A Dynamic Model of Technology Diffusion

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Abstract

The diffusion of new technologies into the market is a critical factor in the success of any technology-based company. This paper describes a system dynamics model which integrates a number of key concepts presently used to understand the diffusion process (e.g., technical progress functions, cost-experience curves). It shows how these concepts, together with management decisions regarding R&D investment, marketing, and pricing, drive the evolution of diffusion between technologies. It then illustrates how simulation can be used to understand the critical success factors in technology diffusion, and what this means for the management of technology-based companies.

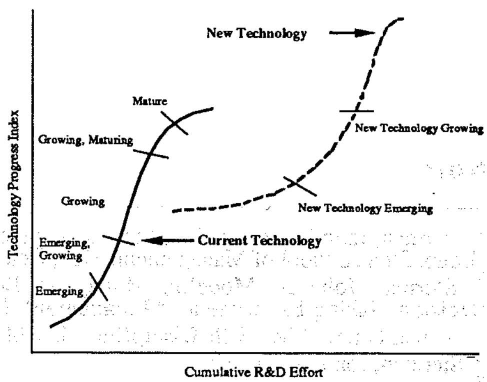
Introduction

Successfully introducing a product based on a new technology can give a company a significant advantage over competitors, both in terms of the opportunity to define the standard for that generation of technology, and in terms of the ability to drive down costs ahead of the competition. However, being market leader also comes with significant risks: introducing a technology before the market is "ready" will yield slow sales growth, and potentially allow competitors to leap-frog your technology with the next generation when customers are finally ready for improved technical performance; introducing too early can also prematurely reduce the sales and profits on the last generation of technology, and trap the industry in a cycle where the costs of the last generation are not recovered before the next generation is introduced. Determining how much to invest in developing the next generation of technology vs. improving the current generation, when to introduce a new generation, how much to spend on marketing, and how to price the product are all critical management decisions affecting success or failure.

A number of techniques and tools have been developed to improve technology forecasting and assessment. For example:

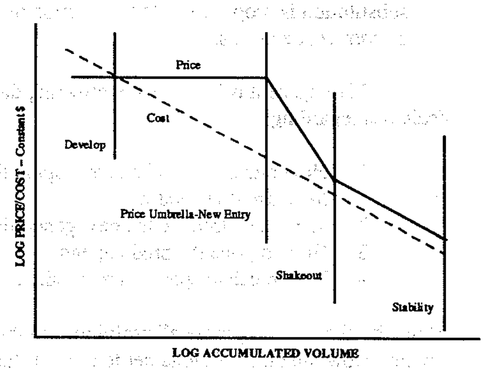
1. Technological Progress or S-Curves -- As illustrated in Figure 1, these curves describe the evolution of technical performance as a function of cumulative R&D effort; for any given technology, relative technical performance follows an S-shaped pattern, starting low and growing slowing as initial R&D effort takes time to bear fruit, then increasing rapidly with further effort, until finally diminishing returns begin to set in; at some point, the industry moves to a new generation technology, the performance of which also follows an S-Curve; note that the initial performance of the new technology can and is often less than the ultimate performance of the prior technology. Technological progress curves help managers understand and forecast the maturity of a technology as a guide to R&D investment decisions.

Figure 1 Technological Progress or S-Curves



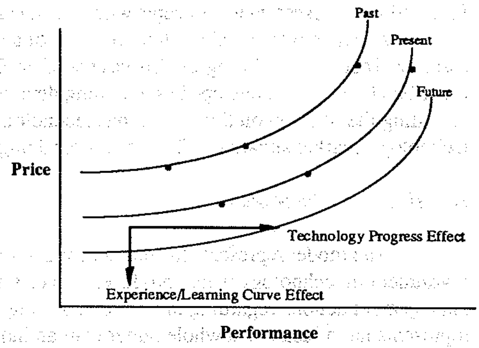
2. Cost-Experience Curves -- As illustrated in Figure 2, these curves describe the behavior of costs as a function of cumulative production volume; they reflect the product, process, and organizational learning that drives down costs as experience accumulates. Cost-experience curves influence a company's pricing strategy. A company must balance the market share impact of reducing prices as costs fall against the need to improve profit margins in order to recover investments.

