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TECHNOLOGICAL INNOVATION AND PRODUCT EVOLUTION: THEORETICAL MODEL AND ITS APPLICATIONS

Junjiro Shintaku*

CONTENTS

ABSTRACT

This paper introduces a model of product evolution, and applies it to analyze in industries characterized by rapidly advancing technology, such as electronic calculator.

Product evolution is described as the process of improvement in cost and product performance. The current available technologies define the current "feasibility frontier." A feasibility frontier is defined as the set of lowest cost products for each level of product performance, or alternatively, the highest performance products at each possible cost level. In addition, a "market frontier" is a subset of the feasibility frontier, limited to the products which are *in demand* in the marketplace.

As technological innovations continue, the feasibility frontier and market frontier shift accordingly, making products with the positive characteristics of higher performance and/or lower cost available. Companies which specialize in producing a product of low cost or a product of high performance on the current market frontier, may not be able to remain competitive following a shift of the feasibility frontier. On the other hand, successful companies which lead a shift in the market frontier may be able to achieve both lower costs and a high degree of product differentiation.

I. Introduction

Many firms encounter fierce competition in industries subject to rapid technological change. Technological progress has been especially rapid in such consumer electronics product lines as electronic calculators, video cassette recorders, personal

* Faculty of Economics, Gakushuin University. The author is grateful to the participants of TIMS/ORSA 25th Joint National Meeting, Washington, D.C., USA, April 25–27, 1988, for their helpful comments on an earlier draft of this paper.

computers, and Japanese language word processors. For these products, performance has been improving while price has been falling at the same time. When new product models with higher performance and lower price are introduced, existing models immediately become obsolete. As a result of fierce competition, new models are developed and introduced in rapid succession. A firm can not sustain its competitive advantage in an innovative product line if it fails to achieve an ongoing process of product improvement.

For example, the first Japanese language word processor was brought to market by Toshiba in 1979 and sold for a price of 6,300,000 yen. Afterwards, many other firms entered the market and 64 new models were introduced in 1985. In 1986, the lowest price model made by Canon was sold for just 38,000 yen. Moreover, the product performance of the Japanese language word processor has been vastly enhanced; reaction time has been cut dramatically, printing has become more rapid, the memory has been expanded, and the machines have been made more "user-friendly." Toshiba, which was the inventor of the Japanese language word processor, has seen its market share fall to only 9% in 1984, while that of Canon has risen to 27%.

For video cassette recorders (VCRs) as well, price has been falling rapidly, while product performance has been improving. The Federal Communications Commission (FCC) of the United States issued a report on video machines in 1979. At that time, Japanese VCRs were sold in the U.S. for about 1,000 dollars, and as a result of their high price, VCRs could be afforded only by high-income consumers. The FCC concluded that general inflation would increase costs and cause the price of the VCR to rise to 1,300 dollars by 1985. At this price level, it was believed that the VCR would not be the leading video product. Video disk systems might be more promising, with a far lower price of about 500 dollars. However, by 1985, Japanese VCRs were selling for less than 300 dollars and the machines' performances had been vastly enhanced. Now, the VCRs dominate video disk systems.

These facts can be explained partly by the experience curve effect. Incremental innovations have enabled firms to advance down the experience curve. If an experience curve effect does exist, it would be advantageous for a firm to cut its prices in order to gain market share at the sacrifice of immediate profits and to travel down the experience curve earlier than its competitors (Dean, 1976). This kind of market penetration pricing policy may prove effective in some industries. But, of course, it is not always successful. During the past ten years, there have been several examples in which this penetration strategy failed, such as Texas Instruments' digital watch and home computer businesses.

Why did TI fail to increase its market share? The reason might be that they did not take into account future performance improvements made possible through technological innovation. In an industry where price and product performance are rapidly changing, firms must develop a competitive strategy premised on this underlying dynamism (Shintaku, 1986).

This paper presents a product evolution model, which describes the process of improvement in cost and product performance, along with expansion of market. The product evolution model is elaborated and applied to a case of the Japanese electronic calculator industry. In conclusion, successful competitive strategies in such industries of rapidly advancing technology are derived from the analytical framework.

