Thus, patent stock should be a reasonable proxy for important knowledge cumulated through R&D in panel production. All else equal, firms with more R&D experience will have a higher chance of innovation. We construct the measure by counting the number of US patents assigned to the technological class of 349. We adjust these counts by an annual depreciation rate of 15% (e.g. Cockburn and Griliches, 1988) to allow for a decay in the impact from earlier technological assets.[21] To account for the lead time, we lag this measure by two years.

Share of industry capacity proxies for firm size. We define the measure as the firm's total capacity divided by the industry's total capacity at each period. This variable not only controls for the demonstrated effect of firm size such as financial constraint (e.g. Audretsch and Elston, 2002) and innovation propensity (e.g. Acs and Audretsch, 1987)[22], but also captures the potential effect from the supply-side constraints. Though a critical process input for panel production, glass substrates are not manufactured by LCD firms but by the firms specializing in developing and manufacturing the substrates. There is typically a close working relationship between substrate suppliers and panel makers as the substrate development and manufacturing requires investments that are largely client-specific and risky. This asset specificity thus entails upfront capital commitment and ongoing technological cooperation from the LCD firms. All others equal, firms with greater market potential—in terms of expected sales from a given investment—are likely to elicit greater cooperation from the substrate suppliers and hence are more apt to succeed in technological improvements.[23]

Japanese firm dummy indicates whether the firm is a Japanese panel manufacturer. Though they were pioneers of the industry, Japanese firms have witnessed a drastic change in their market positions over the period. Sharp Corporation is a prototypical example. As one of the first LCD panel

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[21] The results are robust to variation in the depreciation rate (e.g. a range between 0% and 20%).

[22] Acs and Audretsch (1987) suggest that firm size and industry structure exert independent influence on firm innovation. Thus, we simultaneously control for firm size and industry concentration in the specification.

[23] We do not use other measures of firm size such as assets or sales for two reasons. First, these standard measures are unavailable for private firms or subsidiaries of public firms. Second, and more important, we believe our measure better fits the purpose of control, which is to capture the complementarity effect specific to this market.

manufacturers, Sharp has maintained dominant leadership position until mid-1990s, but has since gradually given way first to Korean firms and then to Taiwanese firms. We suspect that the changes in market positions of Japanese firms are closely related to differences in technological investment. This dummy is thus intended to capture that effect. The dummy is defined in the usual manner.

Lastly, we include a dummy for joint ventures (*Joint venture dummy*) between two or more independent firms. Capacity investments require a nontrivial commitment of resources, but firms are likely to go through different decision-making processes depending on their governance structures. This dummy is intended to control for the effect from such differences. Because *Nikkei Microdevices* does not indicate whether the panel manufacturer is a joint venture, we search company websites and news articles to determine the governance structure. The dummy is defined analogously.

Table 4 provides summary statistics of and the correlations between these variables. For the variables with skewed distributions, we take natural logs of raw values to reduce the effects from heteroskedasticity. In the specification, we also report heteroskedasticity-robust standard errors, clustered by firm to allow for the errors to be serially correlated within firm. In all but one case, no two explanatory variables exhibit a pairwise correlation that is sufficiently high to raise a concern in specification.[24]

Estimation

Our empirical model assumes the following general form:

$$\Pr(Y = y_{it}) = f(K_t, \theta_{it}, Z_{it})$$

where $y_{it} \in \{catching\ up, running\ on\ the\ spot, resizing\}$, K_t is the level of industry capacity with the state-of-the-art generation technology, θ_{it} is the firm's relative technological competence, and Z_{it} is a vector of control variables such as market concentration and time since last investment. Because the dependent variable is an indicator of more than two investment choices, we employ the multinomial logit model for estimation. Specifically, the model takes the following functional form:

$$\Pr(y_{it} = j) = \frac{\exp(X_{it}\beta_j)}{1 + \sum_{j=1}^{3} \exp(X_{it}\beta_j)}$$

where X_{it} is a vector of explanatory variables and β_j is a vector of coefficients associated with the investment choice j. As we are mainly interested in the likelihood of catching up investment relative to that of running on the spot investment, we take the running on the spot as the base category in estimation. Tests of the independence of irrelevant alternatives (IIA) assumption indicate that these three investment choices can be considered as mutually exclusive, justifying the classification as well as validating the use

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[24] The exception is the correlation between technological competence and the share of industry capacity (ρ=0.756). However, excluding one of these two from analysis does not materially change the effect of the included variable. Hence, the two variables, though highly correlated, appear to represent effects that are distinct from each other.

of multinomial logit model.[25] For a robustness check, we also estimate the bivariate probit models of pairwise combinations of investment choices (i.e. catching up vs. running on the spot; running on the spot vs. resizing; and catching up vs. resizing).

