ENCYCLOPEDIA OF COMPUTER SCIENCE AND TECHNOLOGY

EXECUTIVE EDITORS

Allen Kent *James G. Williams*

UNIVERSITY OF PITTSBURGH
PITTSBURGH, PENNSYLVANIA

ADMINISTRATIVE EDITORS

Carolyn M. Hall *Rosalind Kent*

PITTSBURGH, PENNSYLVANIA

VOLUME 28
SUPPLEMENT 13

MARCEL DEKKER, INC. NEW YORK • BASEL • HONG KONG

MARCEL DEKKER, INC.
270 Madison Avenue, New York, New York 10016

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 74-29436
ISBN: 0-8247-2281-7

Current Printing (last digit)
10 9 8 7 6 5 4 3 2 1

PRINTED IN UNITED STATES OF AMERICA

TECHNOLOGICAL SUBSTITUTIONS IN THE COMPUTER INDUSTRY

INTRODUCTION

In 1971 J. C. Fisher and R. H. Pry published an article entitled "A Simple Substitution Model of Technological Change"(1) which became a classic. Their thesis was that man has few basic needs to satisfy: food, shelter, clothing, transportation, communication, etc., and that technological evolution consists of replacing the old ways of satisfaction with new ones. The advancements of technology may seem *evolutionary* or *revolutionary* depending on the time scale of the substitution. Regardless of the pace of change, however, the end result usually is to satisfy an ongoing need or perform an existing function differently than before. The need or the function itself rarely undergoes a radical change.

For such substitutions Fisher and Pry put forward a model based on natural competition. Its basic premise is that the percentage rate of substitution of new for old is proportionate to the amount of the old still left to be substituted. The model is inspired by biological populations which grow in proportion to the extent of the ecological niche still unoccupied (2). There are many examples of industrial one-to-one substitutions which corroborate their model.

It was not until several years later that Marchetti and Nakicenovic generalized the Fisher and Pry model to describe the multicompetitor market (3). Their first celebrated example was the substitution among primary energy sources. They considered the successive transitions from wood to coal to oil to gas to nuclear energy. The adapted model was able to handle the evolution of the "market" shares of all energy types simultaneously competing for society's favor.

In Digital we adopted this methodology to better understand the substitution among our products. We built user-friendly flexible software tools to facilitate nurturing scenarios deep into the future. As product life cycles decreased (less differentiated models), we found ourselves having to deal with *families* of products and computer *generations* rather than individual systems.

What is described in detail below is technological substitutions between Digital's older PDP products and the subsequent VAXes. This is done by market segment and the focus is on the low end, the microcomputers. What we learn are valuable guidelines concerning how to deal with what we are now facing: the rising new technology of RISC products (Reduced Instruction Set Computing).

THE LOGISTIC SUBSTITUTION MODEL

In the heart of the Fisher–Pry model one finds natural growth under competition described as:

The rate of growth at any given time is proportional to both the amount of growth already achieved and the amount of growth remaining.

What is presupposed is a final ceiling on the amount of growth, a niche with a finite capacity. This law was first formulated for species populations by Verhulst in the equation (4):

$$\frac{dP(t)}{dt} = \alpha\, P(t)\, [M - P(t)] \qquad [1]$$

where $P(T)$ is the population at time t, and M and α are constants. The solution of this equation is the S-shaped logistic function:

$$P(t) = \frac{M}{1 + e^{-\alpha(t-t_o)}} \qquad [2]$$

The value of M determines the level of the final ceiling, the niche capacity, and the constant t_o locates the process in time (see Fig. 1a).

For fractional one-to-one substitutions, M is defined equal to one (i.e., 100% of the niche), the market share for the new competitor is f, and for the old one it is $(1 - f)$ with

$$f = \frac{P(t)}{M}$$

Equation (2) can then be cast in the form:

$$\ln \frac{f}{(1-f)} = \alpha(t-t_o) \qquad [3]$$

This expression amounts to a mathematical transformation which makes S-curves look like straight lines (Fig. 1b). It is a particularly convenient representation because plotting the ratio of the number of the new to the number of the old reveals the nature of the process. If the points fall on a straight line, it is a *logistic* growth process and represents a *natural* substitution. The scale on the left in Figure 1b (logarithmic) represents the ratio *new/old*. The one on the right (logistic) shows the market shares in percent.