II. Product Evolution Model

1. Feasibility Frontier

First, the relationship between price and performance of various products in a certain product class (such as the electronic calculator) is considered from the producer's viewpoint. The following assumptions are made to simplify the analysis in this section; 1) There are many producers and the market operates under perfect competition. 2) No producer can obtain excess profit and a product's price is therefore equal to its cost. 3) All producers access to the same technologies. 4) Various product performance characteristics can be aggregated to one dimension—though a product usually has several dimensions of performance that are difficult to aggregate.

If currently available technologies are given, there is usually a trade-off between cost and product performance, a frontier expressing the highest performance level obtainable as an increasing monotonous function of cost (price). The higher the cost, which is equal to price under our assumption of perfect competition, is, the higher the maximum achievable performance level will be. Along the feasibility frontier, any improvement in performance requires an increase in cost. But the improvement in performance obtained by each successive increment of additional cost falls, according to the law of diminishing returns. Under the technology currently available, the maximum performance level is limited at any cost and likewise the minimum cost can not fall to generate a performance level satisfying the minimum requirements for the product to be classified into the product class.

Figure 1 illustrates this trade-off between price and performances for the various products within a certain product class. The horizontal axis expresses the level of product performance, and the vertical axis represents the price. Any product can be plotted as a certain point on this figure.

The currently available technologies define the current "feasibility frontier," which is described as the curve f on Figure 1. A feasibility frontier is defined as the set of maximum performance levels obtainable at a given cost (price). In other words, all products lying on the feasibilty frontier are the most advanced products attainable under the current level of technology. Of course, any products within the feasibility frontier (the "feasible set") can be made, but they are all inferior to lower-priced, higher-performance products, lying on the feasibility frontier.

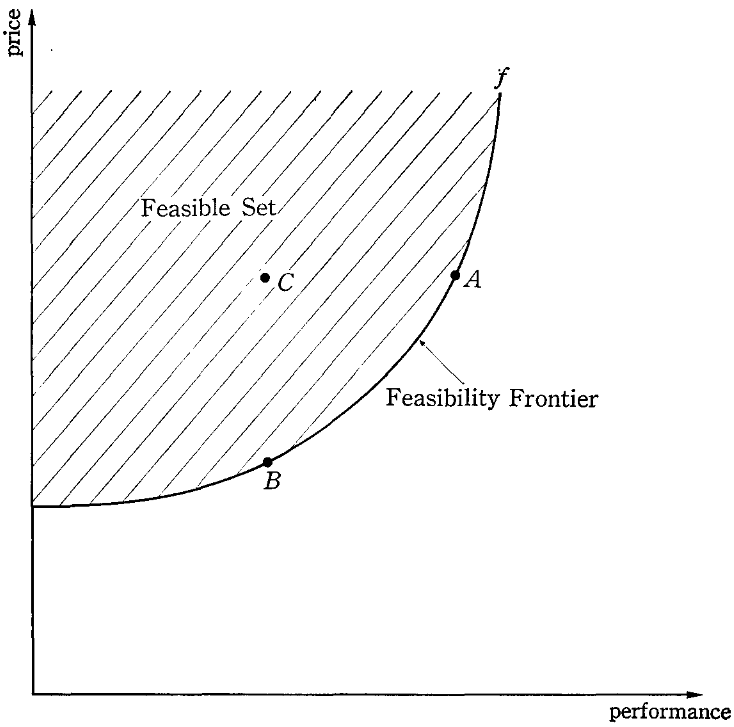

Figure 1. FEASIBILITY FRONTIER

2. Consumers' Choice and the Market Frontier

According to traditional demand theory, the consumer chooses a basket of goods (quantities) so as to maximize his/her utility subject to a budget constraint. A more recent approach to demand theory, however, supposes that the consumer chooses goods according to their particular characteristics, again subject to a budget constraint (Lancaster, 1971). In the latter approach, a consumer's utility is defined in terms of the characteristics of goods. In this paper, this approach to consumer behavior is adopted, because it is helpful in analyzing the choice among differentiated products within a product class. The concept of characteristics corresponds to that of product performance in this paper.

A consumer decides whether he will buy a unit of product in a particular product class and if so, choose a product available in the market. It is assumed that a consumer's utility is a function of product performance and price. Any product with higher performance and the same price or lower price and the same performance leads to higher utility. Price is considered as a characteristic, which has negative utility for consumers. The consumer choose the product in order to maximize his utility.