5. RESULTS

Main Specifications

Table 5 presents the results of multinomial logit regression.[26] Columns (1) and (2) show the coefficient estimates for the catching up investment and the resizing investment, respectively. Columns (3) through (5) exhibit the marginal effects of the explanatory variables. These are measured as instantaneous changes in the probability of catching up, running on the spot, and resizing investment, respectively, in response to a one percent change in the corresponding explanatory variable, holding all other variables constant at their means. Looking first at the case of catching up investment, the coefficient on state-of-the-art generation capacity is significantly positive (column (1)), consistent with our expectation on the variable. The state-of-the-art generation capacity is, however, negatively associated with the probability of resizing investment (column (2)). In terms of marginal effect, a one percent increase in the state-of-the-art generation capacity is associated with a 12% increase in the probability of catching up investment. In contrast, the same increase in capacity implies no change in the chance of running on the spot investment (the effect is insignificant) and a nine percent decrease in the likelihood of resizing investment.

The effect of technological competence on the likelihood of catching up investment exhibits an inverted U-shape; the predicted probability increases up to a threshold after which the marginal effect reverses sign. This implies that firms with intermediate level of technological competence are most likely to make a catching up investment. Put differently, it is those that are neither too close to nor too far from the technological frontier who most actively pursue technological advancements through investments in the state-of-the-art technology. Figure 1 illustrates the simulated probabilities of catching up investment as the technological competence changes incrementally (by one percent point at a time) from its minimum value to the maximum, with all other independent variables held constant at their means. The probability of catching up investment increases with technological competence, peaks at around 60% level of technological competence, and declines monotonically afterwards. In contrast, as technological competence increases, the probability of running on the spot investment decreases monotonically until about 75% level of technological competence and then turns upward (i.e. a U-shape) whereas that of resizing investment continuously increases. These results expand the debate on technology race between

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[25] These tests include the Small-Hsiao test, Wald test, and the Likelihood Ratio test. Test results are not reported here but are available from the authors.

[26] Notice that due to lags in some explanatory variables the number of used observations is reduced by two (N=159).

the leader and the follower by providing evidence of significant heterogeneity among followers in technological innovation. In spirit, this result resonates with Lerner (1997) who finds that firms with an intermediate level of technological gaps from the frontier are the ones that make the most performance improvements. Our result goes further to call for an attention to the within-group heterogeneity in the followers' strategic behavior, which has received little attention in technology race literature.

Turning to the effect of industry concentration on investment choice, the probability of catching up investment positively and significantly correlates with market concentration. As industry becomes more concentrated, firms are more likely to invest in technologies that place them on or beyond the technological frontier. This is consistent with our expectation of a positive impact of market concentration on catching up investments. The magnitude of effect is also large. Expressed in marginal effect, a one percent increase in HHI leads to a 30% increase in the probability of catching up investment. In contrast, the effects of market concentration on other investment choices appear to be generally negative, though the marginal effects are only tangentially significant.

Among other control variables, patent stock is positively correlated with the likelihood of catching up investment and resizing investment but negatively associated with the baseline case. Firms with relatively large shares of industry capacity is no more likely to exhibit catching up behavior, though they are less prone to choose resizing investments. Japanese firms are most likely to opt for running on the spot investments among the investment alternatives. The result that Japanese panel manufacturers on average tend to focus on marginal improvements appears consistent with an overall weakening of their market position. Joint ventures are slightly more likely to make catching up investments but the marginal effect is insignificant at conventional levels, suggesting that governance structure has no material impact on the choice of technological investments in this industry.

Robustness

We perform a series of robustness checks to ensure that the results hold across specifications with variation in controls. None of these tests changes the results in a meaningful way, and hence we discuss them here without reporting all the results.[27] First of all, we estimate bivariate probit models, comparing between pairwise alternatives. Table 6 shows the results from these regressions. Column (6) compares between catching up investment and running on the spot investment with the dependent variable taking a value of '1' for catching up and '0' otherwise. Columns (7) and (8) present the analogues for 'running on the spot vs. resizing' and 'catching up vs. resizing', respectively. Across these models, the coefficient estimates generally echo the results from multinomial logit model, particularly those on state-of-the-art

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[27] The results of robustness tests are available from the authors upon request.

generation capacity and technological competence. The marginal effects (columns (9) through (11)), calculated from estimated coefficients, are also comparable to those from multinomial logit specification.

