# TECHNOLOGICAL SHIFT: A CYBERNETIC EXPLORATION

Jennifer M. Robinson

October 1979
WP-79-104

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

# PREFACE

The innovation process, defined here to incorporate the full cycle from invention to full commercialization, is slow. It cannot be encompassed with time horizons of less than 20 years. Many innovations require half a century or more to reach commercial maturity.

Management of the innovation process is critical to the management of technology, but the slowness of the process makes it difficult for conventional economists or policy makers, who typically consider 15 years a long-term forecast or plan, to understand or control.

The situation, in short, is one in which the absence of theoretical understanding limits the effectiveness of managerial practice. Accordingly one appropriate niche for applied systems analysis in this case is development, application and testing of theoretical models.

Toward this end the innovation task of IIASA's Management and Technology Area is studying the mechanisms of technological substitution. One phase of this work is being conducted through construction and analysis of dynamic simulation models.

The present paper describes TECH1, the first of these models. TECH1 is generic and views technological substitution as the interaction of product and process improvements (learning) and capacity acquisition under circumstances of market competition between an old and a new technology. Accompanying working papers, entitled "Technological Shift: A Graphical Exploration of Progress Functions, Learning Costs and Their Effects on Technological Substitution" and "Technological Shift: as Related to Technological Learning and Technological Change" develop concepts derived from TECH1 in, respectively, graphical and philosophical terms.

Discussion of TECH1 with colleagues from socialist countries suggests that the model could be made more descriptive of technological substitution through making price and investment respond in non-smooth fashion to both exogenous policy goals and to extended product delivery waiting times (or inventory pile-ups) resulting from disequilibria of supply and demand. TECH2 will be developed to take these structural features into account and will be described in a later working paper.

Another likely extension of this work is case application. If time permits the model will be adapted to describe four historical incidences of technological substitution.

In the first six months of 1980 the entire series of working papers will be collected into a IIASA Research Report. Various parts of the series are being adapted for separate journal publication. The author welcomes comments, questions, criticisms and suggestions on this or any related work.

## CONTENTS

# TECHNOLOGICAL SHIFT: A CYBERNETIC EXPLORATION

## INTRODUCTION

The following text describes TECH1, a dynamic simulation model of technological shift. The model is a conceptual device developed to attempt to explain why rates of technological substitution vary and how they can be controlled. It is also a vehicle for integrating partial theories and observations pertaining to technological innovation, for fitting learning curves into a dynamic conceptualization of technological substitution, for describing technological substitution in microeconomic terms and for describing some of the ways in which macroeconomic influences affect the microeconomic processes by which technological substitution takes place.

Like all models, TECH1 is a simplification. Like most, it could use further testing and application. Its structure does not describe all technical substitutions equally well. Interdependent substitutions, such as the co-occuring substitution of shield supports for pillar supports and adoption of continuous, automated coal mining techniques, are poorly described by the model. Likewise, shifts in agricultural or silvacultural techniques in which land is transferred from one activity to another, do not conform to the assumed structure. Nonetheless, the model has greater descriptive power than prevailing models of technological substitution; and should be a useful conceptual base for looking at the technological substitution process.

After further development, testing, criticism, and analysis a TECH2 or a TECH3 may be useful for policy purposes, in the sense that enhanced systematic understanding of the causal mechanisms involved in technological substitution should lead to more effective policy control of the process. For example, the model I am aiming for could help to develop practical, reasonable rules of thumb about the sorts of innovations that will respond to specific policy measures and the point in the life cycle of an innovation at which policy intervention will have the most impact, or to deeper understanding of the influence of macroeconomic conditions on technological substitution.

TECH1 is not intended as a predictive device. If one wishes merely to predict patterns of technological substitution rather than to explain or control them, logistic curve fitting of the sort developed by Fischer and Pry (1970,71) and extended at IIASA by Peterka and Fleck (1978) will be a much simpler and more elegant approach.

## Problem Focus

The cards are stacked against an invention becoming an innovation and most attempted innovations fail. Start up is an uphill battle. To be accepted by management a new technology must be efficient. To become efficient it needs both operating experience--getting rid of original design errors, training staff and generally debugging the system--and capital, to scale up to efficient sizes and to sustain the losses incurred during plant construction and operational debugging. Capital, however, is not easily acquired by a would-be innovation whose efficiency is unproven. Perhaps at the onset someone will fund the attempt as an experiment. But suppose, as often happens, ten years is not long enough for the thing to show a respectable profit. Who will invest then? Who will invest on the scale needed to make the system work?

Most innovations are confronted with this quandry, but they vary greatly in how they survive it. Many innovations never succeed. Some take off the same decade they are invented. Others sit dormant for decades or even centuries until something happens to allow them to get over the hump and become commercialized. Some of this variation is chance. TECH1 investigates the possibility that a major portion of the variation in patterns of innovation take-off is a predictable consequence of factors such as:

- how well the existing technology is established and how well it satisfies consumer needs,

- whether consumers are sufficiently attracted to the innovation to buy its initial products, despite probable high price and unimproved quality during the start-up period,

- how adventurous the economy is about funding new operations,

- the existence and the magnitude of potential production cost advantages brought about by the new technology; and
- how difficult and expensive it is for the new technology to get through the debugging and scaling up stages.

## Overview

### Lay-out

In TECH1 technological substitution is viewed as competition between two production systems. The two have identical cybernetic structures. Their different technical and life cycle characteristics are represented by variation of parameters within the common structural form. This is to say, the same mechanisms govern the growth and reproduction of both technological structures, but the relative strengths and weaknesses of the mechanisms involved varies with the technical attributes of the production system involved as well as with the system's maturity and with variation of the economic environment. The two systems are said to be in competition because the growth of one precludes the other.

In the model the two technological structures compete only on the product market. They do not compete for capital, labor or other inputs. In the product market gains and losses of market share occur on the basis of price competition and relative product attractiveness. Thus in the model's basic layout, as shown below in Figure 1, two similar forms interact in an economic field. To make terminology conform to basic layout I shall refer to the model as being composed of three sectors: old technology, new technology and market.

Figure 1. TECH1 Sectoral layout: The model consists of two identically structured production sectors, parameterized to represent an old and a new technology, which interact on a product market.

Applicability: The structure posed should be applicable to situations in which:

- the product of a new technology competes with that of an old technology. The difference between old and new may either be one of product or of process, or both. In cases, such as television, where a new technology has no strict functional equivalent, old technology can be construed as the items the new technology might conceivably displace. For example, with television, old technology might be viewed as an aggregate of radio, cinema, card playing, newspapers and magazines, etc..

- old and new technologies are produced by different equipment and the production shift requires starting over with new capital.

- production units are sufficiently small in relation to their markets that the substitution can be seen as continuous. For example, the model will poorly describe a technical shift in which a single new steel plant increased a nation's steel production capacity by 50 percent.

- the shift in question can reasonably be separated from other technological changes occuring at the time. For example, it would be very difficult to apply the model to recent technical shifts in underground coal mining due to the difficulty of sorting out the dynamics of adoption of shield supports from those of the shifts to longwall and continuous production methods.

It may also be applicable to situations other than those it was designed to describe, including inter-firm competition or international transfer of technology.

## Exclusions

For the sakes of simplicity and generality, much has been omitted from TECH1. Physical capital and labor are aggregated into production capacity. R & D expenditures are omitted. The investment decision is a simple formulation that makes investment increase when past and expected returns on capital are in excess of the economywide average, and away from it when it shows returns below the economywide norm. Capital and input cost functions are rudimentary. Market operation is represented as price controlled, with prices originating from the relationship between inventory and anticipated sales.

Clearly no industrial structure works so simply and substantial work would be required to fit the model realistically to any specific technological shift. Discounted cash flow calculations might be added to investment functions, taxation could be added to costs and factor costs could be disaggregated. For planned economy applications the price mechanism would need to be replaced by a more complex formulation, although the basic cybernetic mechanism whereby overstocked inventories or backordered demand exerts pressure for contraction or expansion of production would probably remain intact. And so on, until the model becomes so large, complex and specialized that it becomes incomprehensible.

## Methodological note

TECH1 is a system dynamics model and follows the modeling methodology worked out by Jay W. Forrester (as described, for example, in Forrester, 1968). The following text assumes the reader is familiar with several basic concepts which Forrester transported out of control engineering into system dynamics modeling. Those to whom the concepts of state variable, rate of flow and positive and negative feedback are unfamiliar are advised to refer to Appendix A.

## STRUCTURE

I distinguish between dynamic and feedback structures. By dynamic structure I refer to the model's system of state variables, their rates of change and the controls that establish their rates of change. This can be thought of as the framework of slowly changing elements within which the system evolves over time. By feedback, or cybernetic, structure I refer to the network of causes and effects, pushes and pulls created by a dynamic structure. This can be thought of as the patternation of dynamic tension set up within a dynamic structure.

Of the two, dynamic structure is the most straightforward and the most amenable to precise, objective description. A model's dynamic structure is explicitly described by the computer program and can be diagrammed exactly in flow charts.

Feedback structure is elusive. One can, of course, chart all the feedback loops operating within a model, but this exercise is often confusing and unhelpful because of the large number of feedback loops in a model. The trick is to identify a "basic causal structure"--a few feedback loops which play a major part in steering the model's time course, to discover where and why which loops are dominant, and to develop a sense of how the system can be controlled by manipulating its cybernetic behavior. This activity is more difficult than it sounds because over the course of simulation dominance often shifts between loops. (Note that shift in dominance is in effect a change of structure--in contrast to the fairly common assertion that deterministic models cannot describe structural change.)

Though it is elusive, feedback structure is critically important. Indeed, one might say that the primary reason for developing a system dynamics model is to improve decision maker's understanding of system feedbacks and controls. Ideally he can, by such understanding, come to manage the system with a judo master's intuitive sense of balance--with a refined sense of how his limited powers can effectively be employed to bring about desired behavioral change in the much larger forces of the system with which he works.*

The nature of the structural concepts dictates an order of presentation. Understanding dynamic structure is necessary for understanding feedback structure. Understanding feedback structure is necessary for developing control over system behavior Therefore the following text begins with description of dynamic structure and proceeds to description of system feedback structure behavior and control.

---

* To the best of my knowlege, understanding of system cybernetic structure comes only through a combination of pondering what one sees in reality and in one's model of reality (induction) and through simulation (experimentation). Analytic procedures which lead to objective measures of system sensitivity but do not develop an intuitive, verbally communicable sense of how the system operates (such as those described by Markowich 1979 and Rademaker 1973 and others) cannot be substituted.

## Dynamic Structure

### Technology Sectors

Each technology sector is structured around two state variables: production capacity (ot and nt) and cumulative output (otco and ntco). The dynamic behavior of these variables is partially controlled by the variables themselves and partially controlled by information passed between the two technology sectors through the market sector.

Production capacity refers to physical means of production measured in terms of output capability. It is increased by investment after a lag** to account for construction delays, and can decrease either by physcal depreciation or through liquidation of capacity. Depreciation takes place at all times in the model; capacity is only liquidated after a period of economic losses. As previusly mentioned, in TECH1 production capacity is viewed as an aggregate of labor and capital. No distinction is made between monetary and physical capital. Output is proportional to production capacity, subject to production efficiency and capacity utilization.

Cumulative output (otco and ntco) is precisely what its name suggests. It is used as a proxy for experience and is used, through a learning curve function (called in the model an efficiency factor, otef and ntef) to drive actual production efficiency toward potential production efficiency as cumulative experience becomes very large. Thus a sort of energy of activation problem is set up for the new technology. It begins with low cumulative output, thus low production efficiency, while the old technology operates at high cumulative output and high efficiency. As discussed later, a new technology's ability to overcome this activation barrier is one of the primary determinants of whether (as opposed to how fast) the technological substitution process is set into motion.

### Market Sector

The market sector contains three state variables, old and new technology product inventories (ioto and into) and fraction of market to new technology (fmnt). The latter is equivalent to market share. The general lay out of market sector state variables is shown below in Figure 2.

---

** A third order distributed lag is used in this case, or in system dynamics terminology a third order material delay. For further description see Davisson and Uhran (1977 for NDTRAN/DYNAMO), Pugh (1970 for standard DYNAMO) or Forrester (1968:Ch.8 for theoretical description).