There are several advantages to looking at substitutions in relative terms. One is that there is no longer a dependence on M which, after all may not be constant throughout the process [M was required to be constant in order to solve Eq. (1).] Another advantage is the capability of distinguishing and identifying competitive advantages. External factors, such as seasonality, political crises, and the general economic climate no longer have an impact. The rate of substitution in relative terms reflects purely the "genetic" characteristics which make the new competitor better fit for survival then the old one.

To handle the general case where more than two competitors are simultaneously present in a market, Marchetti and Nakicenovic decided to let the trajectories of fractional shares undergo three distinct phases: growth, saturation, and decline. The growth phase is the logistic substitution described by Eq. (3) which now stops before becoming complete. It is followed by the saturation phase during which the rate of growth progressively slows and, finally, ceases altogether. In the ensuing phase of decline the market share trajectory becomes logistic once again, but this time the competitor is losing ground to a newcomer.

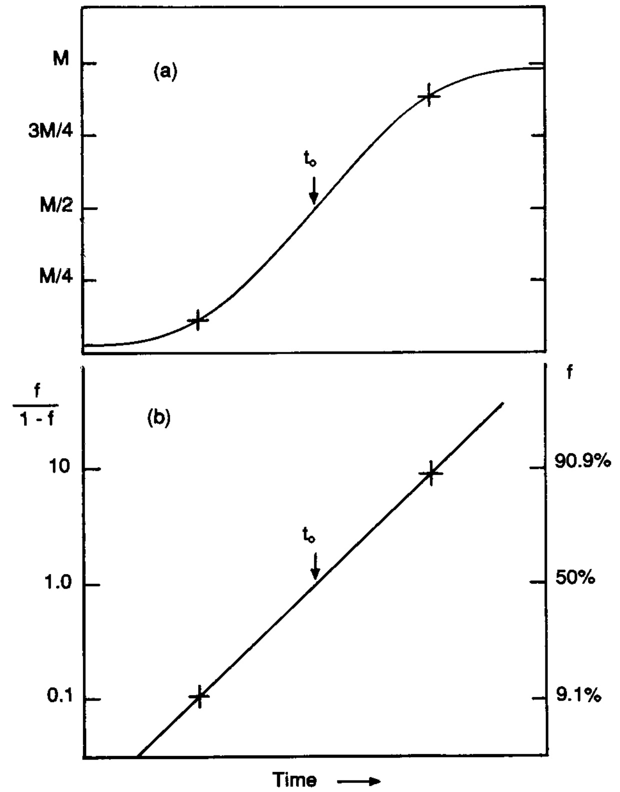

FIGURE 1 Graph (a) plots the function of Eq. (2). Most deviations occur outside the segment delimited by the crosses. Graph (b) shows the transformation from S-shaped curves to straight lines. The scale on the left relates to the ratio "new"/"old," while the scale on the right reveals the values of the fractional share f.

It is imposed that only one competitor is in the saturating phase at any time. Its share is calculated as 100% minus the shares of all other contemporaries, each of which traces out a growing or a declining logistic trajectory. Competitors enter the saturating phase in chronological order and the overall market picture in a semi-log graph takes on the profile of a mountainous landscape. Marchetti's oldest and most favorite example (Fig. 2) is on primary energy substitution worldwide. Such a figure was first published by Marchetti in 1977 (5), he wrote then:

> I started from the somehow iconoclastic hypothesis that the different primary energy sources are commodities competing for a market, like different brands of soap . . . so that the rules of the game may after-all be the same.