Figure 2 Cost-Experience Curve



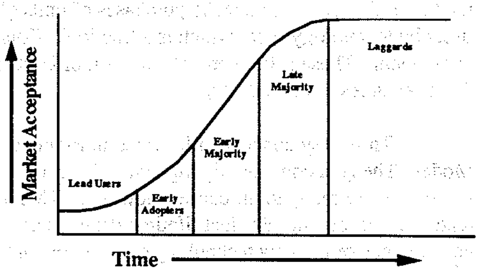
3. Price-Performance Curves -- Price/performance curves depict the tradeoff that exists at any point in time between price and technical performance. As illustrated in Figure 3, over time the tradeoff curve will move down and to the right as a result of cost-experience effects (lower price for same performance) and of technical progress (improved performance for same price). Price-performance curves evolve from management decisions regarding R&D investment and pricing, and from the shapes of the Technical Progress and Cost-Experience Curves. Price-performance is one driver of market acceptance of new technologies.

Figure 3 Price-Performance Curves



4. Diffusion or Product Life Cycle Curves -- As illustrated in Figure 4, diffusion curves describe how sales of a new product or service evolve over time. Diffusion curves are also S-shaped, as at first only lead users are willing to adopt a new technology, then as price drops and performance improves, more and more users switch to the new technology. Eventually, sales slow as laggards are the only remaining non-users. Diffusion curves are used to guide the introduction of new technologies.

Figure 4 Diffusion or Product Life Cycle Curve



5. Substitution Curves -- These curves graph the diffusion curves for succeeding generations of products or services. When sales of a new product will start, how fast the product gains market acceptance, and what its ultimate level of acceptance is (before the next generation makes inroads) depends on many factors, including the price-performance tradeoffs and how management markets the new technology.

6. Fisher-Pry Technique -- A means of estimating a substitution curve based on the assumption that the rate of substitution is proportional to the fraction of the older one still in use. This technique is used to guide investment decisions.

Management is interested in affecting the substitution curves to the company's best advantage through decisions regarding:

1. How much to spend on developing the next generation technology vs. improving the performance of the current generation;
2. When to introduce the next generation;
3. How to price the product; and
4. How much to spend on marketing.

While the above concepts are all useful toward that end, they only describe possible behavior of pieces of the system. How the pieces fit together to drive diffusion, and how alternative strategies can affect that process, has been left to managers intuition and "mental models."

Therefore, a system dynamics model was developed which integrates these common technology forecasting and assessment concepts with key management decisions and with market characteristics and responses. The model simulates the evolution of technologies (Diffusion and Substitution Curves), based on assumed Technological Progress Curves and Cost-Experience Curves, and on management actions. The model described herein was developed as a training device. We are in the process of using the model to develop heuristics regarding the likely evolution of various technologies, and the best management actions depending on the technology-market situation. The process for doing this is illustrated in the concluding section of this paper.

Description of the Model

The model represents the market for a given product or service (e.g., television sets, computers), the investment in technology which produces succeeding generations of products to serve this market, and management actions regarding investment, pricing, and marketing. At this stage of development, the model represents an industry as a whole rather than an individual company.

Figure 5 shows the major elements of the model (Figure 5 omitted because of space constraints; see Figure 6 instead). The key stocks and flows in the market are shown in the middle of the figure. For simplicity, there are only three generations of technology: T1 represents the first/current generation; all users start with technology T1. Over time, users can convert from T1 to T2 and ultimately T3, or they can bypass T2 completely and jump to T3. "Users" is here defined as a fraction, so at any point in time the sum of Users of T1, Users of T2, and Users of T3 must equal 1.0. The critical area of the model determines the conversions between generations of technology. At the top of Figure 5, users make purchases of units ("sales"). Sales by technology type depend on total demand and users by technology type (which is a fraction). Total demand consists of a growth component and a replacement component. These sales then enter a stock of Units in Use (by technology type), and are eventually retired. Sales drive revenues to the industry.

Three key concepts, illustrated in Figure 6, are represented in the Technology Evolution and Diffusion Model. The first concept, highlighted in Section A, is that users are ready to convert ("potential conversions") when they are ready to purchase a new unit. This occurs when a new user enters the market, or when a unit is ready for retirement. Product lifetime depends on a normal lifetime, which can be reduced if user needs and the performance of the new technology obsolete the old technology.

Actual conversions then depend on potential conversions and the second key concept, "willingness to switch" (see B of Figure 6). Users' willingness to switch is first a function of relative price and relative performance: the higher the relative performance of a new technology and/or the lower relative price, the more willing are potential users to switch to the new technology. Price is described further below. Technical performance depends on cumulative R&D spend on a given technology (refer back to Figure 5). The Technical Performance Index for each technology as a function of Cumulative R&D is an input assumption in this model.