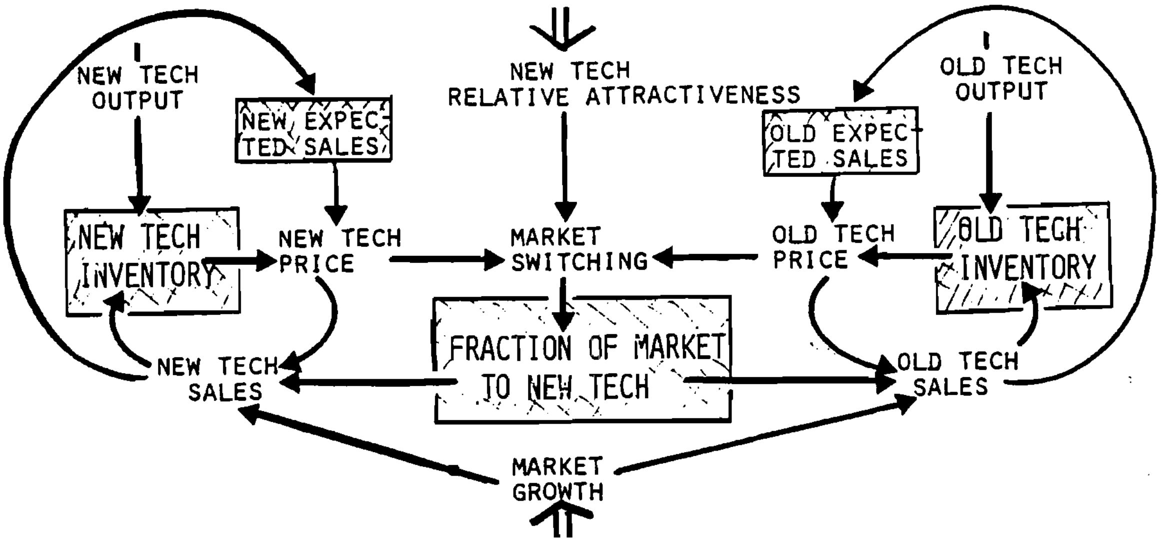


Figure 2. Basic dynamic structure of TECH1 market sector: Old and new product inventories and fraction of market to new technology are the explicit state variables around which the sector is structured. Sales expectations, an exponential average of past sales, introduce implicit state variables into the sector. Growth of total market and new technology attractiveness are exogenous.

As shown by the double stemmed arrows, the size of the entire market, defined in terms of total units purchased of both technologies at a given price and the relative market attractiveness of the new technology are exogenous.

Connections between market and technology sectors are few. Product outputs (oto and nto) are the only input into the market sector from the technology sectors. Information on price, sales and inventories passes from the market sector to the technology sectors.

Product outputs are counted as inventories until they are sold. Inventories may go negative where sales exceed inventory. Negative inventories imply to order backlogs. The ratios of product inventory to expected sales (esoto and esnto, both are exponential averagings of past sales) determines prices (nt$ and ot$). The inventory-price relationship used is of the form shown at left in Figure 3.

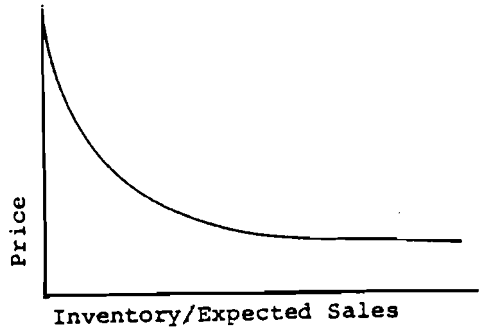


Figure 3. Inventory-price curve.

# Dynamic Structure

## Technology Sectors

Each technology sector is structured around two state variables: production capacity (ot and nt) and cumulative output (otco and ntco). The dynamic behavior of these variables is partially controlled by the variables themselves and partially controlled by information passed between the two technology sectors through the market sector.

Production capacity refers to physical means of production measured in terms of output capability. It is increased by investment after a lag** to account for construction delays, and can decrease either by physcal depreciation or through liquidation of capacity. Depreciation takes place at all times in the model; capacity is only liquidated after a period of economic losses. As previusly mentioned, in TECH1 production capacity is viewed as an aggregate of labor and capital. No distinction is made between monetary and physical capital. Output is proportional to production capacity, subject to production efficiency and capacity utilization.

Cumulative output (otco and ntco) is precisely what its name suggests. It is used as a proxy for experience and is used, through a learning curve function (called in the model an efficiency factor, otef and ntef) to drive actual production efficiency toward potential production efficiency as cumulative experience becomes very large. Thus a sort of energy of activation problem is set up for the new technology. It begins with low cumulative output, thus low production efficiency, while the old technology operates at high cumulative output and high efficiency. As discussed later, a new technology's ability to overcome this activation barrier is one of the primary determinants of whether (as opposed to how fast) the technological substitution process is set into motion.

## Market Sector

The market sector contains three state variables, old and new technology product inventories (ioto and into) and fraction of market to new technology (fmnt). The latter is equivalent to market share. The general lay out of market sector state variables is shown below in Figure 2.

---

** A third order distributed lag is used in this case, or in system dynamics terminology a third order material delay. For further description see Davisson and Uhran (1977 for NDTRAN/DYNAMO), Pugh (1970 for standard DYNAMO) or Forrester (1968:Ch.8 for theoretical description).

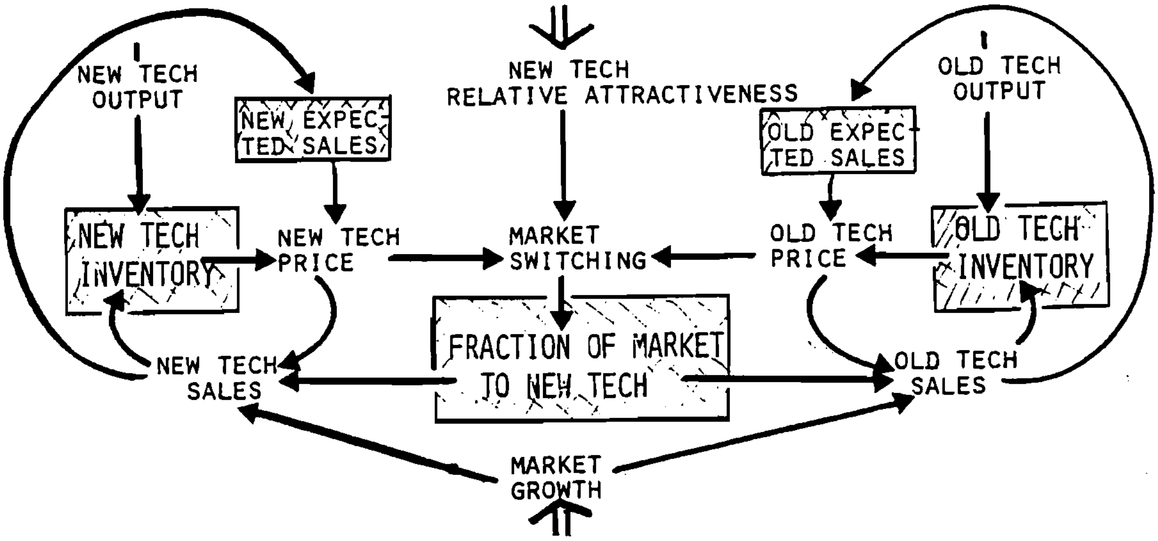


Figure 2. Basic dynamic structure of TECH1 market sector: Old and new product inventories and fraction of market to new technology are the explicit state variables around which the sector is structured. Sales expectations, an exponential average of past sales, introduce implicit state variables into the sector. Growth of total market and new technology attractiveness are exogenous.

As shown by the double stemmed arrows, the size of the entire market, defined in terms of total units purchased of both technologies at a given price and the relative market attractiveness of the new technology are exogenous.

Connections between market and technology sectors are few. Product outputs (oto and nto) are the only input into the market sector from the technology sectors. Information on price, sales and inventories passes from the market sector to the technology sectors.

Product outputs are counted as inventories until they are sold. Inventories may go negative where sales exceed inventory. Negative inventories imply to order backlogs. The ratios of product inventory to expected sales (esoto and esnto, both are exponential averagings of past sales) determines prices (nt$ and ot$). The inventory-price relationship used is of the form shown at left in Figure 3.

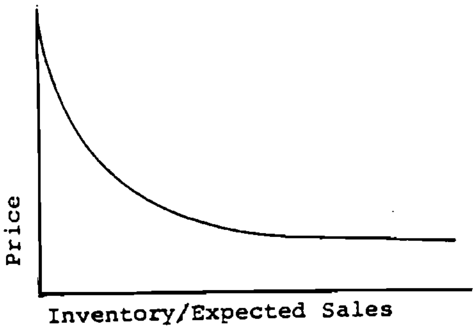


Figure 3. Inventory-price curve.

Fraction of market to new technology (fmnt) is a state variable. This formulation implicitly implies that purchaser behavior changes gradually. The speed at which purchaser behavior shifts (ms) can be parameterized to represent either fast or slow response. I expect that response times are a function of the nature of the substitution being considered. I would expect slow response where producer product innovation requires consumer process innovation, in other words, where the new product requires a change in consumer habits, or consumer learning, or development of new consumer infrastructure. Habits are very important in the consumer sectors, especially for products (such as food) where strong tastes, values or traditions are associated with the old product (e.g. substitution of instant for ground coffee). The need for learning appears in both producer and consumer goods sectors when the new product is not easily used (e.g. computers). Infrastructure factors slow consumer shifts when the product of the product substitution in question is associated with the use of another product, the latter of which is relatively expensive and has a relatively long useful lifetime (e.g. the switch from one fuel to another is slowed by the necessity to purchase new combustion equipment).

## Feedback Structure

Positive feedback causes exponential growth or decay. Negative feedback seeks equilibrium values (implicit or explicit goals or targets). On the hypothesis that technological substitution is a process in which the growth of a new technology pushes out an old technology I anticipate that the relative strengths of old and new technology's positive feedback loops greatly influence system behavior. Thus the following discussion begins with treatment of positive feedback loops and proceeds to discuss how their behavior is mitigated by negative feedback.

### Positive Feedback

I have identified six positive loops in TECH1. Each technology sector has three; the market sector appears to have none. the positive feedback loops in a single technology sector are shown below in Figure 4. The simplest positive loop for each technology is that which operates through the learning curve (upper left corner of Figure 4). Output leads to cumulative output which increases production efficiency, thereby increasing output.

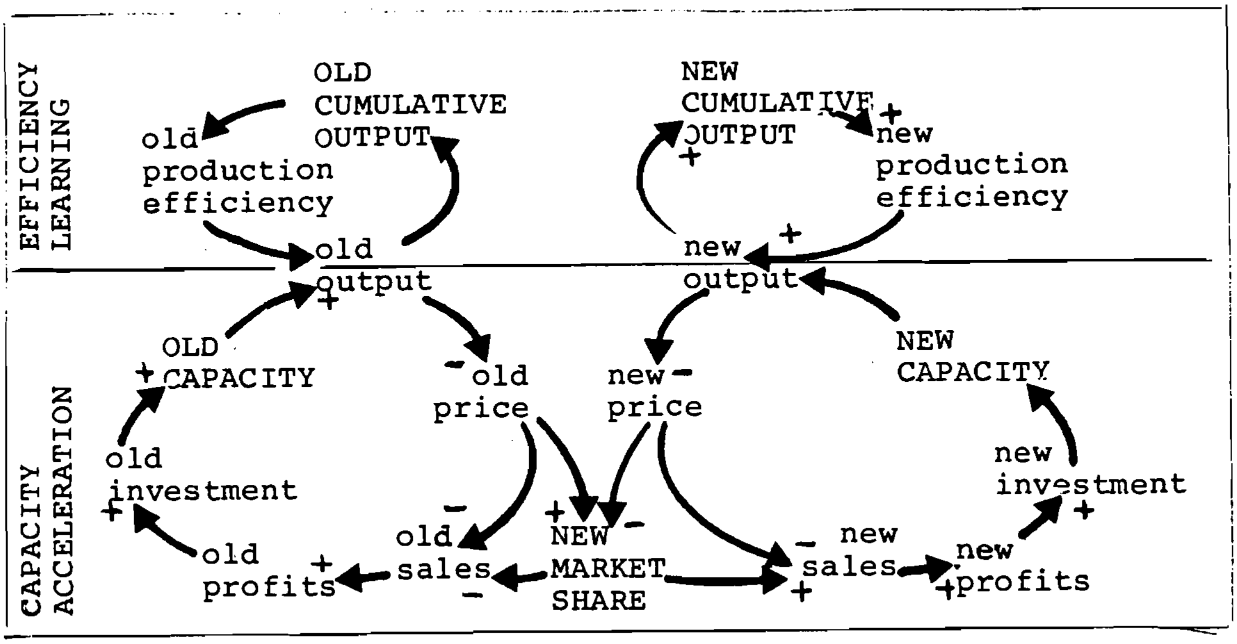


Figure 4. TECH1 positive feedback loops: Both technology sectors have both long and short term capacity accelerator loops (bottom) which are reinforced by efficiency learning loops. These, combined,are the growth forces in the model.