The model gave a surprisingly good description over a historical window of more than 100 years. An updated graph (Fig. 2) published some time later (6), reveal that over the last century, wood, coal, natural gas, and nuclear energy have been the main protagonists in supplying the world with energy. More than one energy source has been present at any time, but the leading role has passed from one to the other. Wind and water power provide an amount of energy which represents less than 1% of the total and is not shown in

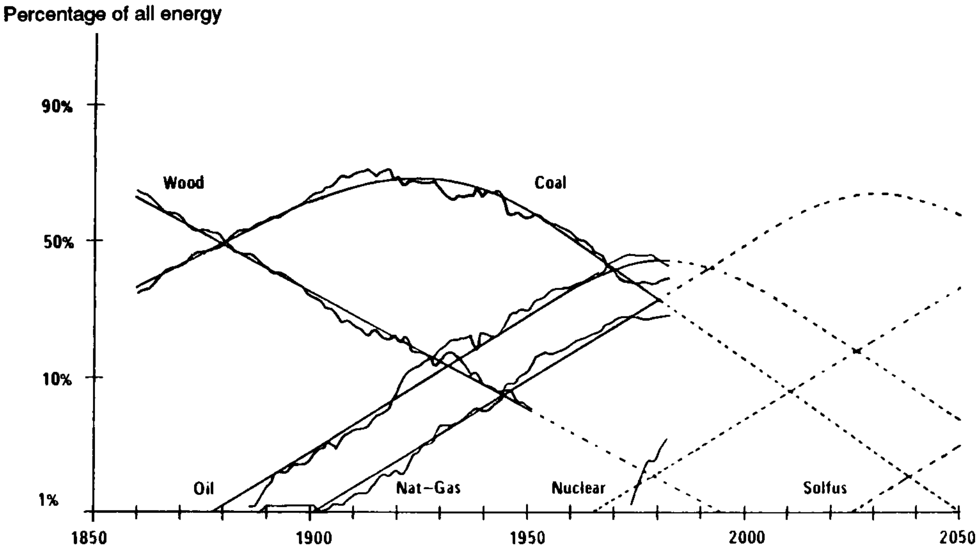

FIGURE 2 Data and substitution model description for the shares of different primary energies consumed worldwide. For nuclear, the dotted straight line is not a fit, but a trajectory suggested by analogy. The futuristic source labeled Solfus may involve solar energy and/or thermonuclear fusion. Adapted from Marchetti and Nakicenovic (6).

the figure, because the simple logistic model breaks down for very small and very large percentages (see next section.)

It becomes evident from this picture that a century-long history of an energy source can be described quite well—smooth lines—with only two constants, those required to define a straight line. The "destiny" of an energy source seems to be cast during its early "childhood," as soon as the two constants describing the straight line can be determined.

The saturating competitor is normally the oldest among the ones who are still growing. Usually it is the one with the largest share, has practically reached maximum penetration, and is expected soon to start declining. The trajectory traces out a curved transition between the end of the growth phase and the beginning of the decline phase. For an industrial product, this phase often corresponds to the maturity phase of the life cycle. It is when competition is keenest. The product has done well, it has attained a dominant position in the market niche, and all other products are trying to chip away on its gains.

The model requires that *one and only one* competitor is in the saturating phase at a given time. This condition is necessary in order to produce a workable model, but it well approximates what happens in a typical multicompetitor arena such as the Olympic Games. Many exceptional athletes all run for the first position, but there is always only one front runner. According to this model, products phasing in and phasing out do not compete with one another; they all compete against the product which is dominating the market.

The predictive power of the logistic substitution model rests with the fact that niches in nature do not remain partially filled (or emptied) for natural reasons. Once a natural process becomes well-established (i.e., it goes beyond the level of infant mortality) its continuation to completion is assured. The market share trajectories of the various competitors can be forecasted (as well as *back*casted.) To be able to construct the future picture one needs the introduction date for each future contender. This can be specified as the time when a significant market share—a few percent—is achieved. The rate of growth (the slope of the straight line) must not change from one contender to the next. The only condition which can perturb this evolution is an ''unnatural'' phenomenon defined here as something of unprecedented nature; a phenomenon that never took place during the historical period.

LIMITATIONS OF THE MODEL

At the extremities of the substitution process deviations from the logistic growth pattern have been observed. As the substitution approaches completion (above 90%) the trajectory pattern breaks into random fluctuations. Similar fluctuations have been observed during the early phases, below the 10% substitution level. These deviations have been explained in terms of states of chaos, which are encountered when the logistic function is put into a discrete form. Discretization becomes essential in order to analyze data via computer programs which employ iterative techniques, but it can be justified theoretically as well, because populations are discrete quantities after all.

