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Product and Process Innovations in the Life Cycle of an Industry

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Abstract

Filson (2001) uses industry-level data on firm numbers, price, quantity, and quality along with an equilibrium model of industry evolution to estimate the nature and effects of quality and cost improvements in the personal computer industry and four other new industries. This paper studies the personal computer industry in more detail and shows that the model explains some peculiar patterns that cannot be explained by previous life-cycle models. The model's estimates are evaluated using historical studies of the evolution of the personal computer industry, and patterns that require further model development are described.

JEL codes: **L10**: Market Structure, Firm Strategy, and Market Performance, **L63**: Industry Studies: Microelectronics, **O31**: Innovation and Invention.

Keywords: technology, technological change, industry dynamics, personal computer market, microelectronics

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1. Introduction

As new industries evolve price falls, quantity rises, and the number of firms rises and then falls (Gort and Klepper, 1982, Klepper and Graddy, 1990, and Agarwal and Gort, 1995). Product quality improves over time. Figure 1 shows that these patterns have occurred in the personal computer industry (the data is discussed in the next subsection).

Although economists generally agree that innovations cause the observed trends (Hopenhayn, 1994, Jovanovic and Macdonald, 1994, and Klepper, 1996), we still lack knowledge about the types of innovation that occur at different stages of the life cycle and their effects on firm size, prices, and profit. This problem is exacerbated by the lack of useful measures of innovation. Patents are hard to value and not all innovations are patented or documented in trade journals. In particular, cost innovations are often kept secret (Levin et al. 1987). Private companies do not report R&D expenditures, and public companies are typically multiproduct firms (IBM, for example), making it difficult to determine R&D expenditures for any particular product.[1]

Figure 1 here

Filson (2001) attempts to overcome the measurement problem by using industry-level data on firm numbers, price, quantity, and quality along with an equilibrium model of industry evolution to estimate trends in quality, variable costs, and fixed costs. The model is estimated using five industries: the early automobile industry, the personal computer industry, the rigid disk drive industry, the computer monitor industry, and the computer printer industry. The estimates for the early automobile industry match conventional wisdom about technological change over the life cycle (Utterback and Abernathy, 1975, Klepper, 1996): the rate of quality improvement is highest early on, the rate of cost improvement is higher later on, and firms obtain lower variable costs and higher fixed costs over time. However, the estimates for the modern microelectronics industries depart from this pattern

[1] Gort and Klepper (1982) and Abernathy et al. (1983) attempt to measure innovation over the industry life cycle. Griliches (1990) and Cohen (1995) discuss the difficulty of measuring innovation. Archibugi et al. (1994) show that the measurement method affects conclusions about the nature of innovation.

in several ways: the rate of quality improvement does not diminish over time, the rate of cost improvement is not always highest later in the life cycle, and while variable and fixed cost tradeoffs tend to occur they do not always involve decreasing variable costs and increasing fixed costs.

As the model's results for the modern microelectronics industries challenge conventional wisdom, this paper attempts to evaluate the model's results for those industries using a case study of the personal computer (PC) industry. There are two reasons for focusing on the PC industry. First, the PC industry is a particularly good example of an industry that cannot be explained by previous dynamic equilibrium life-cycle models. Jovanovic and MacDonald (1994) and Hopenhayn (1994) limit their attention to variable-cost innovations that increase scale; firm size rises over the life cycle. Figure 2 shows that average firm size has not continually increased in the PC industry. Further, the estimates presented below suggest that over much of the life cycle large firms were high-quality firms (they produced large quantities because they faced higher prices than other firms), not low-cost producers. Klepper (1996) presents a model with both quality and cost improvements but continues to associate large size with low costs. Further, Klepper assumes that firms receive a constant exogenous payoff from quality improvement that does not vary over time. The profit estimates presented below suggest that the profitability of quality improvement in the PC industry has varied substantially over time, partly because the rate of quality improvement has changed over time.[2]

Figure 2 here

The second reason for using the PC industry is that historical analyses of the industry by Langlois (1992) and Steffens (1994) along with information from trade journals allow for a rough test of the model to be performed. The problems with measuring innovation described above prevent direct comparisons of the model's results on technological change with data. However, the historical analyses provide a rich set of anecdotal evidence that can be used

[2] Changes in the rate of quality improvement can also explain much of the closing of the price gap between industry leaders and followers that occurred in the late 1980s and early 1990s. The business press attributed this reduction to strategic price-cutting behavior on the part of the leaders.

to evaluate the model's results on quality and cost innovation. The lack of information on innovation in the other microelectronics industries (particularly cost innovation) limits the scope of this study.