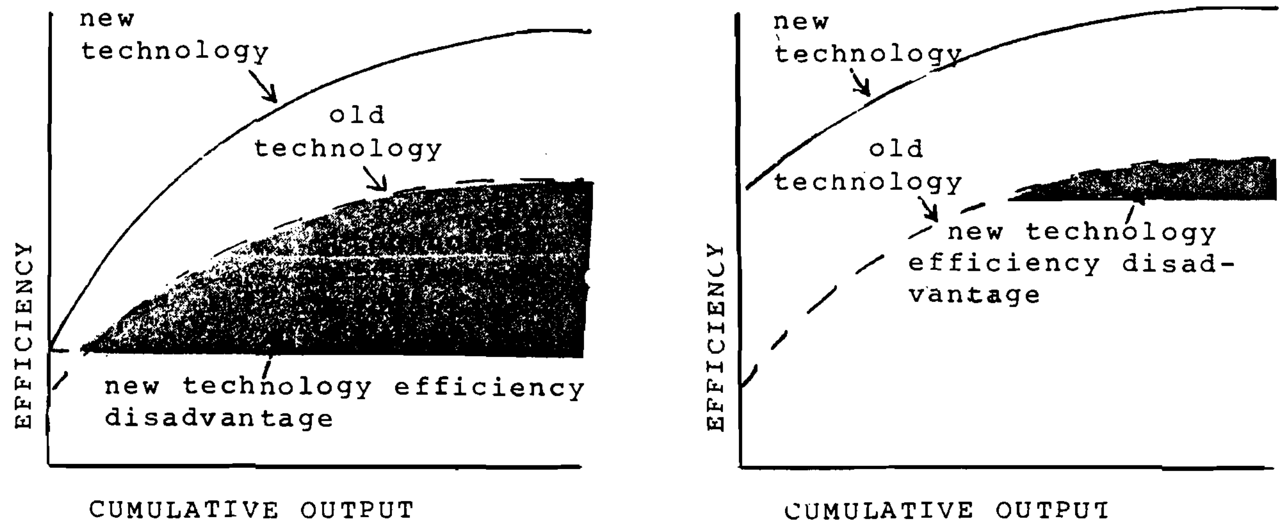
The learning loop is coupled with long term and short term capacity accelerator loops in which increases in capital lead to increases in output, increases in inventories, decreased prices, increased sales and increased revenues, hence to greater investment, more capital and more output. The short-term loop operates through the direct effect of price on quantity demanded. The long term loop operates through the lagged effect of price on market share and market share on sales.

Within each technology sector learning and accelorator loops are mutually reinforcing. Acceleration increases the rate at which output accumulates, hence speeding learning. Learning increases the rate of increase profitibility growth (i.e. its second derivative) and hence speeds the rate of investment growth.

Between the two technology sectors, positive feedback loops are competitive and mutually excluding. The connection occurs through the long-term channel of the accelerator loop. One technology sector's market share gains are the other sector's losses.

The nature of competition changes over the course of technological substitution because learning faces diminishing returns. When competition begins the old technology is (almost by definition) further along its learning curve than the new. Therefore it experiences lower gains in efficiency as its cumulative output increases. On the other hand, the new technology begins competition at the foot of its learning curve and (typically) with the prospect of rapid efficiency gains ahead. It follows that at the outset of competition learning is a very weak impetus for growth for the old technology and a strong one for the new. As the new technology gains experience this difference lessens. This phenomenon, along with its more complex repurcussion such as the defense reactions of the old technology (which TECH1 does not include) are well described in Utterback's work on business invasion by innovation (1978). I am indebted to that source for bringing this phenomenon to my attention.

The positive feedback structure just described is clearly parameter sensitive. Competition differs greatly depending on the relative efficiencies of the old and new technologies at the onset of simulation, on the rapidity with which the new technology can increase its efficiency and on the extent to which the maximum efficiency obtainable by the new technology exceeds the old. If, for example, the new technology starts competition with low efficiency, as in Figure 5a, it will operate at a strong cost disadvantage until it has gained a very large amount of experience. If, on the other hand, the new technology is faced with the situation shown in Figure 5b it never faces a large cost disadvantage, and that which it does face is overcome with only a small amount of experience.



Figures 5a and 5b. Consequences of relative forms of old and new technology learning curves for technological competition: In 5a the new technology begins with low efficiency and will operate at a large cost disadvantage if the old technology is even moderately well established. In 5b it begins with high efficiency and never suffers a serious disadvantage.

The relative heights of learning curves is also important. If the new technology's potential efficiency is much higher than that of the old the growth thrust created by the learning loop will last longer and will put more pressure on both the negative feedback loops of the market. This usually results in lower prices and increased quantities demanded throughout the system.

## Negative Feedback

The primary restraints on the positive loops described above come not from competitive pressures but from mechanisms internal to each technology sector and from mechanisms linking each technology to the market. The power of these restraints is easily demonstrated by holding market share constant, thus making the technology sectors independent of one another. If this is done, internal balancing mechanisms keep the capacities of both technology sectors in proportion with their market sizes. The balancing is dynamic, not instantaneous. Sometimes production oscillates around the equilibrium market size set by market growth. During rapid productivity gains a sector grows considerably before equilibrating. But barring peculiar assumptions (such as learning without diminishing returns or costless inputs) sector growth is effectively constrained by the system's negative feedback.

TECH1 contains a few dozen negative feedback loops, 16 of which are discussed below. For brevity's sake closely related loops are grouped, thereby reducing discussion to five groups of negative loops: three groups internal to each technology sector, one in the market sector and one running between the market and technology sectors.

Technology Sectors: Each technology sector contains five (perhaps more) negative feedback loops running from capacity back to itself. This group of loops weakens the capacity-accelerator loop causing increases in capacity to generate forces that either lead to decrease of capacity or to slowing of capacity growth. Five such loops are shown below in Figure 6. Moving from inside to out they are, respectively:

-the depreciation loop, in which physical deterioration depletes production capacity in direct proportion to capacity size,

-the fixed cost loop, in which costs that are proportional to capacity size (e.g. rent, heating and capital charges) decrease returns and investment as capacity increases,

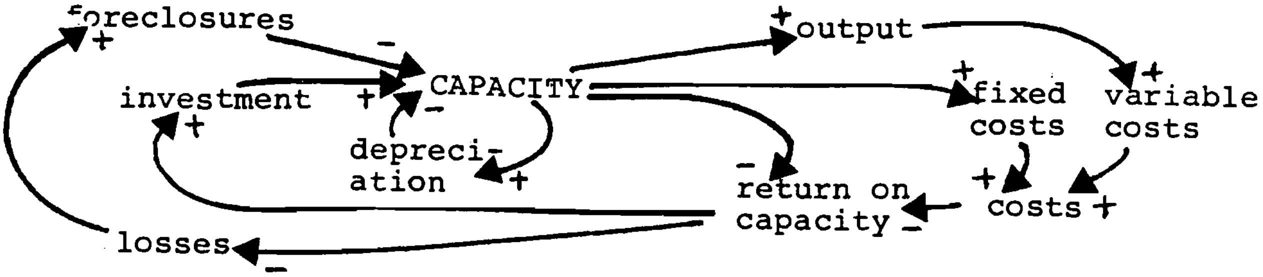


Figure 6. Negative loops from capacity back to itself: The capacity acceleration process shown in Figure 4 is controlled directly by multiple negative feedback loops.

-the variable cost loop, in which increased capacity brings increased output, increased output brings increased costs, and increased costs decrease returns and investment and slow capacity acquisition,

-the returns loop, in which increased capacity decreases return on capacity, leading to decreased investment, and

-the liquidation loop, in which prolonged losses cause producers to liquidate capacity, thereby reducing the overproduction and price depression that caused the losses.

The other important negative loop within the technology sectors is the venture capital loop, which causes venture investment to decrease as experience accumulates and investors realize that the new technology's potential for further learning gain is limited. (It deserves note that the behavior of this loop is sensitive to the mathematical form used, and the choice of form is open to question. In TECH1 the venture capital effect is written in such a way that the existence of large unexploited technical potential amplifies, rather than adds to, that investment that would take place were there no venture capital effects. This means that no venture takes place when a new technology is loosing money its stream of investment is reduced to zero.)

Market Sector: The negative loops of the market sector adjust demand to supply through long and short term responses to price signals. Output (supply) enters the market sector from the technology sectors, whereupon it accumulates as inventory. Inventory buildup reduces price, which tends to increase quantities demanded in both the long and short terms. In the short term decreased price leads immediately to increased sales. In the long term the technology sector with the lowest prices tends to gain market share, thus sales.

Market size (defined in terms of number of units that would be purchased at a given price) is exogenous and the power of the market sector to influence demand is limited by the assumed demand parameters at the lowest price on the price-inventory curve. Adjustment of total quantity demanded occurs only in the short term loop, where loop strength is determined by the parameterization of price elasticity of demand. If maximum demand is high, the loop may increase sales by a factor of two or more or reduce them to near zero. If demand is highly inelastic it may be unable to increase sales by even 50 percent. This inability may cause inventory buildups and chronic depression of prices. It also puts pressure on the supply regulation feedback loops and may cause system oscillations. The long term loop shifts demand between one technology and the other, and in so doing it indirectly increases demand by directing market preference toward the cheaper product.

Market to Technology Loops: As shown in Figure 7, long and short term feedback loops running between market and technology sectors adjust supply to demand. In the short term oversupply, as indexed by inventory buildup, leads to reduced capacity utilization, thus to lower output and reduced inventory accumulation. Over the long term oversupply, as transmitted through inventory buildup to price reduction, leads to reduced profits and lower investment. When investment falls below depreciation this results in reduced capacity and lower output, thus slower inventory buildup. Because there is a significant delay between investment and the time investments mature into production capacity, the long term loop operates quite slowly.

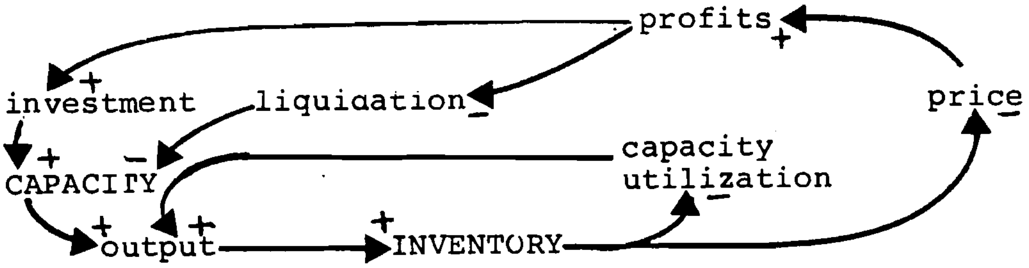


Figure 7. Long and short term feedbacks adjusting production to demand: In the short term (inner loop) oversupply, as indexed by inventory pile-up, leads to low capacity utilization and thus to reduced supply. Over the long term (outer loops) oversupply leads to capacity reduction, either, in the case of moderate price decline, through decreased investment, or, in the case of serious price depression, through liquidation of capacity.