Recall that for the entrants zero values were assigned to the measures of technological competence, time since last investment, and share of industry capacity. One might wonder if any of the results might change with an inclusion of entrant dummy.[28] The multinomial logit model cannot include the dummy because by definition entrants do not make resizing investments and hence the model is not specified correctly with such inclusion. Thus, we try controlling for the entrant effect in the bivariate model of catching up vs. running on the spot. Even with the entrant dummy, most results remain although the coefficients on technological competence terms become weaker (but still significant at 10%).

Each generation of glass substrates enjoys a different duration as the state-of-the-art technology, ranging from 5 to 20 quarters. The duration may then impact the investment decisions via its correlation with the state-of-the-art generation capacity; the longer the duration, the higher the leading capacity is likely to be. It may also affect the decisions through changes in discovery cost due to technology spillovers; the longer the duration, the lower the cost of R&D discovery and hence the cost of catching up investment. Thus, we run separate specifications with controls for the duration effect by including the number of quarters as leading technology (either the total duration of technology or the age of technology at the time of investment decision). Neither the duration of technology nor the technology age has significant impact on firm investment choices.

The LCD panel industry is characterized by the “crystal cycle” with booms and busts alternating. Over the period, the industry has experienced six full cycles of peaks and troughs, with the duration of a cycle averaging to two years (Matthews, 2005; DisplaySearch, 2007). These cycles per se, however, should not introduce material differences to the results because they are likely to affect the investment decisions similarly by either delaying or expediting *all* of them. Nevertheless, we try to control for the cycle effect by including dummies for the period of troughs. With these dummies, we also take into the demand effect into consideration, albeit indirectly. Considering the lead time between plant construction and production ramp-up, we lag the timing of troughs by eight quarters. Even with controls of cycles, the results remain unchanged; the coefficient on trough dummy is insignificant for both catching up and resizing investments.

LCD firms are heterogeneous in their business structure and product focus. For instance, some firms vertically integrate the panel manufacturing unit and the consumer product unit whereas others only produce panels for downstream firms. The integrated firms may be less vulnerable to demand cycles because they can spread the risk over other product lines. Also, some firms focus on TVs but others

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[28] Our sample includes 56 firm-plant level entries (6 catching up investments and 50 running on the spot investments), which take 35% of the total observations.

concentrate on notebooks. Considering that recent technological competition is the most intense in TV applications, firms focusing on TV sets may behave differently from the rest. Roughly speaking, integrated firms are the ones that focus on TV applications. Thus, we include a dummy for these integrated firms (e.g. Samsung, Sharp, LG Philips, and Toshiba) and re-estimate the model. The coefficient on this dummy is strongly significant for catching up investments but insignificant for resizing.

In our main specification, we control for country effects by including a dummy for Japanese firms, particularly to account for the dramatic changes in their market status over the period. Taiwanese firms are perhaps another interesting case that may call for a separate account; they are later entrants (entered after 1999), adopting only proven technologies initially and moving towards more advanced technologies later on. We attempt to control for the possible differences in investment strategies by including a dummy for Taiwanese firms. As expected, Taiwanese firms are most likely to choose running on the spot investments. However, the inclusion of this dummy does not affect other coefficient estimates. These tests taken together, therefore, the demonstrated effects on technology investment choice appear robust to variations in estimation methods and controls.

6. DISCUSSION AND CONCLUSION

Our results reveal that firms are more likely to choose catching up investments over other types of technology investments as the industry's state-of-the-art generation capacity increases. Also, firms with intermediate level of technological gap from the industry frontier are most likely to make catching up investments. A few issues merit discussion to affirm that these results are robust to alternative accounts and potential confounding effects.