Willingness to witch based on price-performance is then modified by the effect of perceived risk: if the risks are high, willingness to switch is less than that indicated by price and performance. Three factors affect perceived risk: (1) users inherent risk aversion; (2) switching costs; and (3) lack of standards for the technology. Inherent risk aversion reflects the fact that not many people are willing to try something new until they see lots of other people using it. They are not sure it will work as promised; they do not want to be stuck with a product that never gains broad acceptance; and so on. Hence, the more users of the new technology, the lower the perceived risk. Marketing can also reduce inherent risk by rapidly spreading the word about existing users, and by overcoming concerns that the technology does not work as promised. High switching costs also increase risk. Switching costs here represent real dollar outlays, and implicit costs such as changes in procedures, required to use the new technology. For example, switching from tapes to CD's requires purchase of a CD player; changing from mainframe computers to PC's requires changes in procedures for control of software and access to information. Again, as the new technology proliferates, switching costs will likely fall as supporting technologies and procedures are developed and fall in price. Lack of standards occurs when several competing versions of the new technology are developed and marketed (e.g., VHS and Beta). Many users are therefore unwilling to convert to the new technology because of the risk of picking the losing standard. As the technology matures and the number of users grows, requirements for a standard force one to develop, and risk diminishes.

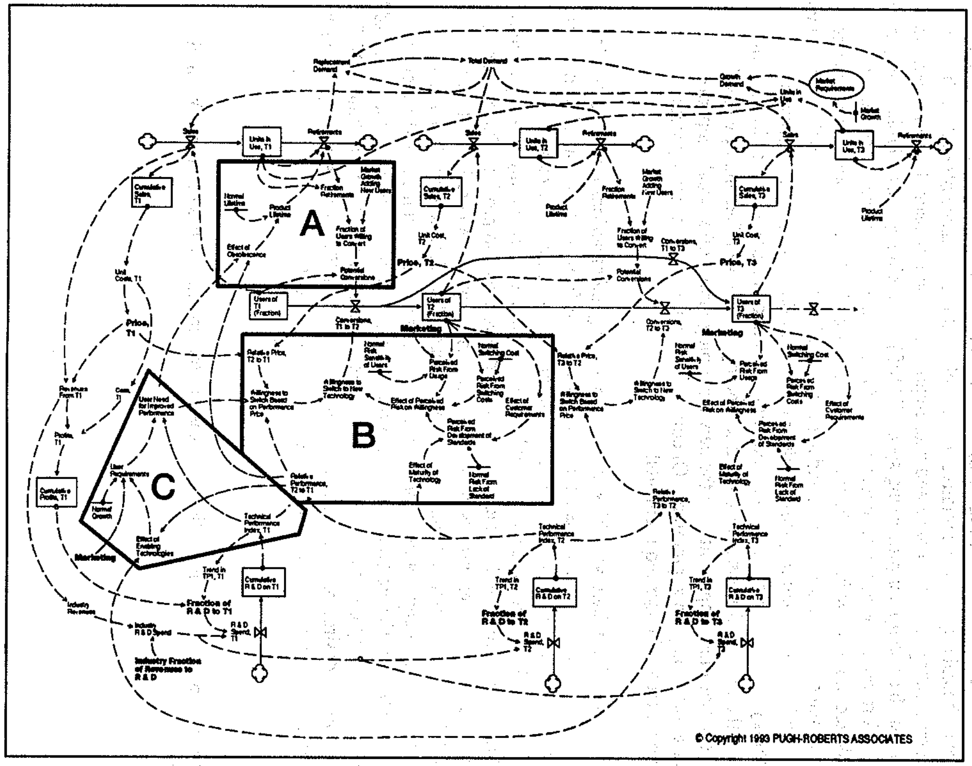
The third key concept in this model (see C of Figure 6) is that of "user need for improved performance." User need depends on the users technical requirements relative to the technical performance offered by the old technology. In this general model, technical performance and user requirements are measured by an index. In an actual application, real concepts such as computer processing speed (MIPS), switching speed and reliability, and so on, could be used to measure performance. When user requirements for technical performance exceed the technical performance of the old technology, we have a "market pull" situation. In this situation, users become more interested in relative performance than relative price, and are more willing to switch even in the face of high prices. Further, users are more willing to prematurely discard their current products to get the improved performance of the new technology. Hence, retirements and potential conversions increase. In a situation in which user requirements are less than the performance of the old technology, we have a "technology push" situation. Here relative price becomes more important, and the new technology must offer vastly superior performance to the old in order to offset any price premium. Of course, especially for consumer products, marketing can create a perceived increase in user requirements!