# BEHAVIOR

Three aspects of model behavior are discussed below. First the models basic tendencies, such as market oscillation and s-shaped market penetration with variable speeds, are considered. Second, observations are made on how and why these patterns vary with changes in model parameters. Third results of experiments with model structure are discussed, including the effects of distinguishing between capital and capacity and the results of introducing a learning curve that affects product attractiveness.

## Basic Tendencies

Model simulations range between runs in which the new technology captures 100 percent market share in a few decades to those in which it fails to take off at all. Where the new technology is able to become established its market share invariably follows an s-shaped growth curve, leveling off at 100 percent market penetration. This may happen so slowly that after 60 years of simulation the new technology has a market share of less than five percent or it may be much more rapid. Failures take two forms. In one the new technology begins to grow and then declines, and one in which it simply doesn't grow at all.

Sometimes the new technology's growth is uneven. In simulations where model parameters introduce a strong market commodity cycle, the new technology tends to make relatively large gains during the high price phases of the cycle and relatively slower gains during the low price periods.

In success cases the s-shaped penetration curve can be divided into a growth phase and an equilibriating phase. In the growth phase, which usually ends at about 50 percent market penetration, the new technology's capacity accelerator and learning loops drive the system. Capacity growth is amplified as learning makes the capacity that has accumulated more effective. This drives up production and down price, which allows the new technology to encroach on the old's markets. Market gains lead to greater revenues, further investment and further capacity accumulation. If the new technology's market gain is rapid and demand is not price-elastic, these growth loops will create severe overproduction, inventory pile-ups and may lead to economic losses for both old and new technology.

In the equilibrating phase the new technology's growth is curbed by a combination of the diminishing force of the learning loop and the market forces that ultimately constrain supply to conform with market size. Prices fall to near cost and investment tends to stabilize at or oscillate around ranges that will just balance depreciation.

A tendency to oscillate and a tendency toward slow behavioral change are present in most runs. The tendency to oscillate arises from the negative feedback loops relating the market sector to the technology sectors as described above. This behavior form arises from the structural configurations common to many commodity production systems as described by Meadows (1970). The oscillation in TECH1 probably isn't a good approximation of the mechanisms in operation in the real world,* and it will not be a focus of discussion in what follows. Nonetheless, fluctuation is characteristic of the environment in which most technological substitutions take place, therefore the presence of oscillation probably contributes to the realism of TECH1's representation of technological substitution.

The tendency to slowness is in part an illusion and in part real. Some of the seeming slowness results from the fact that all model runs shown start with a tiny new technology capacity and cumulative new technology output of only 1 unit (around 0.02% of annual demand). These circumstances correspond to the condition following invention, but prior to the construction of even a medium scale demonstration plant. If one cuts out the first ten to fifteen years of simulation the resulting time trends may more closely resemble those shown in market penetration studies (e.g. Gold 1975). On the other hand, part of the slowness is real, as the delays and time constants in the capacity acquisition loop do not permit very rapid capacity expansion or market penetration.

## Parameter Tests

A vast number of parameter tests could be conducted with TECH1. Only the performance of some of the model's most parameter sensitive variables, including the efficiency learning curve form, variable costs and relative attractiveness of old and new products is discussed below. I have conducted numerous other tests, including alteration of economywide average earnings, shortening investment maturation delay times,

---

* Change the structure and you change the nature of its oscillations. For example, an earlier version of the model that distinguished between monetary and physical capital had longer oscillatory periodicities and greater stability.

increasing price elasticities of demand, increasing and decreasing propensities to invest and shortening the time constants for market switching. So far I have found the model generally insensitive to even large (doubling and tripling) changes in these parameters. One exception was shortening investment delays. In a run in which the investment maturation delay was reduced from 5 to 2 years the new technology's market share at time 10 was 5 percent with a two year delay and 0.7 percent with a 5 year delay. By time 15 the figures had come to 3 percent and 18 percent, respectively, which suggests that market penetration is likely to be considerably slower for technologies with long construction or other delays. Readers interested in the outcomes of tests other than those described below are encouraged, if possible, to experiment with the model themselves, and if not possible, to communicate with the author.

Standard Run, Failure: Most attempts at innovation fail. Accordingly, a failure run, as shown in Figure 8, is used as a standard case. Here the new technology and the old technology would be identical if the new technology could attain sufficient experience to bring it up to full efficiency. However, it cannot. It starts off at a low level of efficiency; it can neither maintain high enough prices to draw a profit or low enough prices to gain market share, therefore it looses money; its losses inhibit investment, which prevents the gains in experience required to develop efficiency. In sum, the low initial condition of the learning loop causes the new technology's negative loops to dominate its capacity accelerator loop.

<u>Moral</u>: <u>If a new technology cannot gain efficiency at a reasonable speed it will not be competitive on the market--regardless of its potential for efficiency gain</u>.

<u>Efficiency Learning</u>: The power and parameter sensitivity of the learning loop were mentioned in discussion of the system's positive feedback. Figures 9a and 9b, which compare market penetration and price behavior trends for four new technologies which differ from one another only in the form of their learning curves.

Efficiency learning behavior is of theoretical interest because upward progress on the learning curve takes place through "minor" or "improvement" innovations--such as measures to cut costs and improve efficiency but do not radically alter either process or product. Statements about the effect of differing forms of the learning curve on technological substitution may be translated into statements about the balance between basic and improvement innovation.

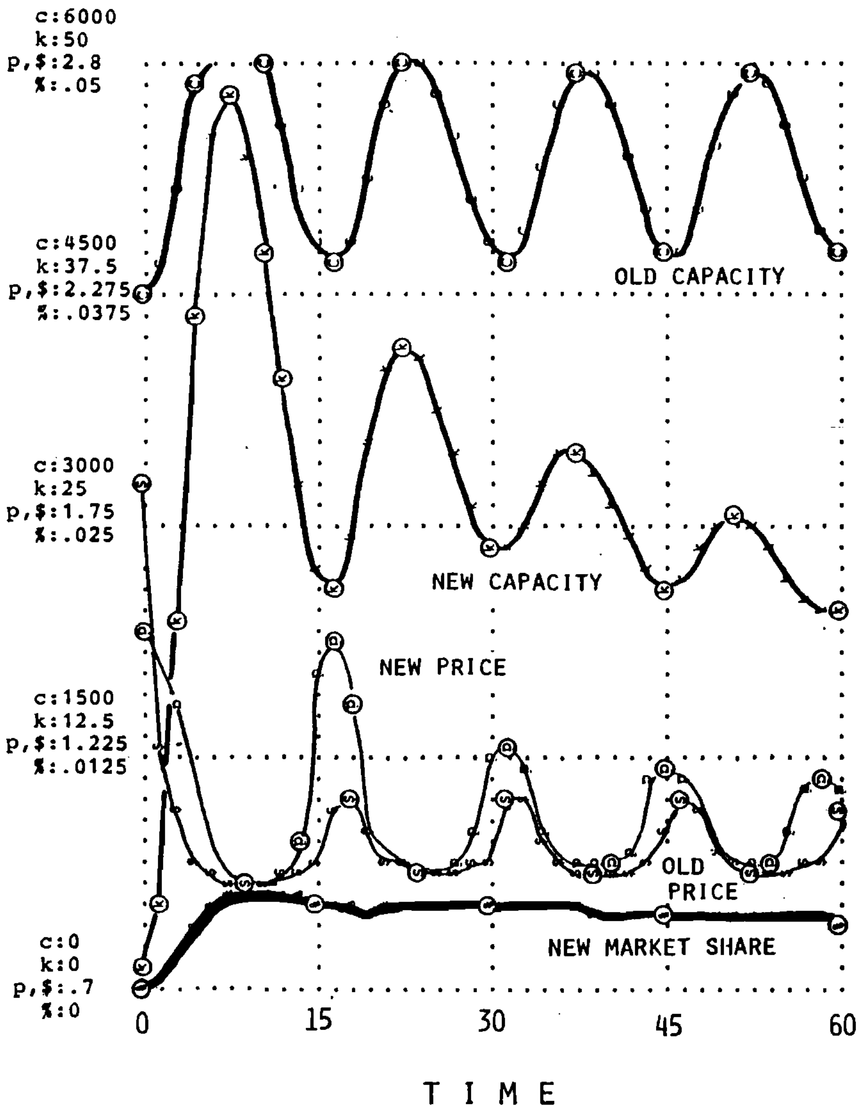


Figure 8. Failure run (standard case): The new technology never becomes efficient enough to compete. It's market share stays under 0.5 percent because it cannot reduce prices sufficiently to promote sales. But on the other hand it cannot raise prices sufficiently to expand production and gain efficiency.

<u>Note</u>: Old and new prices are plotted on the same scale. All other variables are scaled separately. Scales shown on the left. C = old technology capacity, k = new technology capacity, $ and p are old and new technology prices, and % = new technology market share. Prices and capacities in ficticious units. Watch for scale changes in later plots.

In all runs the old technology begins the run with a cumulative output of 40,000 units, which causes it to operate at its maximum potential efficiency value throughout the run. For convenience, old technology maximum efficiency has been scaled to 1. The parameters of the new technology's learning curve in the four runs curve are shown below in Table 1. Cumulative output figures are given both in natural logarithms and in natural numbers, and the efficiency values associated with each cumulative output value are listed in the columns. Because old technology efficiency value is scaled to 1, the numbers given can be read either as absolute or relative efficiency values.

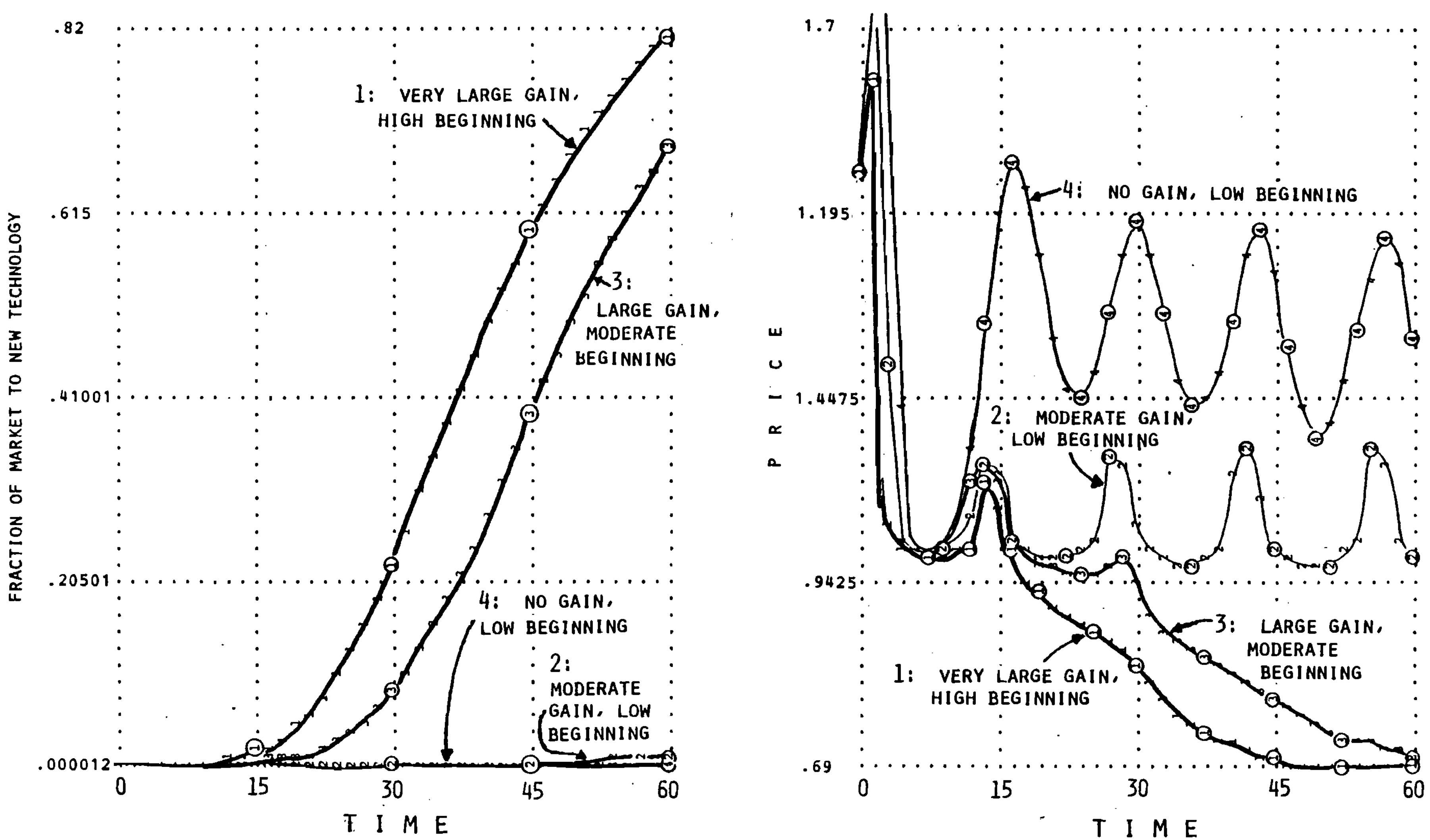
Table 1: Learning Curve Tests: values of curve used to relate output/capacity to cumulative output in Figures 9a,9b,10a and 10b.