Studying the chaotic behavior at the extremities of logistic growth provides explanations for various phenomena mentioned in the literature, such as ''infant mortality,'' ''precursors,'' ''early catching-up effect,'' and ''hunting for the optimum equilibrium level''(7). The main message concerning product substitutions is that a flag of caution must be raised below the 10% and above the 90% level. During product introductions the share trajectory may grow faster than naturally (catching-up effect). Alternatively, a young product which has not yet commanded 10% of its market niche, may not necessarily survive (infant mortality).

In the examples treated below we will see accelerated substitution rates during product introduction. Erratic fluctuations around the 95% level will also be witnessed.

APPLICATIONS IN THE LOW END OF THE COMPUTER RANGE

Here we will analyze technological substitutions among Digital's computer products. Four examples from the low end—microcomputers—are treated in detail. The market is defined as all computer sales of Digital Equipment Corporation in Europe. The data come from Digital's database on order history. For each transaction the price reflects the particular configuration of the system sold. Consequently, systems with different book prices show price distributions which often overlap. Market niches are defined in terms of price bands in which different computer models compete for customers' money. The transitions are in general from the PDP family of products (old technology) to the VAX ones (new technology), but the conclusions drawn can be applied to more recent technology shifts, such as from VAX to RISC.

In Figure 3 we see computer products in the price range $20 to 50K. The first VAX was introduced in the late 1970s, but its average-configuration price was around $350K. Smaller VAX models with lower prices only became available in the early 1980s; this propelled them into competing with the popular PDPs. The substitution started with a

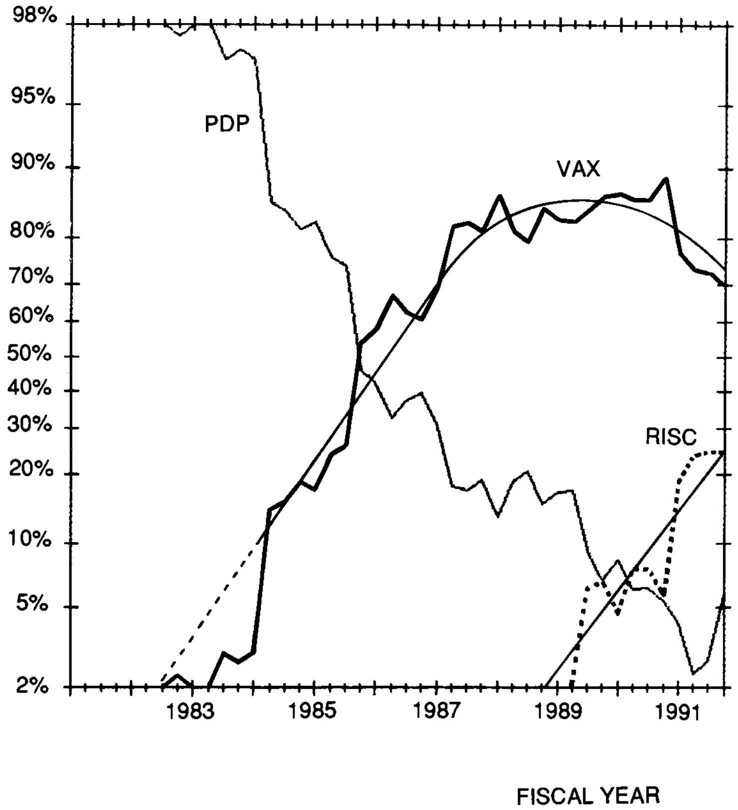

FIGURE 3 Substitution of PDP by VAX products. The market niche is defined as system configurations sold at a price between $20 and 50K. The recent entry of RISC products is also shown. The irregular lines are the actual data, while the thin smooth lines represent the model descriptions.

rather rapid rhythm, but for the most part (10–85%) it proceeded at a slower rate closely following a logistic trajectory (straight line.) It took 11 trimesters for the VAX share to go from 20% to 80%. The model (smooth thin lines) describes well what happened everywhere except during the early 10%, a deviation which can be understood in terms of the discussion of the previous section. The theoretical logistic trajectory starts at $t = -\infty$. When the product finally arrives, a steep early rise can be interpreted as "catching up" for the time lost.