Figure 2 illustrates the mechanism of consumers' choice. All of the technologically

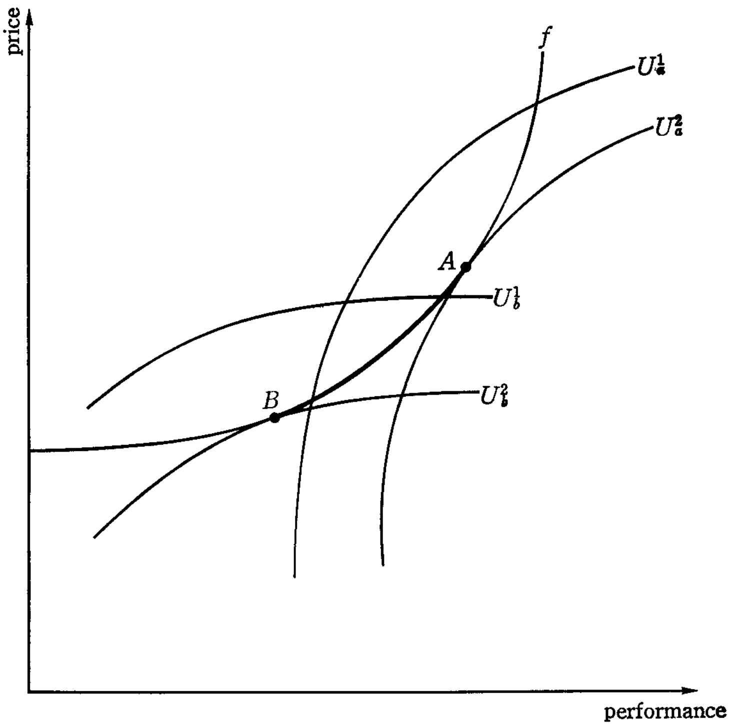

Figure 2. MARKET FRONTIER

feasible products given in the market are represented as the feasible set in Figure 1. But any products within the feasible set not lying on the feasibility frontier are out of the consumers' choice set, because the product which has a lower price and higher performance always exists. U_a and U_b are representative indifference curves of consumer ***a*** and consumer ***b*** respectively. Consumer ***a*** is indifferent between products on the same indifference curve and prefers the products on U_a^2 to the products on U_a^1 Therefore, for consumer ***a***, the optimal product choice in this situation is product ***A***. Similarly, for consumer ***b***, the optimal product choice in this situation is product ***B***.

Consumer ***a***'s indifference curves are different from those of consumer ***b***. The two consumers may differ in income level or desire to buy a product in the product class. Consumer ***a*** regards high performance as more important than low price. Consumer ***b***, meanwhile, regards low price as more important. Suppose that all consumers in the market consist of type ***a*** consumers, type ***b*** consumers, and intermediate types of consumers with preferences lying between those of type ***a*** and type ***b***. The products located to the right of product ***A*** on the feasibility frontier are too expensive and the products located to the left of product ***B*** have too poor performance to attract any market demand at all. Therefore, the products on arc $\overline{AB}$, which we call the "market frontier," are the only ones actually demanded or traded in the market.

3. Shift of the Market Frontier through Technological Innovation

If technological innovation never occurs, the feasibility frontier and the market frontier remain fixed. Any firms that produce products lying along the market frontier are able to survive. Firms choose which products on the current market frontier to produce. Firms pursuing a cost leadership strategy might concentrate on low-price products like product ***B***. Other firms which pursue differentiation strategy might concentrate on high-performance products like product ***A***. But the firms attempting to produce both types of products would be stuck in the middle of the two sources of competitive advantage: lower cost and differentiation, which are subject to a trade-off, as Porter (1980) insists.

Next, we will introduce effects of technological innovation into our model. Abernathy et al. (1983) analyze the relationship between technological innovations and competition, classifying technological innovations based on their impact on the production system and on market linkage. They describe two basic kinds of impact resulting from innovation—conservative and destructive. When innovations strengthen the existing production system or existig market linkage, they are described as conservative, whereas when they weaken the existing production system or existing market linkage and lead to the emergence of new such structures, they are described as destructive. According to their impact, innovations are classified into four categories: 1) *regular innovations* whose impact is conservative both on the production system and on market linkage, 2) *market niche innovations* whose impact is conservative on the production system but destructive on market linkage, 3) *revolutionary innovations* whose impact is conservative on market linkage but destructive on the production system, and 4) *architectural innovations* whose impact is destructive both on the production system and on market linkage (Abernathy et al., 1983, pp. 109–114).