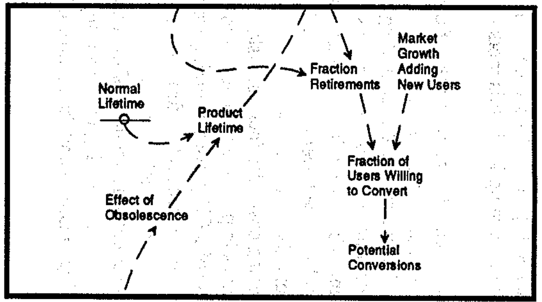
Finally, referring back to the highlighted variables in Figure 5, management actions tie the parts of the system together. (Note also that each of the key concepts applies to conversions from T2 to T3, and T1 to T3 as well.) Cumulative sales (as a proxy for production) drive unit costs through an assumed cost-experience curve. Management must then set prices based on unit costs and profitability considerations (including earning a return on prior R&D investments). Pricing influences willingness to switch, and revenues and profits. The amount and allocation of R&D spending depends on revenues, profits, and technical performance. A certain fraction of industry revenues is spent on all R&D. The amount of this total spend allocated to Technology T1 depends on trends in T1's technical performance and on cumulative profits on T1: as long as T1's technical performance continues to improve, and if cumulative profits are below desired profitability, the industry will allocate most R&D to T1; but as T1's technical performance improvement slows (no longer receiving benefits from continued R&D), and as cumulative profits hit or surpass desired return, less and less will be spent on T1. As described previously, marketing spend can reduce perceived risk, and increase perceived user requirements.

Base Model Behavior

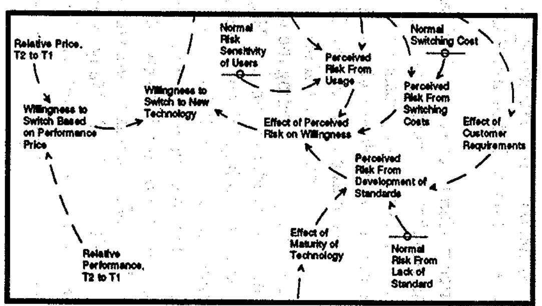
The first step in defining a "Base Case" simulation is to specify the characteristics of the market and technology being represented:

Figure 6: Key Concepts in the Technology Evolution and Diffusion Models

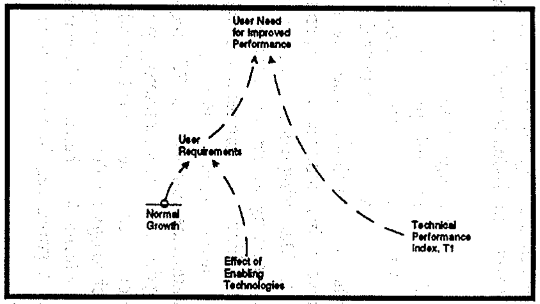




A: Potential Conversions



B: Willingness to Switch



C: User Need

Market Characteristics --

- Rate of growth in demand
- Average product lifetime
- Initial user technical performance requirements and rate of growth in requirements
- Normal risk sensitivity from "newness", switching costs, and lack of standards

Technology Characteristics --

- Technical performance index (for each technology, as a function of cumulative R&D)
- Cost-experience curve (for products from each technology, as a function of cumulative volume)
- Relative production and other costs of products from succeeding generations of technology (before the experience effect)

In this example, the market grows at 10% per year, with a 5-year product lifetime. User technical requirements are set such that the performance of the technologies slightly exceeds need. Hence this is somewhere between pure market pull and technology push situations. The market's risk sensitivities are set in the middle range between a very high sensitivity and a low sensitivity. Technical performance indicies are illustrated in the output below (Figure 7). The required R&D spend to get this performance is assumed to be: for T2, twice that for T1; for T3, three times that for T2. Costs are assumed to fall by 20% for every doubling of volume, with the normal cost of products from each succeeding generation assumed to be the same.