| | ln(cumulative output) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | cumulative output | | | | | | |
| | 1 | 7.4 | 20.0 | 403 | 2981 | 22026 | 162754 |
| case | | | | | | | |
| 1 | 1 | 1.7 | 2.3 | 2.8 | 3.2 | 3.5 | 3.6 |
| 2 | 0.4 | 0.8 | 1.2 | 1.5 | 1.8 | 1.9 | 2.0 |
| 3 | 0.6 | 1.3 | 1.9 | 2.4 | 2.9 | 3.0 | 3.0 |
| 4 | 0.3 | 0.5 | 0.7 | 0.8 | 0.9 | 1.0 | 1.0 |

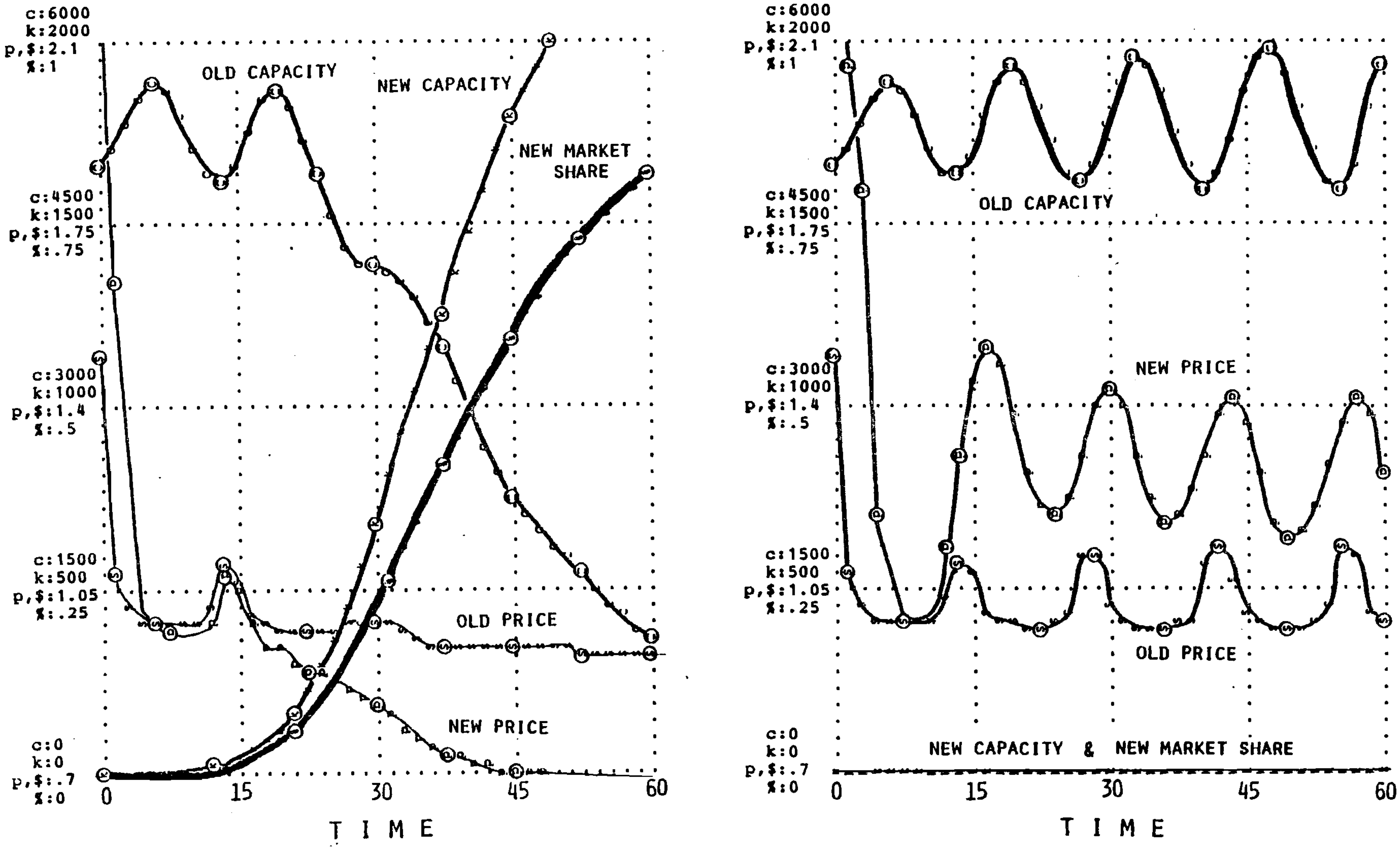
Basically new Technology 1 represents a major breakthrough in production efficiency. It begins at the same level of efficiency as the old technology. After producing 20 units of output (scaled as appropriate...if the new technology is a new kind of production plant, 20 units could mean 20 plants. If it is wheat flour, 20 units could mean ten million tons.) it attains a level of efficiency 2.3 times that of the old technology. By 3,000 units of cumulative production it is more than 3 times as efficient as the old technology. Ultimately it can become 3.6 times as efficient as the old.

Technologies 2 to 4 all begin less efficient than the old. Number 2 has the power to double production efficiency, Number 3 to triple it, and Number 4 it can only hope to equal the old technology's efficiency.

Figure 9a shows that within the system posed even manyfold efficiency gains and high initial efficiency result in a fairly slow substitution process. Even Technology 1, which started out as efficient as the old technology and ended up much more efficient, required more than a decade to attain 1 percent market penetration, and about 30 years for 20 percent penetration. Technology 2, which was able to it match the old technology's efficiency by the 20th year of simulation, only



Figures 9a (left) and 9b (right). 9a compares market penetration curves for four different substitutions which vary from one another only in the parameters of the new technology's learning curve. (See Table 1 for listing of parameters.) Figure 9b shows price trends for new technology output for the same four simulations. For Technologies 1 and 3 rapid efficiency gain leads to substantial price decreases and rapid market penetration. Failure to cut costs and prices prevents the success of Technologies 1 and 3.



Figures 10a (left) and 10b (right). Performance of Technologies 1 (left) and 4 (right) in efficiency tests: New Technology 1 rapidly gains market share as its prices fall below those of the old technology. Old technology capacity declines as new technology capacity increases. By contrast, New Technology 4's prices are consistently higher than those of the old technology and its capacity does not grow. Note that price fluctuations are largely eliminated in the case of successful substitution.

attained a 1 percent market share by the 60th year. Technology 3 was like 1 but slower, and 4 failed even more completely than 2; it was loosing, rather than gaining market share at the end of simulation.

The price pattern for the new technology's product shown in Figure 9b partially explains the market penetration patterns in Figure 9a. As previously noted, in these simulations, consumers buying patterns change solely on the basis of relative price, thus the fastest market penetration occurs for technology 1, whose great efficiency permits it to cut prices faster than any of the other cases considered, and faster than the old technology. Technology 3 is also able to drop prices rapidly, and therefore it too makes rapid market advance. Number 2 and Number 4, however, remain uncompetitively priced commodities throughout most of the simulation, and therefore fail in market penetration. These patterns show more clearly in Figures 10a and 10b, which show price, capacity and market share trends for old and new technologies for new technologies 1 and 4 of described above.

An interesting sidelight of these simulations is the tendency, with an aggressively growing new technology, for price cutting to drive out price fluctuations. Research is required to ascertain whether this pattern is realistic.

A second interesting sidelight is the fact that the system is extremely sensitive to the old technology's initial condition. If the new technology starts up in an uncrowded market it gains market share much more rapidly than it does in a saturated market. For example, in a simulation (not shown) in which the old technology's initial capacity and inventory was reduced by 20 percent technology 2 acquired a market share of nearly 50 percent by year 60, as opposed to just over 1 percent in Figure 9a. This result emphasizes the problems posed for a new technology by crowded markets--at least within the model.

The realism of the system's sensitivity to initial conditions could be checked against historical evidence. If such sensitivity is realistic one would expect to find that periods of relative undercapacity-- such as the late 1940's and 1950's--favor the diffusion of new, efficient technologies while periods of market flooding, such as the Great Depression, would hinder their adoption. The tendency might be less pronounced for product innovation, where replacement of old capacity by new affects only the qualitative aspects, not the volume, of production.

Moral: The mechanisms restraining the growth of a new, efficient technology are stronger than one might think. If it grows in a well supplied market, a new technology tends to hinder its own progress by depressing prices and hence profits, which weakens its impetus for growth. In reality these forces probably lead to pressure for competition on grounds other than price. Creation of new markets through foreign trade, product improvement and advertizement is probably as important to the expansion of a highly efficint new technology as is pure efficiency learning.

Changing Factor Prices: The current energy situation raises the question of what happens to the technological substitution process in times of changing factor prices. Specifically, it is generally believed that increasing oil prices will favor the growth of technologies using either cheaper fuels or less energy altogether.

TECH1 can be adapted to looking at the effects of changing factor prices on the process of substitution by exogenously increasing variable production costs. In the runs below we consider four cases, fast cost increase for old technology with constant prices for the new (case 1), no changes for either (case 2), slow cost increases for the old technology (case 3) and fast cost increase for the old coupled with slow cost increase for the new (case 4). The base case (case 2) is identical to technology 3 in in Figures 9a and 9b above. The variable cost values used for old and new technology (variable costs per unit output) are shown below in Table 2.

Table 2. Variable Cost Scenarios Used to Generate Table 3.

| | time | | | | | |
|---|---|---|---|---|---|---|
| case | 0 | 15 | 30 | 45 | 60 | scenario |
| 1 new | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | old large variable |
| old | 0.3 | 0.6 | 0.9 | 1.0 | 1.0 | cost increase |
| 2 new | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | no cost change |
| old | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | |
| 3 new | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | old small variable |
| old | 0.3 | 0.4 | 0.5 | 0.6 | 0.6 | cost increase |
| 4 new | 0.3 | 0.4 | 0.5 | 0.6 | 0.6 | old large, new |
| old | 0.3 | 0.6 | 0.9 | 1.0 | 1.0 | small variable<br>cost increase |

Persons interested in the details of the above simulation are encouraged to run the program and explore its details on their own. Here we note only, as shown in Table 3, that large increases in old technology variable costs strongly affected new technology diffusion. In year 15, for example, the old technology's high market costs in case 1 have allowed the new technology to gain a market share nearly twice what it would have been given equal variable costs (case 2). By year 30, this widens to a difference of a factor of four--in case 2 the new technology has a market share of about 8 percent, while in case 1 it has nearly 30 percent.