The test of the model focuses on two key sets of results. First, the model's explanation for the pattern in average firm size shown in Figure 2 is that the nature of cost innovation changed over the life cycle. The model's results suggest that cost innovations in the 70s and late 80s decreased variable costs and increased fixed costs, which led to larger firms, and cost innovations in the mid 80s decreased fixed costs and increased variable costs, which led to smaller firms. Second, the estimates suggest that the rate of quality improvement was high initially, dropped in the mid 80s, and then rose again in the mid 90s. Both of these results are consistent with the evidence described below.

1.1. The Data

The data describes manufacturers of desktop and portable computers and excludes related component and software providers. The data describes the American market. Firm numbers are from Stavins (1995) and the *Thomas Register of American Manufacturers*. Price and quantity data are from the *Information Technology Industry Data Book*. The price is the average suggested retail list price deflated using the CPI. The quality series is generated using the following formula:

$$\frac{P_{t+1}}{P_t} \equiv \frac{P_{s(t+1)}}{P_{st}} \frac{\gamma_{t+1}}{\gamma_t}, \tag{1.1}$$

where P_t and P_{t+1} are the actual average prices, $\frac{P_{s(t+1)}}{P_{st}}$ is the what the price ratio would be if quality did not change between period t and $t+1$, and γ_{t+1} and γ_t are average qualities. The price ratio is expressed as a constant-quality price ratio multiplied by a quality ratio. The official quality-adjusted price index of the Bureau of Economic Analysis was used to construct constant-quality price ratios, and then quality ratios were constructed by dividing the actual price ratios by the constant-quality price ratios. The quality-adjusted price index measures how prices change from year to year holding model characteristics such as processing speed and storage capabilities constant. Methods for computing quality-adjusted price indexes for the personal computer industry have been described by Berndt, Griliches, and Rappaport (1995) and Filson (1998). For details on the method the Bureau of Economic Analysis uses, see U.S. Department of Commerce, Bureau of Economic Analysis (1996).

2. The Model

This section summarizes the key features of the model. For further details see Filson (2001). The model describes the evolution of a single industry in a framework with discrete time, an infinite horizon, a continuum of firms, and endogenous entry and exit. The industry has a quality ladder and a cost ladder; the shapes of each determine the magnitude of the available innovations each period. The shapes of each ladder are known and fixed. This implies that firms cannot influence the direction of technological change. Instead, each period each firm invests in an attempt to be a leader on each ladder, and the probability of success is a random function of investment.[3]

Each period each firm in the industry is identified by its quality γ, its variable-cost parameter a, and its fixed cost f.[4] Its quality is determined by its position on the quality ladder and its variable and fixed costs are determined by its position on the cost ladder. Profits $\pi(\gamma, a, f)$ are defined as

$$\pi(\gamma, a, f) = \max_{q} p(\gamma)q - c(a, q) - f, \tag{2.1}$$

where $p(\gamma)$ is the price the firm faces and q is its output. In the estimation routine $c(a, q) = a\frac{q^2}{2}$. This function is strictly increasing and strictly convex in q; this ensures that the number of firms in the market is always positive by ensuring that a firm's size is limited by its technology. When a decreases, the marginal-cost curve shifts down. This implies that variable-cost innovations are *scale-increasing*, as in Hopenhayn (1994), Jovanovic and Macdonald (1994), and Klepper (1996). In contrast, the equilibrium effect of fixed-cost innovation is that firms

[3]Much of innovation in the PC industry is of this type. For example, suppose that Intel develops a new chip. From a personal computer manufacturer's point of view the available improvement in processing power is exogenous (it is determined by the chip). PC manufacturers invest in an attempt to be among the first to incorporate Intel's new chip into their machines.

[4]The interpretation of fixed costs is standard - they include plant and equipment rental costs and other opportunity costs.

enter and price falls; holding a constant the reduction in price has the effect of reducing output-per-firm. Filson (2001) provides formal proofs that illustrate these results. They are important for how the model identifies innovation in the data - periods of rising quantity per firm are associated with improvements in variable costs and periods of falling quantity per firm are associated with improvements in fixed costs.

In addition to choosing their quantities, each period each firm chooses how much to invest in quality improvements and cost improvements. These decisions are made to maximize the firm's expected *value* - its expected net present value of its discounted future return stream. Two assumptions simplify computations. First, all of the followers catch up to the leaders on each ladder at the end of each period. This assumption implies that the diffusion of quality and cost changes takes one period. Second, obtaining a leadership position on a ladder in one period does not give the firm an advantage in innovating in future periods: all firms have access to the same probability-of-success function regardless of their current technology. This implies that in equilibrium all firms invest the same amount in each type of innovation each period and that some followers can leapfrog the current leaders to become leaders the following period. Investment levels are denoted by x_q and x_c and the resulting probabilities of success are denoted by $\lambda_q(x_q)$ and $\lambda_c(x_c)$. Both functions are increasing and concave - in the estimation routine

$$\lambda_c(x_c) = \frac{\alpha_c x_c^{1/2}}{1 + \alpha_c x_c^{1/2}}, \tag{2.2}$$

and $\lambda_q(x_q)$ has the same form as $\lambda_c(x_c)$, with parameter α_q.