As illustrated in Figure 7, at the start of the simulation in 1990 the technical performance of T1 is approaching its maximum level. However, T1's performance is somewhat above user requirements until nearly 2000. In 1996, as progress on T1 slows and because investment has been recovered, the industry begins investing in T2, but it is not until the year 2002 that the performance of T2 surpasses that of T1 (and user requirements). The industry starts investing in T3 in the year 2008, but it is not until about 2014 that T3's performance surpasses that of T2. For the most part, the technical performance of the available technologies slightly exceeds user performance.

Figure 7 Technological Progress Index

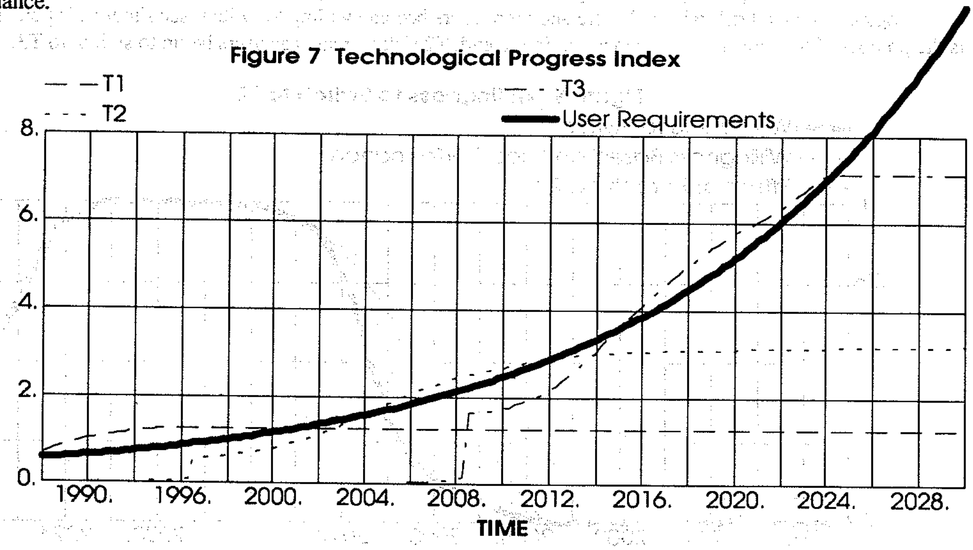
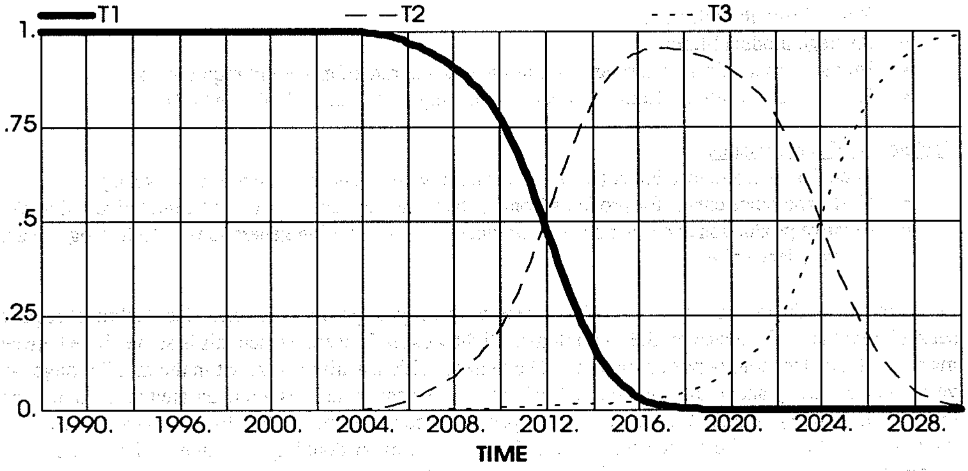


Figure 8 shows the diffusion of the three technologies over time (substitution curves). All of the users stay with technology T1 until 2004. At that time, the technical performance of T2 surpasses that of T1, and users begin to switch. The substitution occurs at an accelerating pace until around 2012, at which point many users have switched from T1 and the rate of gain for T2 progressively slows. By 2017, the fraction of users with T2 peaks and begins to decline as users begin to switch to T3 (because the technical performance of T3 surpasses that of T2 at this time). Substitution from T2 to T3 follows the expected S-curve, reaching completion in 2030.