Table 3. New Technology Market Shares Under Four Variable Cost Scenarios: Large cost increases in old technology variable costs cause rapid substitution (case 1), moderate increases, moderate rates (case 3), and a combination of moderate increases for the new technology and large increases for the almost totally prevent substitution (case 4).

| time | case 1 old high | case 2 no change | case 3 old medium | case 4 old high, new medium X 1/1000 |
|---|---|---|---|---|
| 0 | .00001 | .00001 | .00001 | .01290 |
| 5 | .00058 | .00058 | .00057 | .17706 |
| 10 | .00138 | .00120 | .00126 | .12730 |
| 15 | .00657 | .00348 | .00454 | .08354 |
| 20 | .03101 | .01035 | .01459 | .07300 |
| 25 | .13395 | .02937 | .04270 | .07453 |
| 30 | .35472 | .08396 | .16994 | .06567 |
| 35 | .54049 | .16799 | .27603 | .03300 |
| 40 | .69113 | .26901 | .40644 | .04127 |
| 45 | .80139 | .38913 | .55548 | .03158 |
| 50 | .87488 | .50349 | .67208 | .01893 |
| 55 | .92116 | .60243 | .75608 | .03073 |
| 60 | .95066 | .68884 | .82955 | .01833 |

It is also of interest that in cases 1 to 3 the substitution of the new for the old technology manages to maintain a general trend of price decrease throughout the simulation period, while in case 4, where the new technology also faces cost increases and is unable to get established, the system manifests violent price fluctuations about a rising mean.

Attractiveness: Technological change is not a simple matter of increasing efficiency and reducing costs. Changes in product quality and nature are of equal if not greater importance. It is possible to simulate the situation in which the new technology is prefered by purchasers by shifting the market shift curve upwards and to the right so that given equal prices the market will shift toward the new product. Figure 11 shows the standard form of the market shift curve (lower curve) and two variants of it that have been used in the simulation plots shown in Figures 12a and 12b.

Figure 12a was generated using the uppermost curve shown in Figure 11. In this case the new technology is sufficiently more attractive than the old that consumer preferences switch toward it even when its price is nearly triple that of the old technology--as was seen, for example, in the substitution of color television for black and white. This permits the new technology to sustain relatively high prices for its product, which makes it profitable even before it begins producing efficiently. This initial profitability spurs investment, which allows the new technology to expand capacity and output, thus to gain the experience needed to achieve high efficiency.

By about the 20th year of simulation the new technology attains 90 percent of its potential efficiency--and thus has costs only a few percent higher than the old technology while it draws prices something like 25 percent higher than the old technology. These conditions lead to respectable profits (return on investment of 7.5 percent) and heavy investment. As this investment matures output growth becomes rapid. This leads to increased supplies and serious price depressions. The

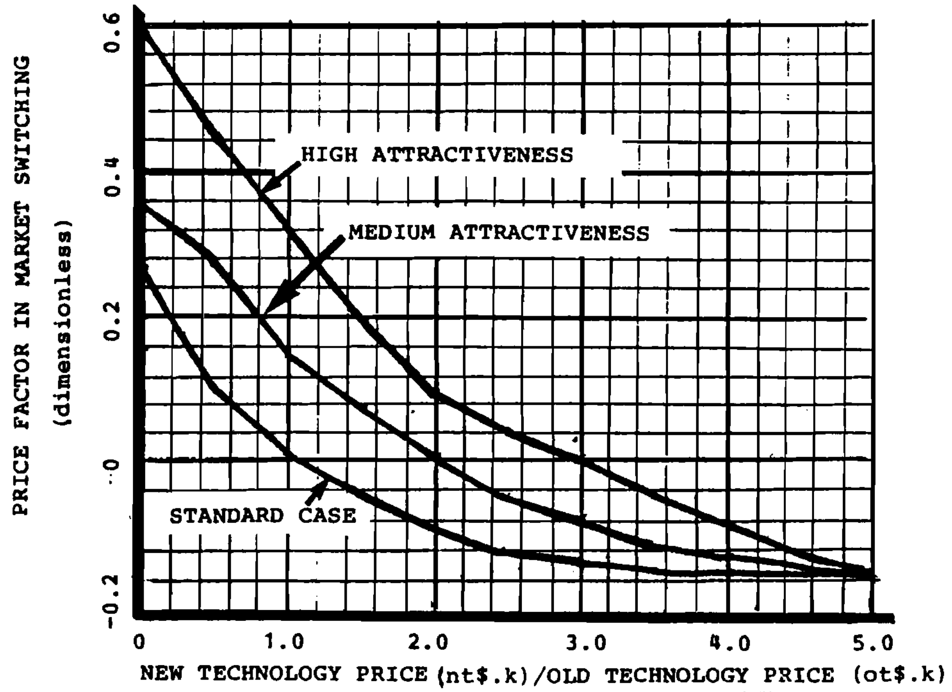


Figure 11. Attractiveness scenarios: Curves used to represent high and moderate gains in product attractiveness as compared to the standard case in which old and new products are equally attractive. In the high case market switching is zero where old technology price is three times new technology price. In the standard case switching stops when prices are equal.

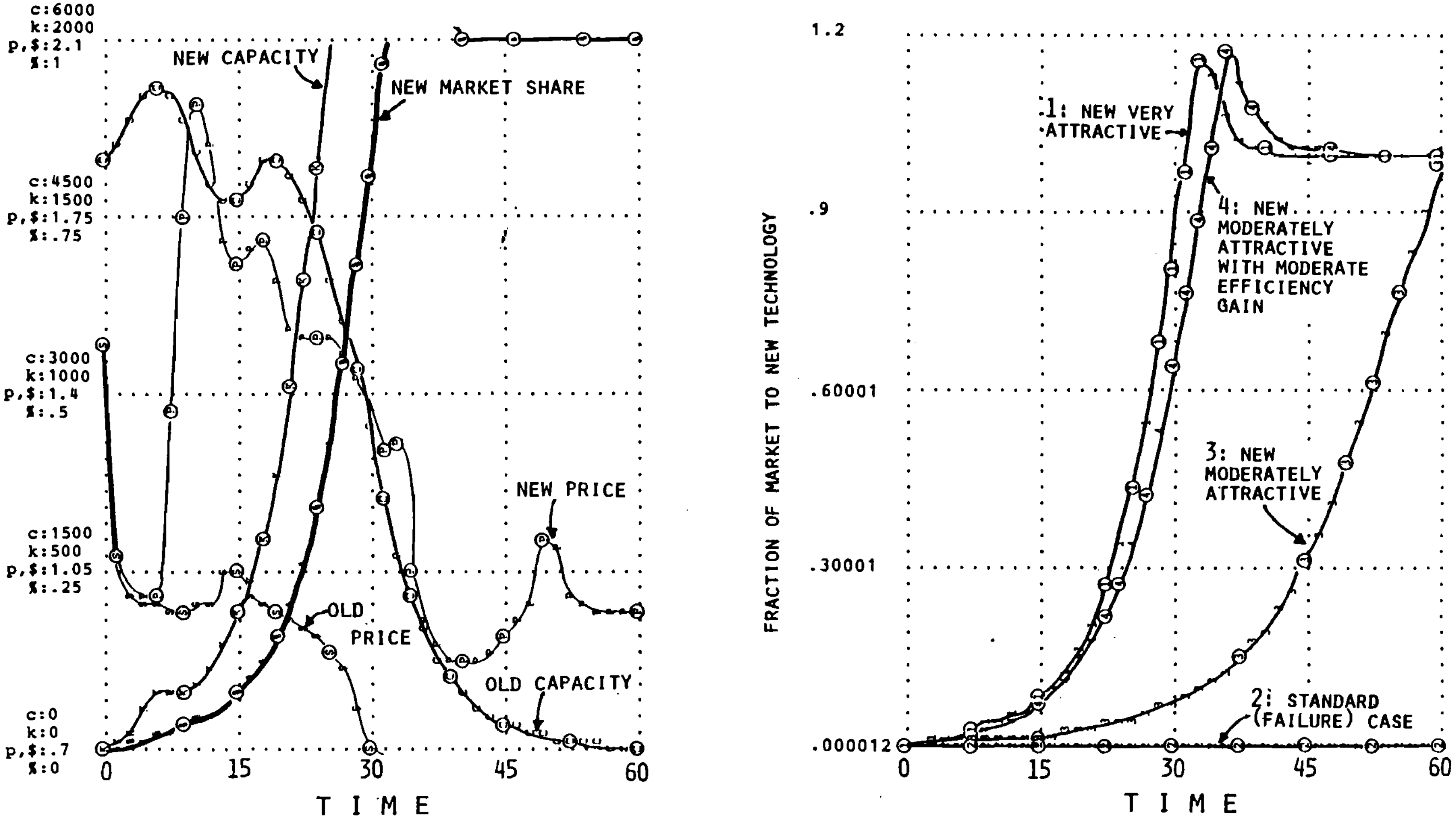


Figure 12a (right) and 12b (left). Attractiveness tests: 12a uses the high attractiveness scenario shown in Figure 11, and manifests rapid growth of the new technology accompanied by a large old/new price differences. The new technology's high relative prices let it grow rapidly but drive the old technology to bankrupcy. 12b compares runs using each curve shown in Figure 11 plus a run assuming moderate efficiency gain and moderate attractiveness and shows the model is very sensitive to attractiveness assumptions.

old technology is affected first. It begins to show losses by the 20th year of simulation, and by the 30th year of simulation its losses are so high (-45 percent) that it liquidates more than half its capacity over the next 5 years. By year 35 consumers have entirely stopped purchasing the old technology's product.

By year 30 even the new technology begins to show heavy losses, which continue for about a decade until depreciation reduces new technology capacity to come in line with demand. (These losses would have lasted less long if the model had been parameterized to let the new technology liquidate assets at the levels of loss shown or if it had been made capable of expanding its markets.)

Figure 12b compares the market penetration curves of all the attractiveness cases conditions shown in Figure 11, and adds one curve (4) showing the results of combining moderately high efficiency with moderate attractiveness. From the figure one can deduce that the system is extremely sensitive to differences in product attractiveness. Indeed, one could generate a very wide spectrum of market penetration curves merely by changing the parameters of new technology attractiveness. The combination of moderate attractiveness and moderate efficiency gain acts similarly to high attractiveness. It is to be noted that both the highly attractive and the moderately attractive but efficient technology briefly exceed 100 percent market penetration, which should serve as a reminder that the model is only a rough approximation of reality.

The model's sensitivity to product attractiveness is commonsense. Clearly, for example, fuels that are cleaner and less troublesome than coal are preferable to households even when their prices are somewhat higher, and clearly automobiles, which are faster and better adapted to urban environments than horses, are preferable to horses, despite higher cost. It is logical to attribute some of the market successes of gas and oil heating and of automobiles to their inherent market attractiveness. In economic terms this amounts to an assertion that a product with higher consumer utility has a strong competitive advantage over one with lower utility.

Moral: Consumer values and perceptions are critical to product success. Design and marketing activities of a soft nature, including advertisement and considerations reliability, user convenience and aesthetics cannot be dismissed as cosmetics. They may be decisive factors in determining the success of a technical innovation of a hard engineering nature.

The program's sensitivity to attractiveness, which is exogenous, raises questions as to TECH1's structural adequacy. Is product attractiveness really independent of variables within the model structure, or does it change with them? Are there snowball effects? When 5 or 10 percent of the relevant market has adopted an innovation does peer pressure--a sense of "keeping up with the Joneses"-- stimulate faster rates of adoption? Also, can poor product performance in the early stages kill the market for a product? Can high rates of defective output caused by putting the product on the market before the "bugs" are out of it cause significant slowdowns, if not permanant curtailment, of product success? Will the near disaster at Harrisburg, Pennsylvania significantly affect the market for nuclear power plants over the next 15 years? Will small scale computer systems undergo a spurt in consumer demand when software and organizational ware becomes more advanced and when the word spreads that they work? In the following section the outcome of linking attractiveness to a learning curve, as has been with sales efficiency is considered. This could represent either customers learning or improvements in product and marketing. Other assumptions could be built into the model for particular situations (such as investigating the longer term consequences of initail low product reliability).

## Structural Variation

I have changed TECH1's structure several times in the course of model formulation and I am still changing it. The original TECH1 had separate state variables for physical capacity and monetary capital, and included no feedback from high losses to asset liquidation. The version I am currently working on includes learning loop from cumulative output to attractiveness, and has the learning curve relationship rewritten in the conventional form in which increased cumulative output leads to decreased costs (instead of increased capital/output ratios). When that version is complete I intend to rewrite the market switching formulations to permit consideration of ununiform market preference--i.e. the situation described by Utterback (1979) in which the new product is able to pay for its initial learning expenses due to the presence of specialized markets which will pay high prices for its product during the early years of its commercial developent. Beyond that, in recognition of the debate as to whether cumulative output, cumulative investment or some other measure is a better proxy for experience (Arrow 1962) I am considering reformulation of the learning loops to investigate whether the choice of experience measure makes a significant difference in system behavior. (I anticipate that it will not.)