The evolution of the industry proceeds as follows. Initially, all firms are on the first rung on each ladder, so all have the same product qualities and cost functions. In the first period, firms can invest in an attempt to move up to the second rung on each ladder. Those that are successful move to the second rung in the second period, while those that fail and new entrants remain on the first rung. In the second period, and in each subsequent period, there are two relevant rungs on each ladder - a rung for leaders (firms that innovated in the previous period) and a rung for followers (firms that did not innovate in the previous period). In the second period, firms can invest in an attempt to move up to the third rung on each ladder. Those that are successful are on the third rung in the third period, while those that fail and new entrants are on the second rung. Both the leader and the follower rungs increase by one each period (after the first), so the followers catch up to the former leaders, but the new leaders continue to be one rung ahead. In period t, leaders are on rung t and followers are on rung $t-1$.

Firms that successfully innovate obtain either a quality advantage, a cost advantage, or both, that lasts for one period. After that, the improvement is available to every firm. Therefore, in every period after the first there are five types of firms: firms that have both a quality and cost advantage, firms that only have one or the other, existing firms that have no advantage, and new entrants, who by assumption have no advantage. Below, firms in the first three groups are called high-tech firms, and firms in the last two groups are called low-tech firms. Below, variables that refer to firms with both quality and cost advantages, just quality advantages, just cost advantages, and no advantage, have qc, q, c, and 0 superscripts, respectively. For example, denote the number of each type of firm in the market at time t by n_t^{qc}, n_t^q, n_t^c, and n_t^0.

In the estimation routine the quality and cost ladders have flexible functional forms. The processes keep track of the quality and cost parameters available to low-tech firms each period after the first ($\gamma_t^0, a_t^0,\ f_t^0$). Recall that leaders each period are one rung ahead on these ladders. The following functional forms are used:

$$\gamma_t^0 = \exp(b_0 + b_1 t + b_2 t^2 + b_3 t^3) \tag{2.3}$$

$$a_t^0 = \frac{\exp(w_0 + w_1 t + w_2 t^2 + w_3 t^3 + w_4 t^4)}{\exp(w_5 + w_6 t)} \tag{2.4}$$

$$f_t^0 = \exp(w_0 + w_1 t + w_2 t^2 + w_3 t^3 + w_4 t^4) * (\exp(w_5 + w_6 t))/2. \tag{2.5}$$

The first rung of each ladder is determined by the restrictions $a_1^0 = a_2^0$, $f_1^0 = f_2^0$, and $\gamma_1^0 = \gamma_2^0$. The amount of flexibility required for each ladder was determined using likelihood ratio tests where the goal was fitting the trends in firm numbers, price, quantity, and quality. The discussion below focuses on the estimated changes in a_t^0, f_t^0, and γ_t^0 in the different industries, and not on the values taken by the various w_i and b_i parameters. Note that if each firm uses the newest technology available to it, then $f_{t-1}^{qc} = f_{t-1}^{c} = f_t^q = f_t^0$, $a_{t-1}^{qc} = a_{t-1}^{c} = a_t^q = a_t^0$, and $\gamma_{t-1}^{qc} = \gamma_{t-1}^{q} = \gamma_t^c = \gamma_t^0$. It is assumed that a firm on a higher rung can decide to use the low-tech technology instead - this ensures that being on a higher rung cannot make a firm worse off.

The value function of a low-tech firm is given by

$$\begin{aligned} V_t^0 = \; & \max\{\max_{x_q,x_c}[\pi_t^0 - x_q - x_c + \delta(\lambda_q(x_q)\lambda_c(x_c)V_{t+1}^{qc} + \lambda_q(x_q)(1-\lambda_c(x_c))V_{t+1}^{q} \\ & +(1-\lambda_q(x_q))\lambda_c(x_c)V_{t+1}^{c} + (1-\lambda_q(x_q))(1-\lambda_c(x_c))V_{t+1}^{0}) - \delta V_{t+1}^{0}], 0\}, \end{aligned} \tag{2.6}$$

where δ is a discount factor. The outside option has a value of 0. The value functions of the other types of firms differ only by current profits. Since all firms have the same future opportunities and investment technologies, all firms invest the same amounts in each type of innovation.

In every period, market supply in terms of services is given by

$$\gamma_t^0 n_t^0 q_t^0 + \gamma_t^c n_t^c q_t^c + \gamma_t^{qc} n_t^{qc} q_t^{qc} + \gamma_t^q n_t^q q_t^q, \tag{2.7}$$

where q_t^0, q_t^c, q_t^{qc}, and q_t^q represent quantities. Each type of firm's quantity is weighted by its quality level.