Figure 8 Users by Technology Type (Fraction)



Willingness to switch from T1 to T2, shown in Figure 9, increases from zero starting in 2004. The increase is initially driven by price-performance. As shown in Figure 7, the performance of T2 surpasses that of T1 at this time, and while T2 is substantially more expensive than T1 (see Figure 10), user requirements also exceed T1's performance and some early risk-takers are convinced to switch technologies. Then, a number of feedback loops accelerate the improvement in willingness to switch: (1) as T2 volumes increase, unit costs and prices decrease, thereby improving price-performance; (2) continued investments in T2 R&D drive up T2 technical performance, further improving the price-performance tradeoff; and (3) as more and more users switch technologies, perceived risk falls and more and more users become willing to switch (see Figure 11; perceived risk is the product of the three risk components). In the end, T2 risk increases as users begin to switch to T3.

Figure 9 Willingness to Switch to T2

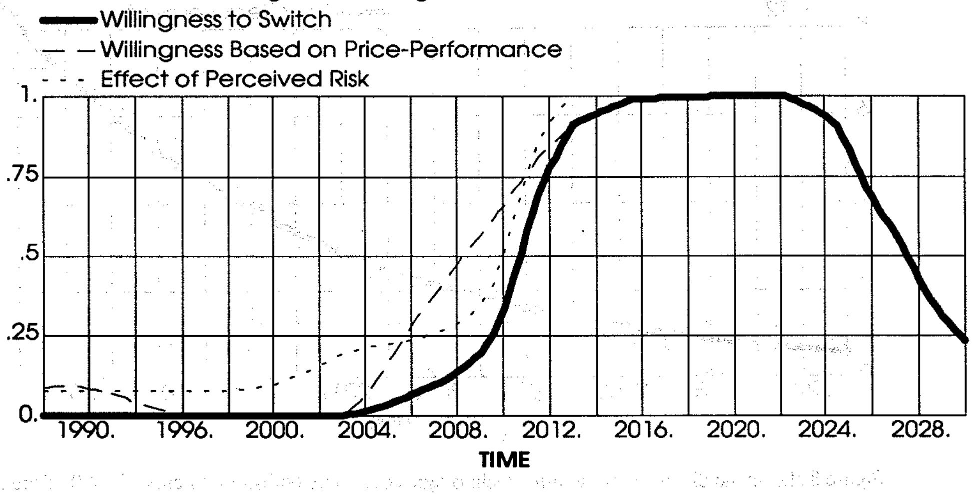


Figure 10 Price

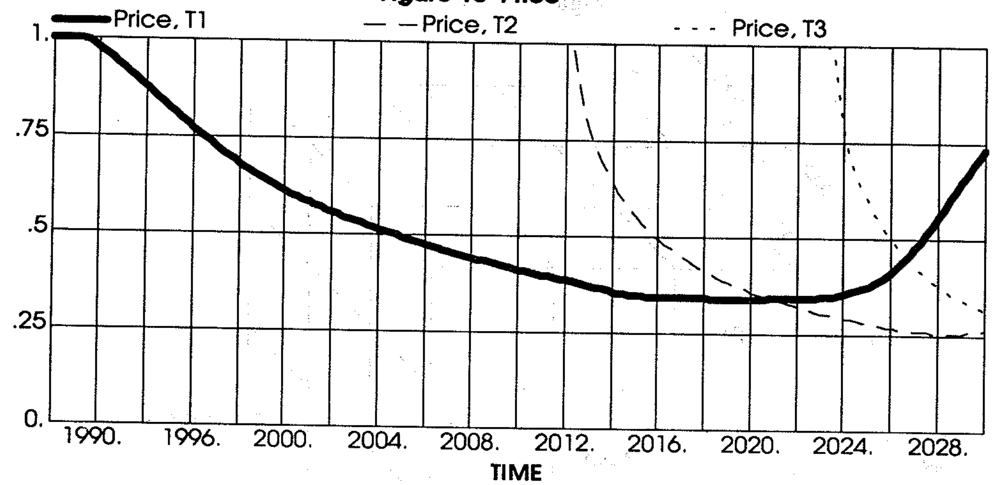
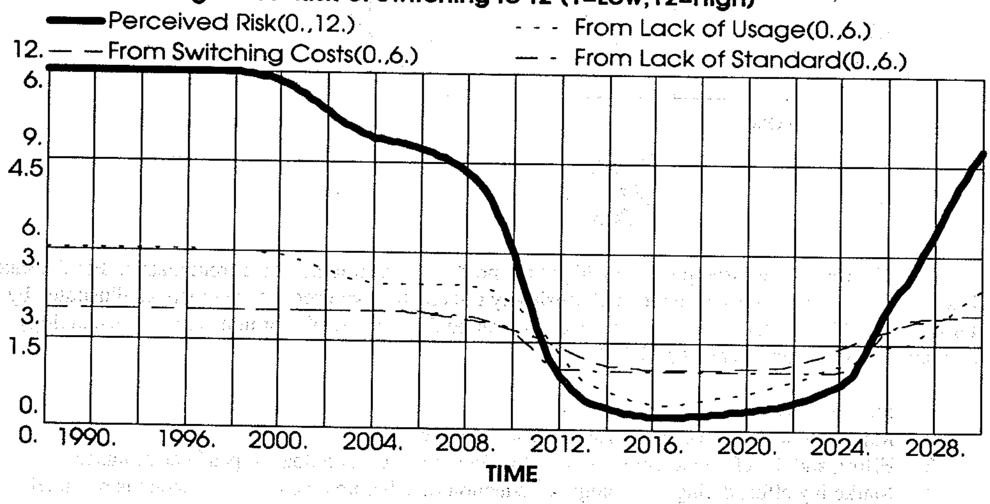