In this section, regular innovations are added to our model. Regular innovations result in the introduction of new products with lower price and/or higher performance that strengthen the existing production system. But these new products are not radically improved compared with existing products, and changes are incremental in nature. As a result, the fesibility frontier gradually shifts to the lower-right hand side of the graph, from f_1 through f_2 and to f_3 (see Figure 3). If regular innovations accumulate in an industry, there may well be a considerable changes in price and performance.

In the case of regular innovation, the distribution of consumer preferences does not change. We can therefore assume that the indifference curves to be considered are same as those in Figure 2. As the feasibility frontier shifts outward, the optimal product for type ***a*** consumers changes from A_1 through A_2 to A_3, and for type ***b***

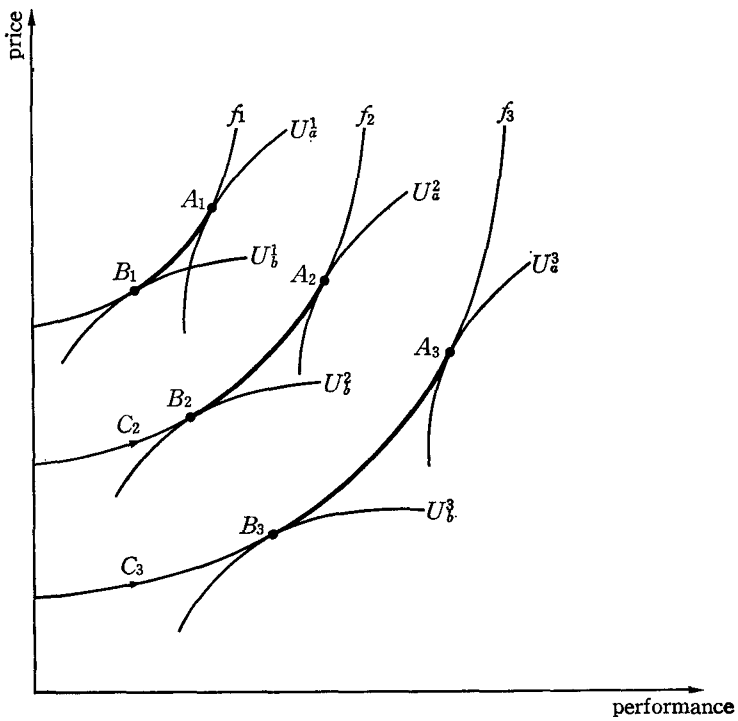

Figure 3. SHIFT OF MARKET FRONTIER BY REGULAR INNOVATIONS

consumers, from B_1 through B_2 to B_3. Thus, the market frontier shifts from $\overline{A_1B_1}$ through $\overline{A_2B_2}$ to $\overline{A_3B_3}$. In this process, consumers' utility increases steadily as firms strengthen their existing market linkage.

In this case, the characteristics of the optimal product for each type of consumer shift toward the lower-right hand side of the graph. A firm may be expected to develop new products with lower price and higher performance if its target segment in the market was same. Simply cutting the price of the same performance product ($B_1 \rightarrow C_2 \rightarrow C_3$) might lead a firm to either change its target segment or to lose market share. The same is true for improving performance for a given price. In other words, pursuing only lower cost or differentiation is not sufficient for a firm to sustain its competitive advantage in this type of environment.

The failure of Texas Instruments in its digital watch and home computer businesses can be explained by this analytical framework. TI introduced lower price models with same inferior performance (such as C_2 or C_3). As a result, TI lost market share and ended up suffering large losses in these lines of business.

In the following section, we will analyze the electronic calculator industry, from its birth through its growth and competitive stages, using the product evolution model outlined above. Market niche innovations and revolutionary innovations will be added to our model.