Now again, 8 years later, a new transition is starting from VAX to RISC products and a similar picture starts to unfold.

Figure 4 shows the price range $10–20K. This price band is narrower than the previous one, but the sales volume in it is not smaller because volume increases as price decreases (8). Again the model offers an excellent description of the process. There are differences and similarities when comparing with the previous figure:

The PDP to VAX transition now is more rapid. Along the straight line it takes only six trimesters to go from 20 to 80%. The mid point (50%) occurs two years later.

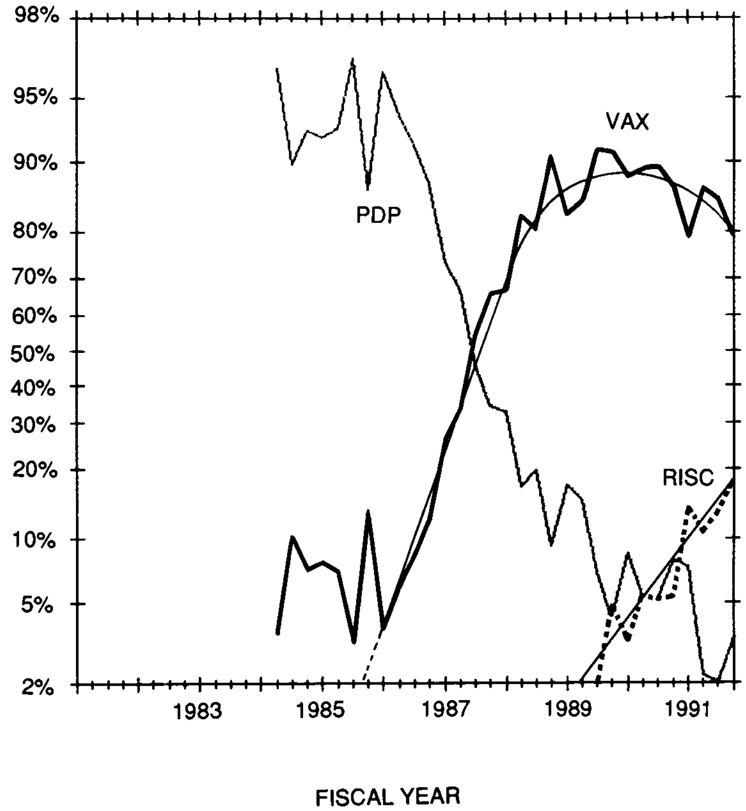

FIGURE 4 Substitution of PDP by VAX products. The market niche is defined as system configurations sold at a price between $10 and 20K. The recent entry of RISC products also is shown. The irregular lines are the actual data, while the thin smooth lines represent the model descriptions.

Again there are deviations below 10% and above 90%, but there is no more significant catching up effect (after all the new technology had already entered this niche two years ago.) There is no evidence that the rate of the VAX to RISC transition has changed.

These observations are reinforced in Figure 5, the lowest price band, for systems with an average-configuration price of less than $10K. The substitution PDP to VAX proceeds even faster (3.4 trimesters to go from 20 to 80%; the mid point is even later, and again no catching-up effect to speak off, only the usual fluctuations above 90%. Once more there is no significant change for VAX to RISC.

One may conclude that a progressive increase in the rate of substitution is correlated with time *and* with a decreasing price. However, correlation does not necessarily imply causality. Are these relationships, in fact, causal?

To answer this question we must consider the issue of software compatibility. PDP software applications did not run on VAXes. Consequently, a user had to rewrite an application before it could be used with the new technology. This is the reason for which later products diffused faster. Their penetration rate was positively influenced by the availability of more software packages.