Consumers value services provided by goods, where the level of services provided by a quantity is given by $s = \gamma q$. Goods are perfect substitutes in providing services, so demand is a function of price per unit of quality. This implies that if consumers are willing to buy all quality types in every period then

$$\frac{p_t^0}{\gamma_t^0} = \frac{p_t^c}{\gamma_t^c} = \frac{p_t^q}{\gamma_t^q} = \frac{p_t^{qc}}{\gamma_t^{qc}}. \tag{2.8}$$

Denote the market demand for services by $D(\frac{\gamma_t}{p_t})$, where $D(.)$ is an increasing function of $\frac{\gamma_t}{p_t}$, the common quality-price ratio.[5] In the estimation routine the demand function for services has the form

$$D(\frac{\gamma_t^0}{p_t^0}) = \exp\{d_0 + d_1 \ln\left(\frac{\gamma_t^0}{p_t^0}\right) + d_2\left(\ln\left(\frac{\gamma_t^0}{p_t^0}\right)\right)^2 + d_3\left(\ln\left(\frac{\gamma_t^0}{p_t^0}\right)\right)^3\}. \tag{2.9}$$

2.1. Equilibrium

In equilibrium firms enter or exit and choose their quality-cost combinations, quantities and investments optimally, and consumers choose their quantities optimally. The following market-clearing condition, which equates the demand for services with the supply, must be satisfied:

$$D(\frac{\gamma_t}{p_t}) = \gamma_t^0 n_t^0 q_t^0 + \gamma_t^c n_t^c q_t^c + \gamma_t^{qc} n_t^{qc} q_t^{qc} + \gamma_t^q n_t^q q_t^q. \tag{2.10}$$

Optimal entry and exit of low-tech firms implies that $V_t^0 = 0$ in every period. If low-tech firms are in the market every period, then the value of operating a low-tech firm in the industry is equal to the outside alternative every period. The estimation algorithm described in the next subsection assumes that this is the case.

2.2. Estimation

The estimation algorithm performs a curve-fitting exercise. Given the functional forms and a set of parameter values, the exogenous quality and cost ladders are constructed. Then the model is simulated. Time series for firm numbers, price, quantity, and average quality are outcomes of the equilibrium of the model. The parameters of the model are adjusted in an iterative process to minimize the distance between the observables that the model generates and the data - the final estimated quality and cost ladders are those that provide the best fit. For a mathematical description of the algorithm see Filson (2001).

Once the final quality and cost ladders are available the model is simulated to generate

[5] Consumers can be heterogeneous. Suppose consumers solve $\max_{q^0,q^q} U = M - p^0q^0 - p^qq^q - \theta e^{-(\gamma^0 q^0 + \gamma^q q^q)}$, where M is income and θ is a heterogeneous taste parameter. Given prices and qualities, there is a value of θ such that consumers with a lower value of θ purchase nothing. Thus, new market segments can emerge as price drops and quality improves.

estimated quantities, profits, and other variables of interest. The estimation results overstate the contribution of quality and variable and fixed cost changes to an industry's evolution because other factors are not in the model (brand names and network effects are two examples). However, the estimation results still yield some broad trends in innovation that should be important if the forces of the model are partly responsible for the observed dynamics.

Because the data are annual, in the analysis below a quality innovation is made up of all the quality innovations that occur over the year, and a cost innovation is defined similarly. It is also assumed that the time it takes for innovations to spread to every firm in the industry is one year.

3. Innovation in the Personal Computer Industry

Figures 3 and 4 graph firm numbers, price, market quantity, and quantity per firm along with the estimates generated by the model. The model fits the data well and matches the main trends in the industry-level data, including the trend in quantity per firm. The good fit is not an end in its own right, since the flexible functional forms ensure this. It is important, though, because a bad fit would make the estimates of quality and cost change unreliable.

Figure 5 presents the main estimation results. Figure 5 graphs the estimated trends in quality, variable costs, and fixed costs, and shows that substantial changes in all three components have occurred over the life cycle. Taken together, Figures 3-5 show that previous dynamic equilibrium life-cycle models (Hopenhayn, 1994, Jovanovic and MacDonald, 1994, and Klepper, 1996) that ignore one or more of the three components cannot explain the trends in the data. In particular, explanations based solely on variable-cost innovations (Hopenhayn, 1994, Jovanovic and MacDonald, 1994) are inadequate because they imply that firm size rises over time. A comparison of Figures 4 and 5 shows that while periods of rising average firm size are associated with variable-cost improvements, periods of falling firm size are associated with fixed-cost improvements. Interestingly, variable and fixed cost tradeoffs occur over the life cycle - changes in the two cost components offset each other.