III. Evolution of the Electronic Calculator

1. Substitution of the Electronic Calculator for the Mechanical Calculator

The first electronic calculator using vacuum tubes was introduced onto the market by Samlock Comptometer Co. in 1962. Two years later, two Japanese firms, Sharp and Canon, simultaneously came out with an improved desk-top electronic calculator using transistors. Since that time, the market has been expanding rapidly. By 1982, Japanese firms dominated world markets, with sales of electronic calculators amounting to 152 billion yen.

During this twenty-year period, the price of electronic calculators has fallen dramatically. The first product introduced by Sharp in 1964 sold for 535,000 yen. But by 1982, the average price of a calculator on the Japanese market had fallen to only 2,420 yen. In terms of performance, meanwhile, calculators have made remarkable progress. Their calculating speed and reliability have improved, while their size has become ever smaller. Today, calculators with the size of credit card are available, whereas the size of first electronic calculators was the same as that of a cash register. Moreover, some models have additional functions beyond simple arithmetic calculations, such as keeping time and storing telephone numbers.

Currently, Casio and Sharp together dominate the market for electronic calculators with a combined sales share that reached 70% in Japan, 1982. In the 1970's, many Japanese firms had entered the calculator business, with about 30 firms still competing in 1972. After a period of fierce competition, however, a major shake out occurred, with Casio and Sharp emerging predominant in the market.

Initially, the electronic calculator was perceived as a substitute for the mechanical calculator, which had already undergone more than one hundred years of product improvement since its invention. Calculators were produced in Japan for the first time in 1923 by Tiger Calculator Co. By the late 1950's, the product had penetrated into Japanese business offices and laboratories. But after the introduction of the electronic calculator, the new product was increasingly used as a substitution for the mechanical calculator. In this early period in the evolution of the electronic calculator, its market was composed mainly of substitution-oriented demand.

The mechanical calculator and the electronic calculator are based on entirely different technologies. The performance characteristics of the latter are far superior than those of the former, in terms of calculating speed, ease of operation, and reliability. In addition, electronic calculators can perform far more complicated mathematical functions. Nonetheless, in the early years, the electronic calculator was more expensive by far than the mechanical calculator. In fact, the price of the first electronic calculator was as much as ten times greater than the average price of mechanical calculator at that time (52,800 yen in 1964).

The development of the electronic calculator can thus be understood as a revolutionary innovation. Compared with the mechanical calculator, its market was similar, but its basic technologies was quite different as mentioned above. Such a revolutionary product based on new technology often starts with both higher performance and higher price. However, subsequent regular innovations in this new technology tend to improve both cost and performance. The speed of improvement for the new technology is typically faster than that for the old technology. In terms of a particular type of technology, product performance increases along an S-shaped curve as time goes on (Georghiou et al., 1986; Foster, 1986). On the other hand, production cost decreases along a longarithmic curve with cumulative production volume due to experience curve effects (Day and Montgomery, 1983).

Figures 4-a and 4-b illustrates a shift of the market frontier due to a revolutionary innovation. The curve f and g are the feasibility frontiers for the old technology and the new technology, respectively. If the distribution of consumer preferences is the same as assumed in Figure 2, the new market frontier is the union of arc $\overline{AC}$ and arc $\overline{DB}$ when the new technology first emerges in the market (see Figure 4-a). Assuming that the new technology progresses faster than the old technology in terms of performance and cost, the market frontier changes as shown in Figure 4-b.