While these structural changes are informal and lack rigorous control, they do constitute an important sort of model testing, and in some cases their outcomes are worthy of note. Accordingly the outcomes of separate accounting of capacity and capital, deletion of foreclosures and adding a market learning loop are discussed below.

## Separation of Capacity and Capital

In the first version of TECH1 each capacity sector had three explicit state variables, capacity, capital and cumulative output. Capital, like capacity, increased with investment and decreased by depreciation. However, it was depreciated at a faster rate than capacity, to take into account the fact that (at least in welfare state market economies) most corporations write capacity off the books faster than it physically depreciates. Furthermore, capital and capacity were dynamically non equivalent because capital increased immediately upon investment, while capacity increased only after an investment maturation delay.

Separation of capacity and capital tended to slow the course of technological substitution. Because capital was written off the books faster than it depreciated, the old technology, which had had more time to build up a stock of written off capital, tended to show returns on capital in excess of what it would have shown had book value corresponded more closely with physical plant. The difference between instant increase of monetary capital and delayed increase of capacity also worked against the new technology. In the first years of simulation, when new technology tended to be operating at a strong efficiency disadvantage, the presence of investment costs that had not yet contributed to output tended to be more than the fledgling technology could endure.

In short, separation of capacity and capital indicated that the accounting procedures assumed were discriminatory against innovation--an interesting finding and one worthy of checking for its real world validity. Do firms use simplistic accounting procedures for their new ventures or do they make compensations for start-up costs? If so, what sort of compensations do they make? Frankly I do not know, and it is beyond the present scope of my work to find out.

Aside from raising the question of whether corporate accounting procedures discriminated against innovation, separation of capacity and capital greatly complicated model structure and did not appear to add sufficient insight into system behavior to justify their cost in complexity. Therefore they were aggregated.

## Foreclosures

In former versions of TECH1, capacity could decrease only through depreciation. This resulted in implausable simulation results, such as returns on capacity of -300 percent, particularly in cases where the new technology was growing vigorously and driving prices down below production costs. Clearly reality disallows sustained losses on that order of magnitude. A firm with sustained losses of more than a few percent is very likely to begin liquidating assets. Accordingly I added a negative feedback loop in which sustained losses lead to foreclosure of capacity. This greatly improved the realism of model behavior. Extremely high rates of loss still appear in simulations on occasion, but they tend to be accompanied by very rapid declines in production capacity--in extreme cases capacity may be halved in three years.

While removing the problem of heavy losses, the addition of foreclosures introduced a new problem. The new technology, in most circumstances, faces heavy losses over much of the first decade of simulation. In the absence of a foreclosure mechanism these simply resulted in reduction or cessation of investment. With foreclosures these resulted almost invariably in the new technology liquidating its assets in the first decade of simulation. I remedied this situation crudely by parameterizing the new technology with a lower propensity to foreclose than the old. This is tantamount to an assumption that innovative new product lines can secure small volume long term loans to cover their start up costs more easily than declining technologies can secure loans to cover their losses. It might also be equated to the situation in which a Galbrathian firm (Galbraith 1967:Ch 4,5,6)) supports a new technology using its massed reserves. It might have been of greater descriptive value to add a formulation in which loss tolerance was a function of cumulative output.

TECH1's behavior with and without foreclosure mechanisms suggests that in some cases the foreclosure of the old technology may be an important part of technological substitution. If foreclosure is not permitted--or not included--both technologies suffer severely from the consequences of overproduction. This points to the problems created by policy assistance to failing industries.

Foreclosures, in reality, may have a high social cost in terms of displaced labor and liquidation of assets. Optimal management of an innovation might in some cases involve development at a slower rate than would follow from laissez faire management in order to permit a smoother transition. With further work TECH1 could serve to identify cases in which restraint of the speed of innovation would prevent disruptive displacements.

Market Learning

As mentioned above, I am presently working on a model variant in which cumulative output is linked to product attractiveness under the assumption that product quality and marketing efficiency increase with experience. So far this structural alteration has behaved pretty much as expected. It introduces a positive feedback loop from cumulative output through the market mechanism, profits, investment and capacity acquisition, as shown below in Figure 13. This loop appears to operate in a fashion similar to the learning loop for production efficiency described earlier. Inability to overcome initial low attractiveness can create a vicious circle for a new technology, while initial high attractiveness can permit it to overcome such cost disadvantages as it may suffer from initial low efficiencies.

Production efficiency learning and market learning operating together tend to reinforce one another with a net effect of making the upswing of the new technology's market penetration more steep than it would have been with either form of learning operating alone. The implications of dual and multi-facited learning processes are described in a companion paper (Robinson 1979) and need not be discussed at length here. It is, however, worth noting than market learning is probably

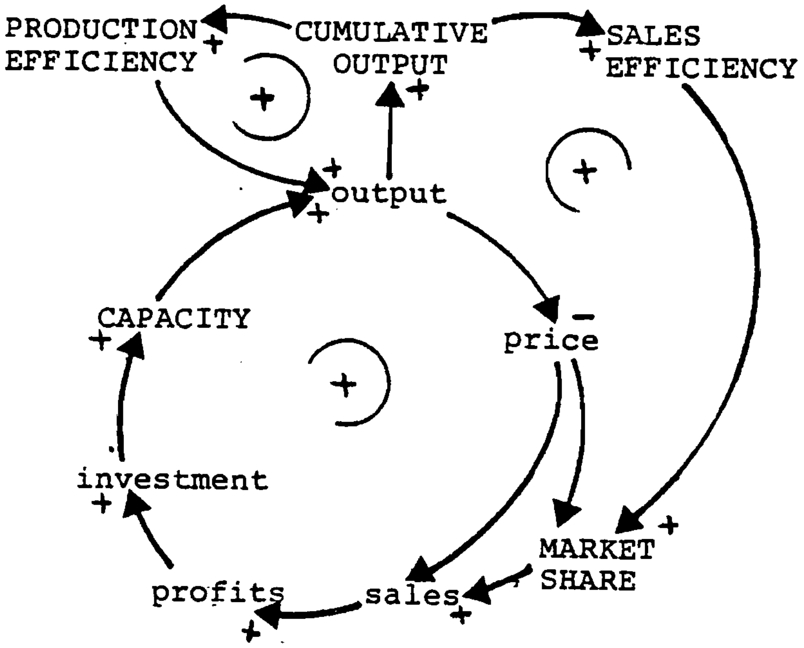


Figure 13: Adding market learning: A new positive feedback loop is introduced if sales efficiency is subject of learning.

equally, if not more, important than production efficiency learning in non-commodity products, and that the relative importance of market learning vis a vis production efficiency learning probably increases with income.

## TENTATIVE CONCLUSIONS

TECH1 is too theoretical for its numerical output to be taken seriously. All of the model's functions, especially critical functions such as market switching and investment, need careful review, and more testing and analysis of model tests is in order. Nonetheless, the model's structure appears to be robust under a fairly large variety of circumstances and some of the model's conceptual implications appear to be significant. In particular the model suggests that:

- The process of building up markets, capacity and efficiency is slow. It may take a few decades for a new technology to capture ten percent of the market, even when its attributes destine it for success.

- The level of efficiency at which a new technology enters competition and the rate at which it learns greater efficiency thereafter are critical parameters with strong influence on the course of technological substitution.

- Ability to get over the hump--to survive the long period of high initial investment costs and poor initial performance--is a critical factor in determining which inventions become innovations. Technologies that enter competition with low efficiency have great difficulty getting over the hump, regardless of the level of efficiency they might attain through experience.

- Complex, large scale, high technologies, such as nuclear power generation, with large technical difficulties and high costs associated with their development, have a hard time taking off. Process innovations with steep learning curves are likely to fail unless they bring large gains in efficiency.

- Market attractiveness is often critical to the success of a new technology. The system rewards adaptive cleverness as much as technical efficiency. A technology that would fail on efficiency criteria alone may succeed if customers prefer it over the old technology.

- If market attractiveness is subject to learning curves it amplifies the tendencies of efficiency learning. That is, it makes the task of getting over the hump harder for a new technology, but provides a more intensive growth thrust for those technologies that manage to get over the hump.

- The state of the market at the time when the new technology is introduced may critically influence its pattern of market penetration. A technology introduced onto a buyers'market is less likely to succeed than one introduced onto a sellers' market. If it does succeed it takes longer getting going.

-The new technology is likely to begin operation with book value corresponding to actual measures of production capacity, while the old technology is likely to have written-off capital in operation. If investors accounting procedures are insensitive to this condition and if if investment decisions are influenced by returns, innovation will be retarded.

- Long construction times contribute significantly to slowness of substitution.

In sum, the structural triad of the learning curve, capacity acquisition and market competition looks like it is capable of generating many insights into the economics of the innovation process.

# APPENDIX A: METHODOLOGICAL PRECEPTS

TECH1 is a system dynamics model, following the modeling methodology developed by Jay W. Forrester. It will be more comprehensible in the context of a few system dynamics concepts, including that of a state-determined system, positive and negative feedback and nonlinearities in regions of extreme circumstances. These are explained briefly in the following section. Readers looking for a deeper and more complete treatment should refer to Forrester's Industrial Dynamics (1968).

State determined systems: Like all system dynamics models, TECH1 is state-determined; that is, its behavior is structured around endogenous state variables. State variables (also refered to as stocks or levels) are relatively slowly changing, inertial system elements that structure the way systems behavior changes over time. System dynamic models are said to be state determined because because the rates at which system state variables change over a given time interval are determined by their values at the start of that interval (as moderated by exogenous variables and noise within the system). In system dynamics models the calculation interval is set sufficiently small that the system approximates time-continuous behavior. Thus, in operation the system is a complex intertwined network of flows and accumulations, continuously adjusting to and pushing against one another as the system moves through time. Information on the state of levels establishes the rates at which levels change; changing levels alter the information stream that determines the rates at which levels change.

Positive and Negative Feedback: The iterative passage of information from levels through rates and back to levels creates feedback loops. A feedback loop must pass through one level--although this may be a level implicit in a system delay rather than one of the levels explicitly named in the computer program. If it contained no levels, a feedback loop would be reduced to simultaneous equations, which are not permitted in system dynamics modeling, as it is axiomatic to the methodology that causal influences are separated in time.

In the following analysis dynamic structure and behavior will often be explained in terms of feedback loops. These are of two general behavioral types: positive loops (see figure A1.1), which produce self-reinforcing, destabilizing (non-convergant) behaviors, and negative loops (see figure A1.4), which tend to drive the system state variables toward some equilibrium value (goal), and thus serve a homeostatic function. One can ascertain a loop's type by counting the number of (-) relationships going around the loop. If, as in figure A1.1, there are an even number (or zero) of (-) relationships, the loop is positive. If there are an odd number, the loop is negative.

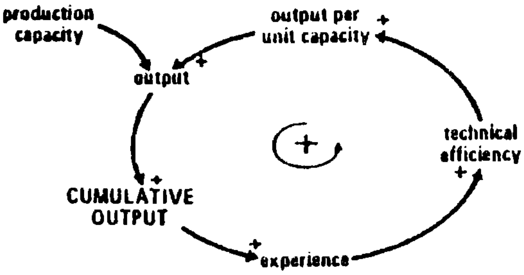


Figure A1.1 Positive feedback loop

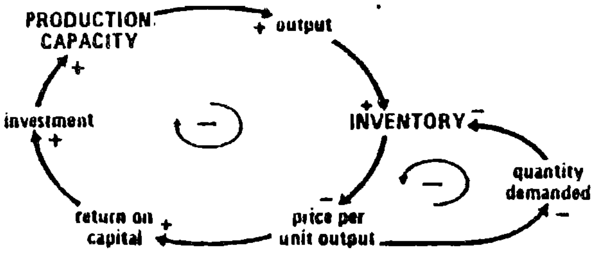


Figure A1.2 Negative feedback loop

Interpreting Causal Loop Diagrams: A----- B means A influences B. If the arrow terminus is marked with a (+) sign an increase in A will cause an increase in B. If it is marked with a (-), an increase in A will cause a decrease in B.