Figures 3-5 here

The conclusion that fixed costs fell in the early 80s comes from the fact that quantity per firm fell dramatically and then remained low for a long period, while market quantity rose and entry occurred. Other explanations are unsatisfactory. Demand reductions cannot be the cause because market quantity rises. A selection effect in which firms enter in order to obtain a scale-increasing innovation and temporarily accept low output and low profits is not likely to be the cause, as quantity per firm would fall only briefly, and then rise as firms began to obtain the scale-increasing innovation.

The remaining figures suggest other ways that previous models could be improved. For example, Klepper (1996) allows for both quality and cost improvements but continues to link large firm size to cost advantages. Figure 6 graphs the estimated quantity per firm for each type of firm and shows that large size is not always associated with low costs. Over much of the life cycle large firms were high-quality firms, not low-cost producers. In the model high quality increases firm size because by equation (2.8) high-quality firms face higher prices, and by equation (2.1) firms that face higher prices produce larger quantities.

Figure 6 here

Further, Klepper (1996) assumes that firms receive a constant exogenous payoff from quality improvement that does not vary over time. This does not appear to be the case in the PC industry - profit varies with technological opportunities. Figure 7 graphs the estimated rate of quality improvement each period and shows that opportunities for quality improvements vary over the life cycle. The estimated rate of quality improvement follows a U-shaped pattern, reaching peaks in 1977 and at the end of the series. Figure 8 graphs the estimated profitability of innovating and shows that the profitability of obtaining a quality advantage varies considerably over the life cycle. Note that the rate of quality improvement is not sufficient for determining the profitability of quality advantages - the profitability of obtaining a quality advantage is much higher late in the life cycle even though the rate of quality improvement is roughly similar to that in the late 70s. The reason why this is the case is that the profitability of improving quality depends on the cost function. Late in the life cycle firms have relatively low variable costs and thus produce a larger output. This implies that any given quality improvement is incorporated into more units of output, resulting in larger profits for successful innovators.

Figures 7 and 8 here

3.1. Evidence

The remainder of this section evaluates the estimates of the model using accounts of innovations drawn from Langlois (1992), Steffens (1994), and various issues of *Datamation*, *Electronic Business*, and *Standard & Poor's Industry Surveys*. The test of the model focuses on two key sets of results on technological change described above. First, the model's explanation for the pattern in average firm size is that the nature of cost innovation changed over the life cycle. Is it reasonable to conclude that cost innovation involved variable and fixed cost tradeoffs, and that variable costs fell while fixed costs rose during the late 70s and early 90s and that fixed costs fell and variable costs rose during the mid 80s? Second, the estimates suggest that the rate of quality improvement was high initially, dropped in the mid 80s, and then rose again in the mid 90s. Is it reasonable to conclude that the rate of quality improvement was relatively low during the mid 80s?

The evidence presented in the following paragraphs suggests that the model's results are reasonable under two assumptions. First, assume that in the short run, capital (plants and equipment) is a fixed input and labor is a variable input. This implies that any increase in automation that saves labor has the effect of increasing fixed costs and reducing variable costs. Second, assume that an increase in vertical integration replaces variable inputs (components) with fixed inputs (machines that can be used to produce components). This implies that vertical integration reduces variable costs and increases fixed costs.

Figure 7 shows that quality improved at a rapid rate in 1977, and the evidence supports this result. The first PC was the MITS Altair, introduced in 1975. It bore almost no relation to modern PCs - toggle switches and lights were the only input and output devices. Early PCs were similar to the Altair, but in 1977 Apple, Commodore, and Tandy introduced products that made dramatic improvements. For example, the Apple II had a built-in keyboard, drove a color monitor, and connected to a cassette recorder.

Figure 5 shows that estimated variable costs fell and fixed costs rose in the period 1977-1981. Two trends are consistent with the estimates. First, Apple, Commodore, Tandy, and other entrants during this period introduced volume manufacturing methods that improved on the early batch processes used by MITS by substituting capital for labor. Second, most entrants in the late 1970s were partially vertically integrated and produced microprocessors, printed circuit boards or peripherals in house.

Figure 5 shows that following 1981 the nature of cost innovation changed - fixed costs fell and variable costs rose. This pattern can be attributed to events that followed the entry of IBM in 1981. IBM adopted an *open standard;* most of its PC's design was not protected through patents or other means. Third parties were encouraged to manufacture components and software, and as a result new firms entered the market and cloned IBM's PC. By the mid 80s the vast majority of firms were small clone producers that were not vertically integrated - they bought parts off the shelf and assembled PCs. The changes sparked by IBM's entry affected all firms, not just small clone firms - the larger firms also began to buy more parts instead of producing them in house.