One might argue that the positive correlation between the state-of-the-art generation capacity and catching up investments could arise also from an information spillover effect. That is, an increase in leading capacities may imply reduced uncertainty around new technology investments. This would trigger more catching up investments by the followers whose concern that the new technology might be infeasible should now be alleviated (e.g. Choi, 1991).[29] Then the same result would follow without necessarily resorting to the technology race argument we propose. If that were the case, we should not observe leapfrogging by followers because leaders always stay ahead and followers always trail (assuming their risk preferences do not change over time). But our dataset tells a different story. There are seven cases of leapfrogging in the strictest sense—i.e. the follower comes up with a breakthrough innovation that surpasses the current state-of-the-art technology. Also, there have been frequent changes

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[29] The leader's success in new technology development creates two types of information spillovers for the followers: reduced uncertainty and lowered cost of discovery. We already discussed the impact through discovery cost in the robustness of results.

in technological leadership so that today's leader easily becomes tomorrow's follower. Moreover, the build-up of leading generation capacity does not necessarily resolve the uncertainty that followers face due to the long lead time between investment decision and production ramp up; many unforeseen events (e.g. demand shock, delays in the development of complementary technologies, arrival of a next generation technology, etc.) could occur in the course of irreversible investment, drastically altering the payoff. Further, the hazard rate in R&D discovery or the investment cost does not decline owing to the rival's early investment. Thus, this alternative account appears inconsistent with our data.[30]

In the analysis, we use the state-of-the-art generation capacity cumulated up to time t-1 to predict the investment choice at time t. One may also wonder if the long lead time between investment decision and actual production might cause temporal inconsistency in the leading capacity–technology investment link. We do not consider this to be a problem, however, because the lead time in capacity construction is likely to be very similar for all players. Assuming an equal lead time for the leader and the follower, the leader capacity that the follower takes into account at the time of plant investment decision—which, if approved, will begin production at time t—will reflect all known state-of-the-art capacities that will be in production at time t-1.[31] Hence, our design appears consistent with the reasonable assumption that firms make investment decisions based on all available information on industry capacity including the announced and/or planned plants by their competitors.

We believe that, in at least two ways, our findings provide novel contributions to the research on technology race. First, the finding of a positive link between leading technology capacity and catching up investments paints an interesting wrinkle to the classical Bain-Spence-Dixit model of strategic entry deterrence. When capacity investments are not sunk (i.e. resalable) and the game is repeated over a longer horizon, the market leaders' capacity is no longer a credible threat to the followers; technological laggards always have incentives to hop on before the window of opportunity closes as the next generation technology evolves, which expectedly shrinks the payoff from maintaining their status quo.

Second, the finding of an inverted U-shape relationship between technological competence and catching up investments offers a significant empirical counterpart to the vast theoretical works on "who runs harder" in technological races. This finding corroborates the prediction from prior theoretical works

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[30] Technology adoption literature suggests another possible route to explain the effect of leading capacity on catching up investments. Choi (1997), for instance, explains the herding behavior in technology adoption by the tendency of prospective adopters to wait until others first adopt the new technology. Using the analogy of penguins that jump into the sea only after observing a first mover, he shows that, to avoid being stranded with a wrong technology, firms optimally choose to become late adopters. Though an interesting possibility, this penguin effect argument does not agree with our understanding of the industry. The LCD firms always have strong incentives to adopt a new technology, or leapfrog if possible, because the upsides of success are much greater than the downsides including the possibility of choosing a wrong technology. Further, under this alternative scenario, technological leapfrogging is not possible. But from the data, we do observe multiple such occurrences.

[31] The same reasoning applies to the explanatory variables that are measured up to time t-1 (technological competence, time since last investment, and share of industry capacity) in the main specifications.

that the follower with a sufficiently large lag loses its motivation to catch up with the leader. It is also consistent with the theories that propose nonmonotonicity in the followers’ catching up efforts (e.g. Doraszelski, 2003; Hörner, 2004). More important, it uncovers what we believe is deficient in our understanding of technology race behavior: although many theoretical works on technology race predict reduced incentives for the bottom-followers to exert innovative efforts, none of them explains—to the best of our knowledge—why the followers with an intermediate level of technological competence are most likely to invest in catching up whereas those with a small lag from the frontier choose to maintain their technological status quo or even opt for rationalizing capacities by consolidating or liquidating existing lines. Together with Lerner (1997) who also finds the same nonmonotonic effect on the middle follower group, our study calls for a formal model to elucidate the rationale behind such regularity. Also, further examinations on other technology-intensive industries would test the generality of our finding. We leave these tasks for future research.