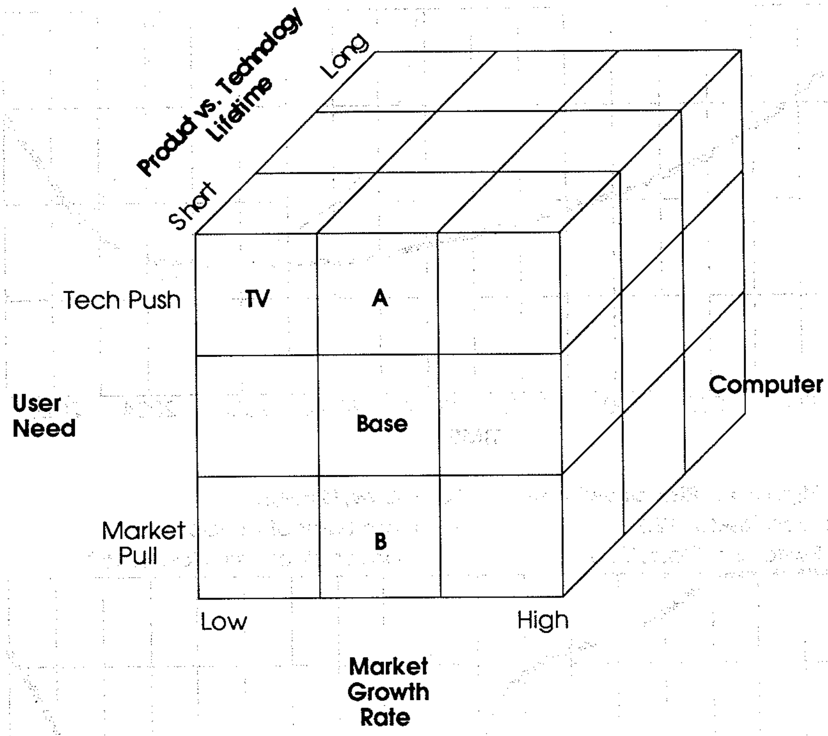
Figure 11 Risk of Switching to T2 (1=Low,12=High)



Understanding the Critical Factors in Technology Diffusion

As at this stage the generic model is primarily a learning device. Its principal purpose is in determining heuristics regarding the most critical factors affecting the successful diffusion of downstream technologies, and in particular how management actions can improve performance. It seems likely that different factors may be more or less important in different market situations. The matrix illustrated in Figure 12 captures a possible range of environments. Three factors are assumed to vary: (1) user need (i.e., technology push vs. market pull); (2) market growth rate (the higher the growth rate, the more new users there are relative to replacement users, and therefore the higher the willingness to switch to a new technology); and (3) product lifetime vs. technology lifetime (the shorter the technology lifetime relative to the product lifetime, the more critical the timing of technology introduction relative to the replacement cycles becomes). As an example, we might imagine TV's being in the upper left box (technology push, relatively low market growth rate, and short product life relative to technology life). In contrast, personal computers may be in the back right corner (market pull, high market growth, and long product life relative to technology life).