Figure 7 shows that though quality continued to improve in the mid 80s, the rate was relatively low compared to the 70s and 90s. After IBM's entry quality improvements occurred within IBM's standard. The improvements were not as dramatic as the improvements during the late 70s when PCs went from being kits for hobbyists to modern computers. During the 80s the PC became increasingly commoditized, and by 1986 Compaq, a clone manufacturer, beat IBM to market by introducing the first PC using Intel's 386 chip.

Figure 5 shows that in the late 80s the direction of cost innovation changed again, and variable costs fell and fixed costs rose. Several facts are consistent with the models results. In the late 80s companies including Acer, Dell, Gateway, Goldstar, Hyundai, and Packard Bell developed low-cost manufacturing and distribution methods that reduced variable costs. Process innovations began to involve less outsourcing and labor and more automation. For example, approximately 60% of the value of the IBM PS/2 line, introduced in 1987, had a source within IBM. The original IBM PC, in contrast, had an *external* source for approximately 94% of the value. The PS/2 had fewer components per machine, and was easier to assemble - labor usage was reduced 24-30%. Compaq, IBM, and several Japanese firms began using surface-mount technology, an extremely capital-intensive technology that required multimillion-dollar equipment investments, and usage expanded over time.[6] In 1990 Compaq began to invest in tape automated bonding, another highly automated and capital intensive technology.[7]

The remaining trend is the increased rate of quality improvement in the 1990s shown in Figure 7. The explanation for this trend is that in the 90s dramatic improvements in size, weight, storage capacity, and battery life occurred in portable computers, while processor speeds and storage capacities for desktops continued to improve at undiminished rates. The move towards miniaturization and portability along with undiminished improvements in other characteristics led to an increased rate of quality improvement relative to the mid 80s.

In sum, the patterns that are consistent with the model's results are as follows: 1) The high rate of quality improvement in the late 70s was due to dramatic improvements over the first PCs; 2) falling variable costs and rising fixed costs during this period were due to the increased use of volume manufacturing and vertical integration; 3) the relatively low rate of quality improvement during the mid 80s was due to incremental improvements to IBM's open standard; 4) falling fixed costs and rising variable costs during the mid 80s were due to vertical disintegration that occurred once specialized component manufacturers emerged; 5) falling variable costs and rising fixed costs in the late 80s and 90s were due to less outsourcing and labor use and more automation; 6) the increasing rate of quality improvement in the late 90s was due to improvements in miniaturization, speed, and storage.

4. Conclusion

The model estimated here extends previous work on industry life cycles by considering quality and variable and fixed cost improvements simultaneously in a flexible framework. The

[6] Surface-mount technology involves mounting chips right on the board rather than using a plug or a socket. It reduces wiring and allows for more chips to be packed on each board - this was crucial for building smaller and more portable computers. There are other advantages to using surface-mount technology, one being that the board can dissipate heat better than a plug. For further discussion of the emergence of surface mount technology in 1987 and 1988 and its spread in the early 90's see *Standard and Poor's Industry Survey*, June 9, 1994, p. E34.

[7] See Compaq's 1990 annual report. Tape automated bonding enabled greater minitiarization of components on printed circuit boards. It contributed to greater reliability, faster computing speeds, and smaller products.

estimation results show that all three components are necessary to explain the evolution of the PC industry, and the historical analysis shows that the estimates of technological change generated by the model are consistent with industry facts.

Although the model improves on the previous literature, there are still several possible avenues for further improvement. Richer environments with heterogeneous choices deserve further study. The model here has four types of firms, but focuses entirely on leader-follower relationships. In reality many innovations are only pursued and imitated by a subset of firms, successful firms become much larger than new entrants, and path-dependence is relevant. Eeckhout and Jovanovic (1998) introduce a model that allows some firms to be persistent imitators.

Further, a more complete explanation of innovation in the PC industry requires several additional factors. Steffens (1994) emphasizes different stages in PC industry's life cycle associated with different standards and modes of competition. Transitions occurred in the nature of the consumers, from hobbyists early on to businesses, educators, and households later on. Different types of consumers may value different product characteristics and have different views on what determines high "quality." For example, hobbyists enjoy assembling PCs themselves and thus do not require a completed product, whereas other users place a high value on not having to build their own PC. Transitions also occurred in the operating systems, from CP/M early on, to Apple's, Commodore's, and Tandy's operating systems, and then to Microsoft's. Network effects and brand name effects have been important.