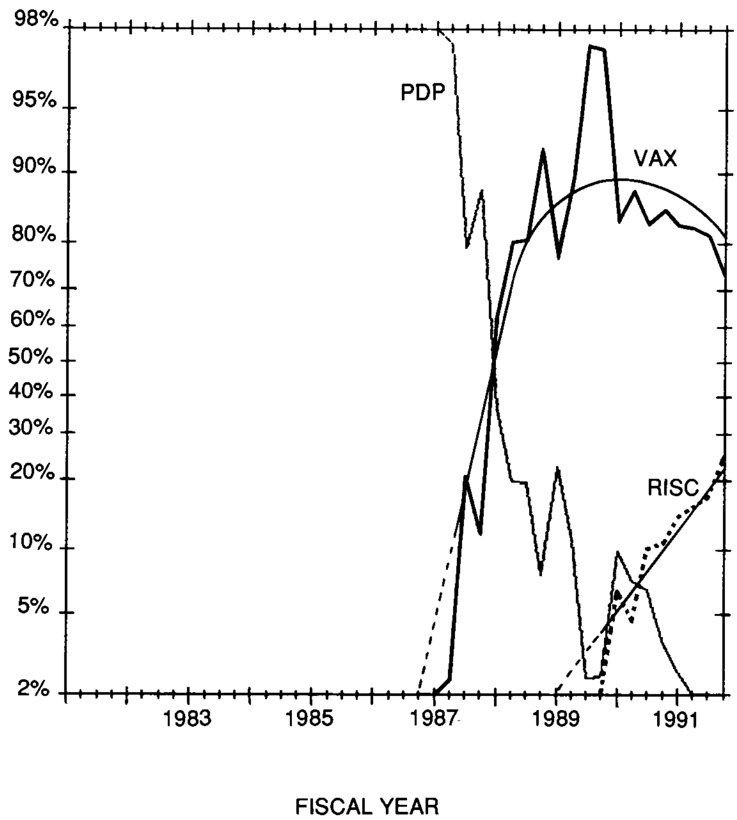

FIGURE 5 Substitution of PDP by VAX products. The market niche is defined as system configurations sold with a price below $10K. The recent entry of RISC products is also shown. The irregular lines are the actual data while the thin smooth lines represent the model descriptions.

There is evidence in support of this conclusion:

1. The newer technology, RISC, which is as different from VAX as VAX was from PDP (in the sense that there is again software incompatibility), proceeds with the same slow rate in all three price bands examined. This rate is very similar to that of the very early PDP to VAX substitution (1985).
2. *Compatible* computer models substitute each other rapidly even at a higher price. Figure 6 shows a microniche where MicroVAX II substituted the VAX 11/750 in a price-overlapping range ($50–180K). The substitution goes from 20 to 80% in 3.5 quarters just as it finally did for PDP to VAX (1987).
3. At Digital we have observed much larger systems (minis and superminis) also go through the bulk of a substitution process over one year as long as there was compatibility of software. (VAX to VAX).

Attention must be drawn to the fact that compatibility must not be restricted to software. Software was the main factor in the examples mentioned earlier. However, compatibility of peripherals, storage devices, and other installations all influence the rate of substitution in a similar way.