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Table 1 Major LCD Panel Manufacturers

Ranking (U$ sales)	1990	1995	2000	2005	2007
1	Sharp (JP)	DTI (JV)	Samsung (KR)	LG Philips (KR)	Samsung (KR)
2	Hosiden (JP)	Sharp (JP)	LG Philips (KR)	Samsung (KR)	LG Philips (KR)
3	Hitachi (JP)	NEC (JP)	DTI (JV)	AU Optronics (TW)	AU Optronics (TW)
4		Matsushita (JP)	Hitachi (JP)	Chi Mei (TW)	Chi Mei (TW)
5		Hitachi (JP)	Sharp (JP)	Sharp (JP)	Sharp (JP)

Note: Nationality in parentheses (JP: Japan, KR: Korea, TW: Taiwan, JV: Joint Venture). DTI is a joint venture between Toshiba and IBM.

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Table 2 Size of Glass Substrate by Generation

Generation	First introduction	Substrate size (mm×mm)	Minimum area (m^2)	Maximum area (m^2)	% Increase within generation 1)	% Increase between generation 2)
1	1988 Q3	200×270 ~ 320×400	0.054	0.128	137.0	..
2	1993 Q4	360×465 ~ 410×520	0.167	0.213	27.4	30.8
3	1996 Q4	550×650 ~ 650×830	0.358	0.540	50.9	67.7
4	2000 Q3	680×880 ~ 730×920	0.581	0.672	15.6	7.7
5	2002 Q1	1000×1200 ~ 1300×1500	1.200	1.950	62.5	78.7
6	2004 Q1	1500×1800 ~ 1500×1850	2.700	2.775	2.8	38.5
7	2005 Q2	1870×2200 ~ 1950×2250	4.114	4.388	6.6	48.3
8	2006 Q4	2140×2400 ~ 2200×2500	5.136	5.500	7.1	17.1

Note: 1) Percentage increase from the generation's minimum size to the generation's maximum size
2) Percentage increase from the previous generation's maximum size to the current generation's minimum size

Table 3 Number of Firms and Market Concentration Measures by Year

Year	Number of Firms	HHI	CR4
1989	2	5739.6	100%
1990	3	4351.6	100%
1991	5	3107.5	93%
1992	5	3579.6	93%
1993	7	2498.8	87%
1994	10	2337.7	86%
1995	10	2083.7	84%
1996	10	1607.9	73%
1997	11	1358.5	67%
1998	13	1345.7	66%
1999	18	1049.5	55%
2000	18	1090.6	58%
2001	20	1083.6	54%
2002	16	1042.7	55%
2003	17	1278.2	63%
2004	19	1371.0	66%
2005	20	1419.7	69%
2006	19	1495.2	72%
2007	18	1576.9	75%

Note: All the values are evaluated at the end of each year. The number of firms counts active firms for which nonzero sales are reported in the data sources.

Table 4 Summary Statistics and Bivariate Correlation Matrix

	Variable	Mean	S.D	Min	Max	1	2	3
1	Investment choice	1.93	0.67	1	3			
2	State-of-the-art capacity	0.31	0.24	0.01	1	-0.365*		
3	Market concentration	0.16	0.09	0.10	0.57	-0.350*	0.589*	
4	Technological competence	0.004	0.32	-0.34	0.66	-0.169*	0.018	-0.060
5	Technological competence^2	0.10	0.10	0.00	0.44	-0.125	0.107	0.099
6	Time since last investment	5.65	7.23	0	44	0.084	0.002	-0.078
7	(Log) patent stock	2.60	2.18	0	6.62	-0.095	-0.099	0.006
8	Share of industry capacity	0.04	0.05	0	0.22	-0.283*	-0.128	-0.016
9	Japanese firm dummy	0.40	0.49	0	1	-0.187*	0.255*	0.355*
10	Joint venture dummy	0.21	0.41	0	1	-0.061	-0.090	-0.021
		4	5	6	7	8	9	
5	Technological competence^2	0.481*						
6	Time since last investment	0.205*	-0.215*					
7	(Log) patent stock	0.546*	0.183*	0.212*				
8	Share of industry capacity	0.756*	0.337*	0.078	0.553*			
9	Japanese firm dummy	0.001	0.093	0.070	0.098	-0.130		
10	Joint venture dummy	-0.196*	-0.048	-0.043	-0.290*	-0.054	0.173*	

Note: N=159. *: $p<0.05$.