It is difficult to evaluate the robustness of the results to the inclusion of network and brand effects. Some facts cannot be explained without network effects; Apple's persistence and growth is one example. The combination of the model's results and the historical analysis presented above suggest that links between network effects and cost functions have been important. For example, the rise of independent suppliers following IBM's entry with an open standard allowed clone companies to enter as non-vertically-integrated firms; this lowered fixed costs and led to smaller firms. As another example, the consolidation of Intel and Microsoft's dominance in the 80s contributed to the commoditization of the PC. This is captured in the model as an exogenous decline in opportunities for quality improvement and an increase in opportunities for cost reduction, but it would be interesting to endogenize the events.

In sum, it would be useful to consider heterogeneous choices, transitions between stages, network effects, brand effects, and other sources of persistent market power along with the three types of technological change. However, it should be noted that introducing these factors would complicate the analysis considerably and require additional data. One theoretical issue is that the model here has a unique equilibrium, and while such a model is much easier to estimate than multiple-equilibria or evolutionary models (for which we lack data on all paths but the one observed), the latter are required to model network effects.

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Fig. 1. Firm Numbers, Price, Market Quantity, and Quality

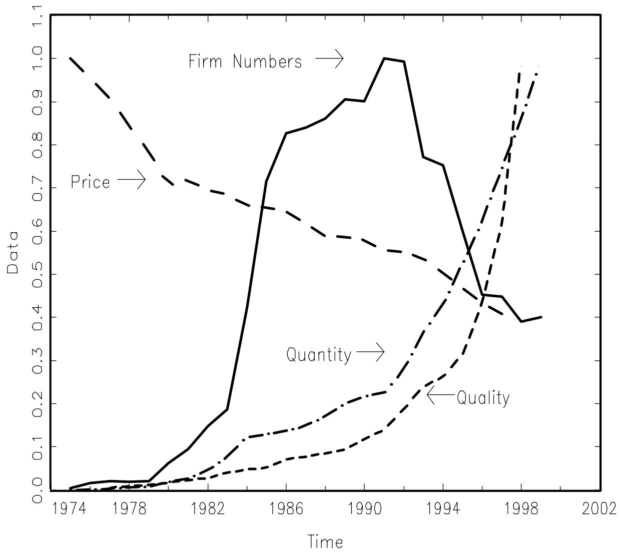

Fig. 2. Average Quantity per Firm

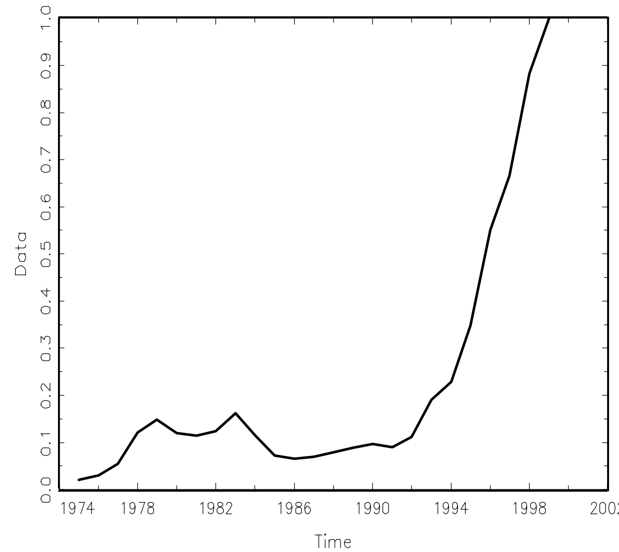

Fig. 3. Firm Numbers, Price, and Market Quantity
(Solid lines: data Dashed lines: simulation results)

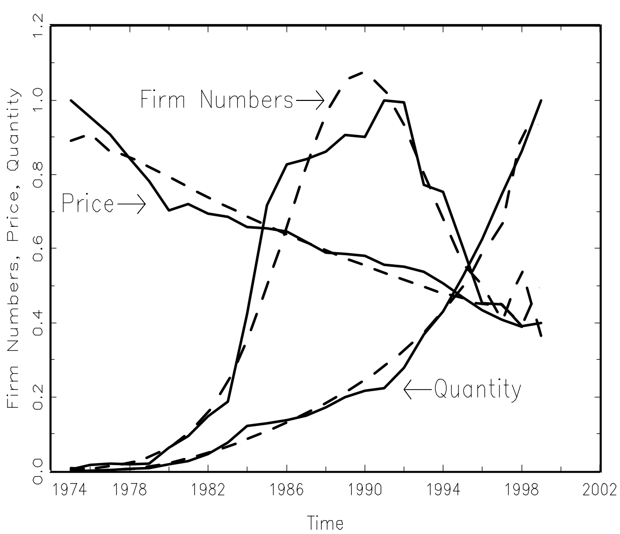

Fig. 4. Quantity per Firm
(Solid lines: data Dashed lines: simulation results)