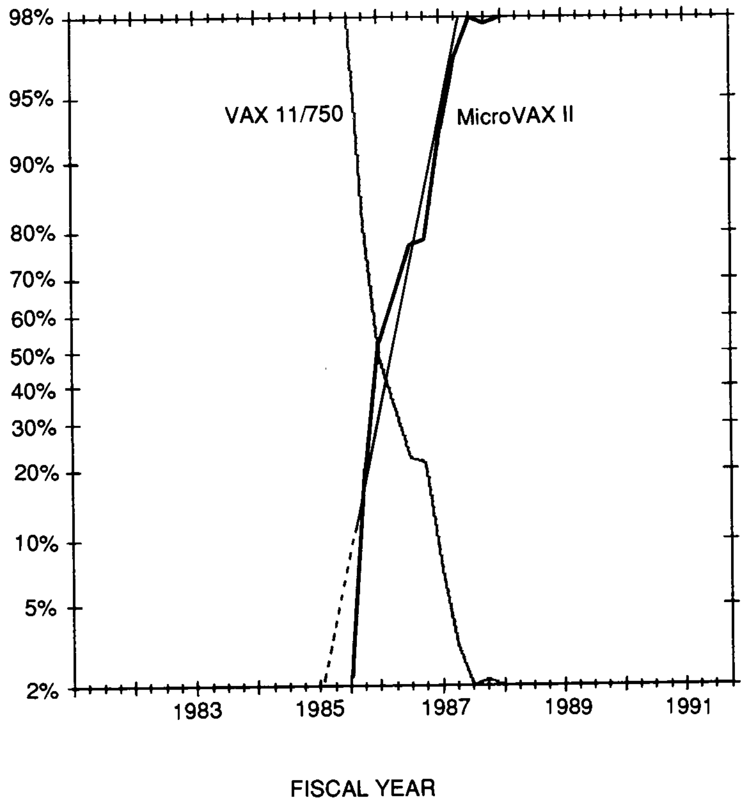

FIGURE 6 Substitution of the VAX 11/750 by MicroVAX II. The market niche is defined as all configurations of these two computer models sold at a price between $50 and 180K. The irregular lines are the actual data while the thin straight line represents the model description.

CONCLUSIONS

The major part of a competitive substitution between products, families of products, and computer technologies is well described by a *logistic-growth* process. Contrary to what one may intuitively expect, the rate of such a substitution does not depend on the price of the transaction. All new-technology computer models which have penetrated the market niche to 10% have proved their competitive advantage and will continue diffusing with comparable rates. Their diffusion will be hampered only by the degree of incompatibility with the previous technology. The replacement of PDPs by VAXes took around three years before it reached the substitution rates later observed among VAX products themselves.

Compatibility among computers mostly concerns software, but peripherals and other accessories can play a similar role. Under full compatibility, a new technology which becomes established (one which survives infant mortality) will pass from a 20% market share to an 80% one in less than one year. This transition can be up to three times slower for incompatible products.

During the early phases the substitution rates are different. The fully compatible idealized transition requires one trimester to pass from 10 to 20%, but also one trimester to pass from 5 to 10%. Moreover, there are deviations to be expected. An accelerated growth rate may be witnessed as a catching up effect, or erratic fluctuations may appear similar to those seen when approaching the ceiling (above 90%).

Despite these uncertainties the logistic substitution model can be used to understand the competitive dynamics. It can also be used to forecast market shares, but this was not done in Figures 3 to 6 as it fell outside the scope of this article. Such forecasts must be supplemented with added value from marketers, thus becoming a company's internal affair. What must be emphasized here is that this methodology conceived by Fisher and Pry and generalized by Marchetti and Nakicenovic is unquestionably a valuable one.

REFERENCES

1. Fisher, J. C., and Pry, R. H., A Simple Substitution Model of Technological Change, *Technol. Forecast. Soc. Change*, *3*: 1971, pp. 75–88.
2. A special form of Pearl's law; cf. Raymond Pearl, *The Biology of Population Growth*, New York: Alfred A. Knopf, 1925, as cited by Fisher and Pry, ref. *1*.
3. Nakicenovic, N., Software Package for the Logistic Substitution Model, *RR-79-12*, IIASA, Laxenburg, Austria, 1979.
4. Verhulst, P.-F., Notice sur la loi que la population suit dans son accroissement, *Corres. Mathématique et Physique*, *10*: 113–121 (1838).
5. Marchetti, C., Primary Energy Substitution Models: On the Interaction Between Energy and Society, *Technolog. Forecast. Soc. Change*, *10*: 345–356 (1977).
6. Marchetti, C., Infrastructures for Movement, *Technol. Forecast. Soc. Change*, *32* (4): 373–393 (1987); and Nakicenovic, N., Growth to Limits, Long Waves and the Dynamics of Technology, doctoral dissertation an der Sozial-und Wirtschaftswissenschaftlichen Fakultat, Universitat Wien, 1984.
7. Modis, T., and Debecker, A., Chaos-Like States Can Be Expected Before and After Logistic Growth, to appear in *Technolog. Forecast. Soc. Change*, 41(2): 111–120 (1992).
8. Bagwell, P., and Modis, T., Price Elasticity and Market Trends in the Computer Industry, *J. Mktg.*, *Rev.* (submitted for publication).

THEODORE MODIS