At first, the new products based on the revolutionary technology were preferred

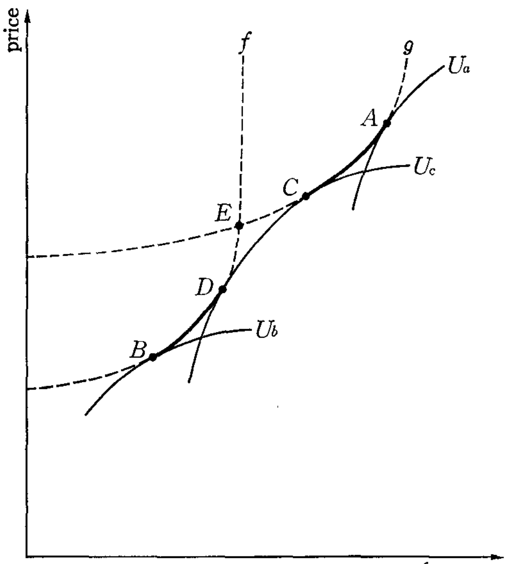

Figure 4-a. EMERGENCE OF REVOLUTIONARY PRODUCTS

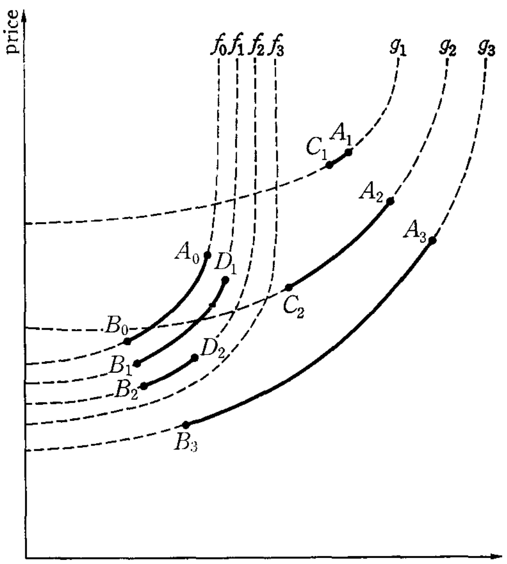

Figure 4-b. TRANSITION FROM OLD TECHNOLOGY TO NEW TECHNOLOGY

only by consumers attaching more importance to high performance than to low price ($\overline{A_1C_1}$). As the new technology progresses, however, the share of consumers who prefer the new product increases ($\overline{A_2C_2}$). At last, the new technology dominates the old technology completely and all consumers prefer the new product ($\overline{A_3B_3}$).

This process corresponds closely to the historical changeover process in the calculator industry described above. At first, the electronic calculator was purchased by scientists and engineers who required advanced functions for professional purposes. As its price fell, however, its use spread to the ordinary offices. The total production value of electronic calculators first exceeded that of its mechanical alternative in 1967, its production volume first exceeded in 1970, and finally, in 1975, electronic calculators began to sell for a lower average price. In this process, the average price of mechanical calculators also fell—as low as 10,000 yen in 1974. However, this decrease is primarily a reflection of a shift of the composition of demand in the process of substitution, rather than of technological improvement. In lower-price segments, it took longer for the electronic calculator to be substituted than in the high-price, high-performance segments.

2. Creation of a New Market Niche

In its early years, the market of electronic calculator was similar to that of the mechanical calculator, as described above. However, the rapid sales growth in this market can not be explained entirely by the substitution effect alone. A brand-new market, composed of personal users, was discovered and cultivated in the first half of the 1970's. During this period, Sharp's sales share fell from 25.5% in 1971 to 14.5% in 1975, and that of Canon declined from 14% in 1971 to 8.8% in 1975. These two technological innovators were losing their market share. Meanwhile, Casio, which was technologically a follower, increased its sales share dramatically from 6.5% to 26.3%, during the same period.

In 1970, the market was dominated by products with a twelve-digit display, selling for a price of 110,000 to 140,000 yen. For office use, this level of performance was regarded as the average requirement. In fact, Sharp introduced the "QT-8D" with an eight-digit display and a price of 99,800 yen in 1969, but the product did not sell well. The performance of the eight-digit calculation ability was inadequate for office purposes and the price of 99,800 yen was considered too expensive for personal users.

In 1972, Casio introduced a new product, "Casio Mini," with a six-digit display that just performed the four basic arithmetic functions. The Casio Mini was based on a new concept and sold for a price of 12,800 yen. Casio scored a big hit with the Casio Mini, selling two million units in the first 18 months. This was the launching pad for Casio's future growth.

Early in the process of developing this product, Casio decided to target housewives and aimed at selling it for less than 10,000 yen. Six-digit calculation was considered the minimum requirement for housewives, although this level of performance was insufficient for office users. Clearly, preferences differed sharply between the existing office users and the targetted housewives in terms of price and performance characteristics.