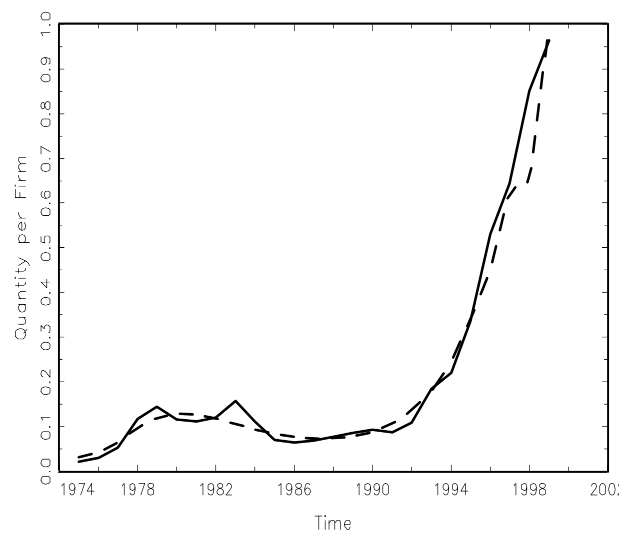

Fig. 5. Estimated Avg. Quality, Variable Cost Parameter, and Fixed Cost

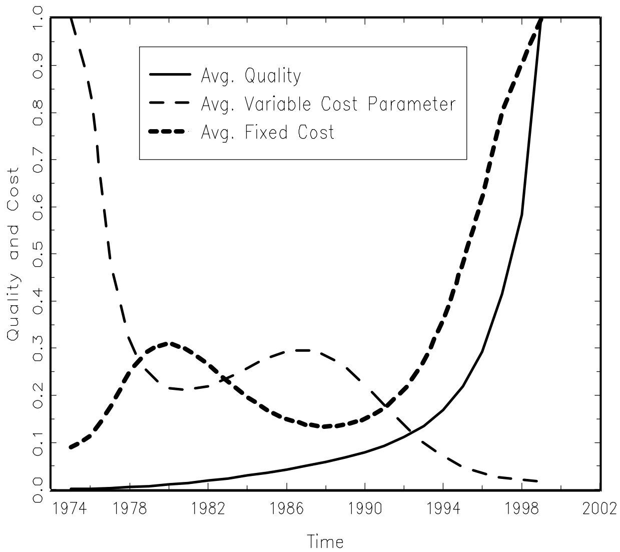

Fig. 6. Estimated Quantity per Firm By Type of Firm

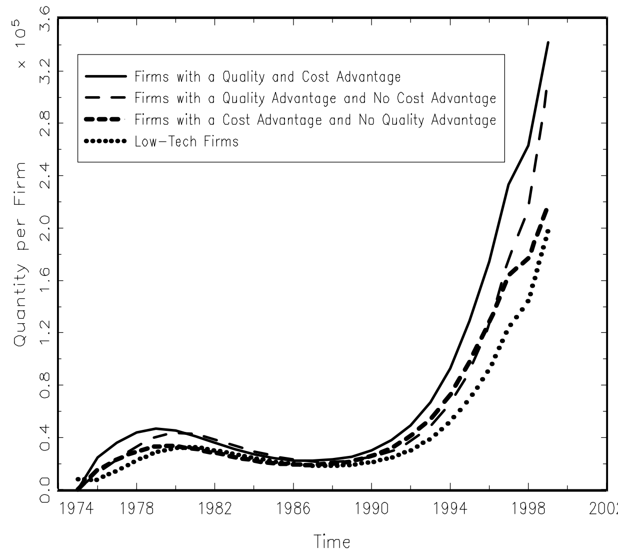

Fig. 7. Estimated Rate of Quality Improvement

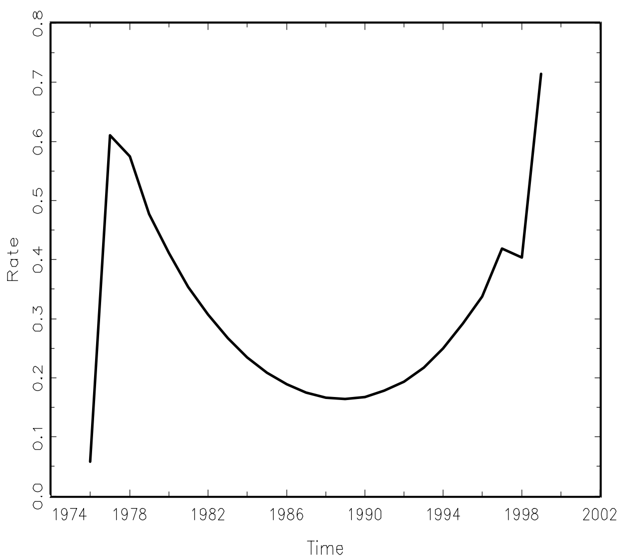

Fig. 8. Profits of the Various Types of Firms