Figure 12 Scenario Matrix



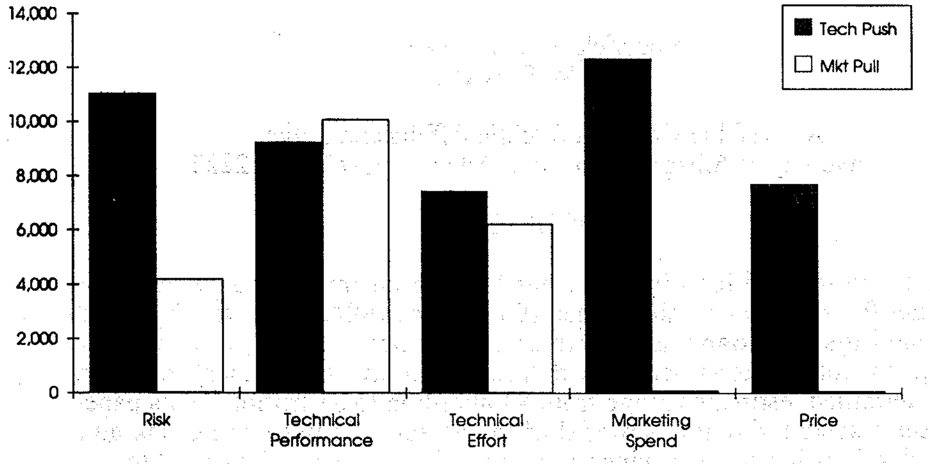
The Base Case assumptions would put the product in the middle of the front matrix. For the sake of illustration, we have conducted a range of sensitivity tests on the two user need alternatives illustrated by A (Tech Push) and B (Market Pull). In these tests, we have varied 5 factors by plus or minus 25% (3 technology assumptions and 2 management policies):

1. Inherent risk level of users
2. Maximum technical performance of the technology
3. Effort, and therefore the time, required to bring the new technology to peak performance
4. Marketing effort during technology introduction (i.e., before revenue-based spend is practical)
5. Initial product price (i.e., before enough investment has been recovered to switch to cost-based pricing).

The results of these experiments are summarized in Figure 13, which compares the differences in volume for Technology T2 between the +25% case and the -25% case for each of the five factors. The higher the line, the more sensitive volume is to changes in either the input assumption or to the management policy. These results indicate that:

1. Technology diffusion is almost always less sensitive to technical uncertainties, risks, and management actions in a market pull environment than in a technology push environment.
2. Marketing and pricing are much more critical factors in successful diffusion in a technology push environment than in a market pull environment.
3. Technical performance is the most important factor in a market pull environment (ability to satisfy user need is the primary factor determining which technology succeeds).
4. In general, achieving higher technical performance is somewhat more important than the effort (cost and time required) of doing so.

Figure 13 Variations in Cumulative Volume, Technology T2



While these observations are based on a limited set of experiments, should they hold up under more rigorous testing they point to several guidelines for managers:

1. The technology push situation requires the greatest balance among technical, marketing, and pricing policies, but marketing and pricing are critical determinants of success: marketing because it can create a perceived need for the product and because it can reduce perceived risk; pricing, because given the relative lack of need for a "better mousetrap," price becomes the dominant factor in the price-performance tradeoff. Therefore, prices should be set relatively low, and investments recouped over a longer period (and because the next generation technology is not needed, this generation should have a longer life to earn back the investment).
2. In a market pull environment, success is enhanced by getting the best technical performance, as fast a possible. Once in the market, the product will sell itself. Prices can and should be set relatively high in order to recoup investments before the next generation of technology is ready (the next generation is likely to diffuse rapidly, and therefore limit the period over which investments can be recovered).

Further Work

Several parallel activities are in progress:

1. Further sensitivity and policy analyses to more rigorously identify the key factors in the diffusion of new technologies and to develop guidelines for management policies;
2. Development of case studies and a numerical data base to illustrate the diffusion concepts and policy guidelines; and
3. Applications of the model to current technology decisions.

As this work progresses, a body of empirical results together with the simulation model will provide managers with valuable tools for determining strategies for investment in and marketing of new technologies. By drawing on the case studies and heuristics, it should be possible to quickly classify a new technology along critical performance dimensions (e.g., user need, rate of market growth, product vs. technology lifetime), develop management guidelines, and then set up the model to adapt these guidelines to the new situation. Further, the model can be modified to represent alternative situations. For example, technologies T2 and T3 could represent competing solutions for the next generation technology, and more technologies added downstream (T4).