These differences are depicted in Figure 5. Even if the feasibility frontier were to remain at its current level, a new market frontier could be found by innovative niche creation. Arc $\overline{AB}$ represents the market frontier for the existing market. U_c is a typical indifference curve for a type *c* potential consumer. If only products on arc $\overline{AB}$ were available in the market, type *c* consumers might not buy any of them, because of low utility or their budget constraint. Product ***B'***, which is located near product ***B***, would fail to win over either existing consumers or type *c* consumers. However, if a firm can perceive the potential demand and introduces product ***C***, located far to the lower of product ***B*** on the current feasibility frontier, product ***C*** might be bought by some type *c* consumers.

In the case of the electronic calculator, type *c* consumers correspond to personal users, product ***B'*** to Sharp's "QT-8D," and product ***C*** to "Casio Mini." In order to create and exploit a new market niche, it is essential for a firm to identify the

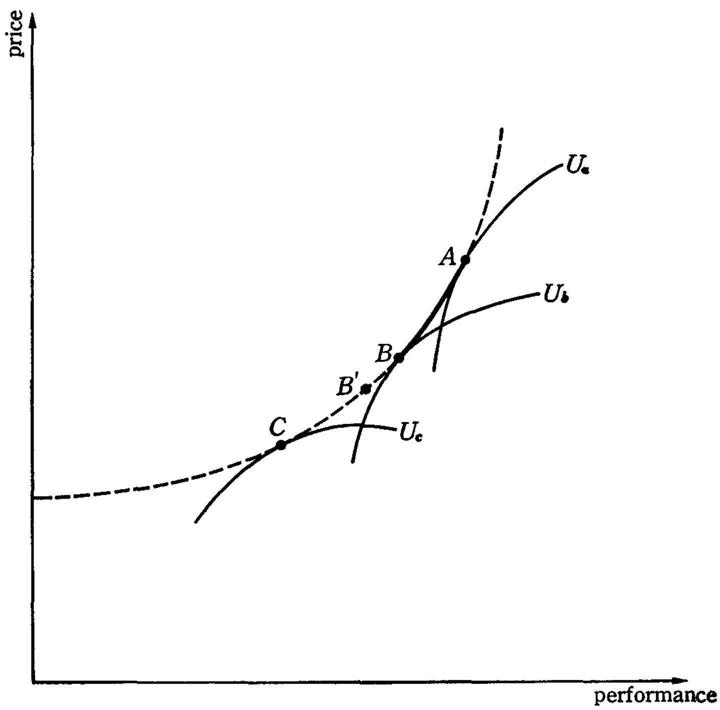

Figure 5. CREATION OF A MARKET NICHE

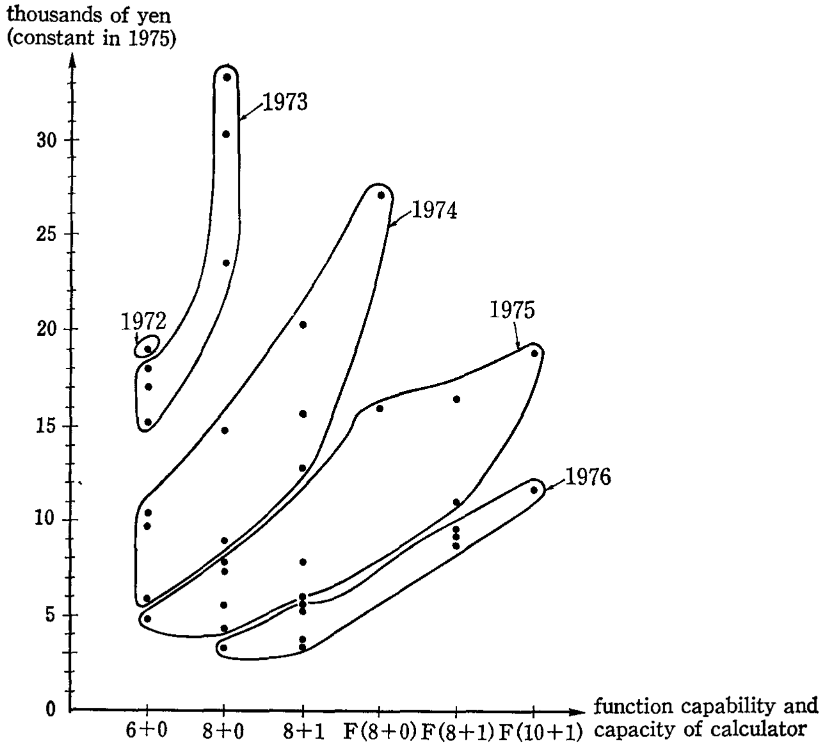

Figure 6. RRODUCT LINE CHANGE OF CASIO's HANDHELD CALCULATOR (1972–1976)

preferences of a class of potential consumers.