Table 5 Multinomial Logit Estimation of Investment Choice

	Coefficient		Marginal Effect		
	(1)	(2)	(3)	(4)	(5)
	Catching up	Resizing	Catching up	Run on spot	Resizing
State-of-the-art capacity	3.454	-5.435	0.124	-0.033	-0.091
	(1.463)	(1.617)	(0.048)	(0.060)	(0.033)
Technological competence	6.087	6.283	0.003	-0.004	0.001
	(1.743)	(1.519)	(0.001)	(0.001)	(0.0004)
Technological competence^2	-8.931	-4.911	-0.094	0.113	-0.020
	(2.407)	(2.821)	(0.028)	(0.032)	(0.014)
Market concentration	17.88	-10.72	0.301	-0.201	-0.100
	(3.962)	(9.838)	(0.079)	(0.106)	(0.067)
Time since last investment	0.080	0.119	0.043	-0.074	0.031
	(0.045)	(0.038)	(0.024)	(0.030)	(0.014)
(Log) patent stock	0.630	0.572	0.062	-0.087	0.024
	(0.185)	(0.160)	(0.018)	(0.018)	(0.012)
Share of industry capacity	2.141	-26.99	0.015	0.038	-0.053
	(5.669)	(9.630)	(0.024)	(0.036)	(0.022)
(Dummy) Japanese firm	-2.238	-2.889	-0.189	0.307	-0.117
	(0.771)	(0.850)	(0.065)	(0.077)	(0.056)
(Dummy) Joint venture	1.232	1.177	0.150	-0.212	0.061
	(0.736)	(0.758)	(0.130)	(0.113)	(0.074)
Constant	-6.459	0.888	..	..	..
	(1.277)	(1.615)			

Notes: N=159. Log-likelihood=-86.72. Wald $\chi^2(18)=281.25$. Prob>χ^2=0.00. McFadden's pseudo-R^2=0.4500.
Marginal effects are computed by the command 'mfx compute, predict(outcome(i)) dyex' in Stata (for logged variables and dummies, dydx is used instead) after estimating the multinomial logit model. For dummies, marginal effects represent the change in probability for the change of dummy variable from 0 to 1.

Table 6 Bivariate Probit Estimation of Investment Choice

	Coefficient			Marginal Effect		
	(6)	(7)	(8)	(9)	(10)	(11)
	CUP vs. ROS	ROS vs. RES	CUP vs. RES	CUP vs. ROS	ROS vs. RES	CUP vs. RES
State-of-the-art capacity	1.870	2.989	9.224	0.130	0.085	0.234
	(0.732)	(1.192)	(1.752)	(0.054)	(0.046)	(0.170)
Technological competence	3.357	-3.508	0.573	-0.015	0.027	0.008
	(0.934)	(1.045)	(2.615)	(0.004)	(0.009)	(0.037)
Technological competence^2	-5.605	2.944	-4.438	-0.120	0.030	-0.039
	(1.167)	(2.292)	(3.598)	(0.029)	(0.021)	(0.042)
Market concentration	9.498	12.99	23.24	0.314	0.189	0.301
	(1.868)	(10.19)	(7.025)	(0.070)	(0.131)	(0.190)
Time since last investment	0.025	-0.068	0.002	0.023	-0.037	0.001
	(0.028)	(0.023)	(0.043)	(0.026)	(0.018)	(0.026)
(Log) patent stock	0.293	-0.367	0.209	0.059	-0.039	0.016
	(0.075)	(0.114)	(0.149)	(0.016)	(0.015)	(0.012)
Share of industry capacity	3.189	14.03	17.86	0.025	0.038	0.086
	(3.360)	(6.457)	(5.192)	(0.028)	(0.020)	(0.072)
(Dummy) Japanese firm	-1.038	1.591	-0.049	-0.200	0.143	-0.004
	(0.373)	(0.478)	(0.574)	(0.069)	(0.061)	(0.044)
(Dummy) Joint venture	0.643	-0.822	-0.193	0.157	-0.128	-0.016
	(0.343)	(0.523)	(0.706)	(0.101)	(0.113)	(0.068)
Constant	-3.312	-1.102	-6.769	..	..	..
	(0.559)	(1.439)	(1.643)			
No. Observations	129	118	71			
Log-likelihood	-39.16	-38.98	-21.46			
Wald χ^2	91.99	48.04	101.00			
Prob. > χ^2	0.00	0.00	0.00			
McFadden's pseudo-R^2	0.5145	0.4174	0.5562			

Note: CUP: Catching up, ROS: Running on the spot, RES: Resizing. Marginal effects are computed by the command 'mfx, dyex' in Stata (for logged variables and dummies, dydx is used instead) after estimating the probit model. For dummies, marginal effects represent the change in probability for the change of dummy variable from 0 to 1.

Figure 1 Technological Competence and Predicted Probability of Investment Choice