3. Full Line Policy through Successive Regular Innovations

After the introduction of the Casio Mini, other firms—including many new entrants—competed for market share in the segment of personal users. Some firms focused on cutting the price of relatively low-performance products, while other firms concentrated on developing products with ever higher performance characteristics. Casio and Sharp, meanwhile, have maintained a full line of products, spanning a range of prices and features. Their product lines have evolved continuously through successive regular innovations. This full line policy made possible for them to win a dominant market share.

Figure 6 depicts the evolution of Casio's product line from 1972 to 1976. The 36 points in this figure represent a segment of Casio's product line: hand-held calculators selling for a price of less than 25,000 yen. The horizontal axis shows a ranking of products according to performance as measured by three criteria: 1) the number of digits used in calculations, 2) memory capacity, and 3) additional functions such as the logarithmic function. For example, F(10+1) means that the calculators in this category have some additional functions in addition to basic arithmetic, perform calculations to ten digits, and contain one unit of memory capacity. The vertical axis shows the real price in 1975 yen. The 36 products are grouped into five subsets according to the year in which each product was put onto the market.

Casio's product line shifted repeatedly to the lower right during this period. Figure 6 bears a remarkable resemblance to Figure 3, which shows the shift of the market frontier by regular innovations. By accumulating a series of regular innovations, Casio was able to develop higher performance products and cut prices of the same performance model at the same time. It should be noted that Casio stopped production of the six-digit model in 1976.

The highest performance model and the lowest price model played an especially important role in the evolution of Casio's product line. Developing the highest performance model made it possible for Casio to keep up with technological progress and to achieve product differentiation. The highest performance model is relatively profitable though its sales volume is not large. On the other hand, the lowest price model is far less profitable because of severe price competition. New entry into this segment is technologically easy. But the lowest price model is important because the volume is very large. It helps to reduce the cost of all models due to economies of scale in purchasing or production and to the experience curve effect.

IV. Concluding Remarks

In this paper, a product evolution model was developed, allowing for shifts in the market frontier, and the evolution of electronic calculator was analyzed by using this model. A tentative conclusion can be derived from this analysis. The successful competitive strategy may be quite different for each phase of a product evolution. A firm should construct a dynamic strategy in order to sustain its competitive advantage throughout the process of product evolution.

First, revolutionary products tends to be introduced within a small segment of an existing market. Such a segment is often composed of high-end users with special needs. Sometimes, the early generation of revolutionary products is inferior to the old product in terms of price or reliability, but superior in terms of some particular performance characteristics. Substitution usually proceeds gradually along with cost reduction and incremental improvements in performance. But there have been some revolutionary products that barely survived in their limited market segment, or were replaced by another superior revolutionary products. These unsuccessful revolutionary products might have suffered from a limited potential for future improvement. Therefore, it appears pioneering firms should search for new technologies with potential for further refinement.

Second, creation of a new market niche makes it possible to expand the entire market further, well beyond the maximum growth attainable by complete substitution for the old product. In this phase, the key to success appears to be the identification of potential consumers' preferences, rather than the development of new technologies.

Third, after the introduction of a revolutionary product or the creation of new market niches, successive regular innovations may play an important role. Usually, substitution cannot proceed and a new market niche cannot grow unless many regular innovations are allowed to accumulate. The cumulative effect of regular innovations may be quite considerable in terms of both price and product performance. A firm competing in industries of rapidly advancing technology should pursue both cost reduction and continuous improvement of its products. The full-line policy adopted by Casio, is an example of a successful strategy in this phase.

Of course, further study is needed in order to generalize this conclusion. Other types of product evolution may be observed in other product classes. Furthermore, there may be operational problems in applying our product evolution model to some cases. For example, it is difficult to aggregate the many dimensions of performance and to incorporate the subjective aspects of performance evaluation into the model. Such problems provide a wealth of important topics for further work.

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