Nonlinearities: The above is a deceptive oversimplification. Positive feedback loops do not always explode, nor do negative loops always equilibrate. For one thing, nonlinear relationships are widely used in TECH1 (as all system dynamics models), which means that feedback loops behaviors are much more complex than their nominal characteristics indicate. A loop's strength--for a positive loop, the velocity of its thrust toward growth or decline,for a negative loop, the rate at which it moves a level toward its goal (equilibrium position)--varies as the systems region of operation moves from states with steep functional relationships to regions with flat ones. As loops are moved by changing system states into regions with weak (flat) functional relationships their power diminishes. For example, the loop shown in Figure A1.1 is totally inactivated when high cumulative output brings the system to the point of maximum technical efficiency. At that point further experience brings no further gain, and the loop passes on on a constant information stream (which amounts to being inactive).

Complex behavior can result from sources other than changing slopes of functional relationships. For example if the goal of a negative loop is established within a positive loop the negative loop may be driven to exponential growth or decay. Where a time lag intercedes between a change in system conditions and adjustment to that condition (or between the action to adjust and the time the action takes effect), a negative loop, like a marksman shooting for a moving target may systematically overshoot or undershoot its goal. This can lead to convergant or divergant oscillation or to overshoot and decline. In short, the dynamic behavior of higher order systems tends to be complex and non-intuitive.

# APPENDIX B: DOCUMENTED PROGRAM LISTING

```
0001  title TECH1.doc
0002  * abint
0003  * nostats
0004  * doc

0005  l ot.k=intgrl(otim.jk-otd.jk-otf.jk)
          ot     - production capacity (ru)
          otim   - investment maturation (ru/yr)
          otd    - depreciation (ru/yr)
          otf    - forclosures (ru/yr)

0006  n ot=otz
          ot     - production capacity (ru)
          otz    - initial production capacity (ru)

0007  c otz=4500
          otz    - initial production capacity (ru)

0008  a otrd.k=ot.k/alt
          otrd   - real depreciation (ru/yr)
          ot     - production capacity (ru)
          alt    - average capacity lifetime (yrs)

0009  r otd.kl=otrd.k
          otd    - depreciation (ru/yr)
          otrd   - real depreciation (ru/yr)

0010  c alt=15
          alt    - average capacity lifetime (yrs)

0011  r otf.kl=otfr.k*ot.k
          otf    - forclosures (ru/yr)
          otfr   - foreclosure rate (%)
          ot     - production capacity (ru)

0012  a otfr.k=tabhl(otfrc,otrt.k,-.2,0,.05)*0.01
          otfr   - foreclosure rate (%)
          otfrc  - foreclosure rate (%)
          otrt   - returns trend (%)

0013  t otfrc=10,5,2.5,1.2,0
          otfrc  - foreclosure rate (%)

0014  expnd dlinfl(otrt,otr,ltt) returns trend (average%/yr)
0015+ r $rll.kl=(otr.k-$lll.k)/ltt
0016+ l $lll.k=intgrl($rll.jk)
0017+ n $lll=otr
0018+ a otrt.k=$lll.k
0019+ mend

0020  c ltt=5
          ltt    - loss tolerance time (yrs)

0021  expnd dlinf3(otli,otqi,ii) last investment (ru)
0022+ r $rl2.kl=(otqi.k-$l12.k)/(ii/3)
0023+ l $l12.k=intgrl($rl2.jk)
0024+ n $l12=otqi
0025+ r $r22.kl=($l12.k-$l22.k)/(ii/3)
0026+ l $l22.k=intgrl($r22.jk)
0027+ n $l22=otqi
0028+ r $r32.kl=($l22.k-$l32.k)/(ii/3)
0029+ l $l32.k=intgrl($r32.jk)
0030+ n $l32=otqi
0031+ a otli.k=$l32.k
0032+ mend

0033  c ii=1
          ii     - investment interval (yrs)

0034  n otqi=otiz
          ii     - nvestment interval (yrs)
          otiz   - initial investment (ru)

0035  a otqi.k=otre.k*pfiot.k*upmiot.k
          ii     - nvestment interval (yrs)
          otre   - residual earnings ($/yr)
          pfiot  - profit factor investment (%)
          upmiot - unrealized potential mult on investment (%)

0036  a upmiot.k=tabhl(upmic,log(otco.k),0,12,2)
          upmiot - unrealized potential mult on investment (%)
          upmic  - unrealized potential mult on investment (%)
          otco   - cumulative output (ru)

0037  a pfiot.k=tabhl(pfic,otr.k/ear,0,2,.25)*.1
          pfiot  - profit factor investment (%)
          pfic   - profit factor investment (%)
          otr    - return on capital (%/yr)
          ear    - economywide average return (%/yr)

0038  t pfic=0,1,2.5,5,10,12.5,13.7,14,15

          pfic   - profit factor investment (%)

0039  a otr.k=(otre.k-otli.k)/ot.k
          otr    - return on capital (%/yr)
          otre   - residual earnings ($/yr)
          otli   - last investment (ru)
          ot     - production capacity (ru)

0040  c ear=.06
          ear    - economywide average return (%/yr)
```

```
0041  r oti.kl=otqi.k
          oti    - investment as a rate ($/yr)
          ii     - nvestment interval (yrs)

0042  expnd delay3(otim,oti,otid) investment maturation (ru/yr)
0043+ l $113.k=intgrl(oti.jk-$r13.jk)
0044+ n $113=oti*otid/3
0045+ r $r13.kl=$113.k/(otid/3)
0046+ l $123.k=intgrl($r13.jk-$r23.jk)
0047+ n $123=oti*otid/3
0048+ r $r23.kl=$123.k/(otid/3)
0049+ l $133.k=intgrl($r23.jk-otim.jk)
0050+ n $133=oti*otid/3
0051+ r otim.kl=$133.k/(otid/3)
0052+ mend
0053  n oti=otiz
          oti    - investment as a rate ($/yr)
          otiz   - initial investment (ru)

0054  c otiz=375
          otiz   - initial investment (ru)

0055  c otid=5
          otid   - investment delay (yrs)

0056  a otc.k=ot.k*otfc+oto.k*otvc.k+otrd.k
          otc    - costs ($/yr)
          ot     - production capacity (ru)
          otfc   - fixed costs ($/ru)
          oto    - output (ru/yr)
          otvc   - variable costs ($/yr)
          otrd   - real depreciation (ru/yr)

0057  a otre.k=otqd.k*ot$.k-otc.k
          otre   - residual earnings ($/yr)
          esoto  - expected sales (ru/yr)
          ot$    - price ($/ru)
          otc    - costs ($/yr)

0058  c otfc=.5
          otfc   - fixed costs ($/ru)

0059  a otvc.k=tabhl(otvcc,time.k,0,60,15)*.1
          otvc   - variable costs ($/yr)
          otvcc  - variable costs ($/yr)

0060  t otvcc=3,3,3,3,3
          otvcc  - variable costs ($/yr)
```

```
0061  a oto.k=ot.k*otef.k*otcu.k output (ru/yr)
          oto    - output (ru/yr)
          ot     - production capacity (ru)
          otef   - experience factor (%)
          otcu   - capacity utilization (%)

0062  a otcu.k=tabhl(cuc,ioto.k/esoto.k,0,2,.5)
          otcu   - capacity utilization (%)
          cuc    - capacity utilization (%)
          ioto   - inventory (ru)
          esoto  - expected sales (ru/yr)

0063  t cuc=1.3,1.1,1,.85,.75
          cuc    - capacity utilization (%)

0064  expnd dlinfl(esoto,otqd,seft) capacity utilization (%)
0065+ r $r14.kl=(otqd.k-$114.k)/seft
0066+ l $114.k=intgrl($r14.jk)
0067+ n $114=otqd
0068+ a esoto.k=$114.k
0069+ mend

0070  n otqd=5000
          esoto  - expected sales (ru/yr)

0071  c seft=2
          seft   - sales exp'tn formation time (yrs)

0072  a otef.k=tabhl(oefc,log(otco.k),0,12,2)*.1
          otef   - experience factor (%)
          oefc   - experience factor (%)
          otco   - cumulative output (ru)

0073  t oefc=1,3,5,7,9,10,10
          oefc   - experience factor (%)

0074  l otco.k=intgrl(otoa.jk)
          otco   - cumulative output (ru)
          otoa   - output accumulation (ru/yr)

0075  n otco=otcoz
          otco   - cumulative output (ru)
          otcoz  - initial cumulative output (ru)

0076  c otcoz=40000
          otcoz  - initial cumulative output (ru)

0077  r otoa.kl=oto.k
          otoa   - output accumulation (ru/yr)
          oto    - output (ru/yr)
```

```
0078  l nt.k=intgrl(ntim.jk-ntd.jk-ntf.jk)
          nt     - real production capacity (ru)
          ntim   - investment maturation (ru/yr)
          ntd    - real depreciation (ru/yr)
          ntf    - foreclosures (ru/yr)

0079  n nt=ntz
          nt     - real production capacity (ru)
          ntz    - initial production capacity (ru)

0080  c ntz=1
          ntz    - initial production capacity (ru)

0081  a ntrd.k=nt.k/alt
          ntrd   - real depreciation (ru/yr)
          nt     - real production capacity (ru)
          alt    - average capacity lifetime (yrs)

0082  r ntd.kl=ntrd.k
          ntd    - real depreciation (ru/yr)
          ntrd   - real depreciation (ru/yr)

0083  r ntf.kl=nt.k*ntfr.k )
          ntf    - foreclosures (ru/yr)
          nt     - real production capacity (ru)
          ntfr   - foreclosures (%)

0084  a ntfr.k=tabhl(ntfrc,ntrt.k,-0.2,0,.05)*0.01
          ntfr   - foreclosures (%)
          ntfrc  - foreclosures (%)
          ntrt   - returns trend (%)

0085  t ntfrc=10,5,2.5,1.2,0
          ntfrc  - foreclosures (%)

0086  expnd dlinfl(ntrt,ntr,ltt) returns trend (average%/yr)
0087+ r $r15.kl=(ntr.k-$115.k)/ltt
0088+ l $115.k=intgrl($r15.jk)
0089+ n $115=ntr
0090+ a ntrt.k=$115.k
0091+ mend

0092  expnd dlinf3(ntli,ntqi,ii)
0093+ r $r16.kl=(ntqi.k-$116.k)/(ii/3)
0094+ l $116.k=intgrl($r16.jk)
0095+ n $116=ntqi
0096+ r $r26.kl=($116.k-$126.k)/(ii/3)
0097+ l $126.k=intgrl($r26.jk)
0098+ n $126=ntqi
0099+ r $r36.kl=($126.k-$136.k)/(ii/3)
0100+ l $136.k=intgrl($r36.jk)
0101+ n $136=ntqi
0102+ a ntli.k=$136.k
0103+ mend
```

```
0104  n ntqi=ntiz
          ntli   - last investment (ru)
          ntiz   - initial investment ($/yr)

0105  c ntiz=0.067
          ntiz   - initial investment ($/yr)

0106  a ntqi.k=ntre.k*pfint.k*upmi.k
          ntli   - last investment (ru)
          ntre   - residual earnings ($/yr)
          pfint  - profit factor investment (%)
          upmi   - unrealized potential mult on invest

0107  a pfint.k=tabhl(pfic,ntr.k/ear,0,2,.25)*.1
          pfint  - profit factor investment (%)
          pfic   - profit factor investment (%)
          ntr    - returns (%/yr)
          ear    - economywide average return (%/yr)

0108  a upmi.k=tabhl(upmic,log(ntco.k),0,12,2)
          upmi   - unrealized potential mult on investment (%)
          upmic  - unrealized potential mult on investment (%)
          ntco   - cumulative output (ru)

0109  t upmic=9,7,5,3,1.5,1,1
          upmic  - unrealized potential mult on investment (%)

0110  a ntr.k=(ntre.k-ntli.k)/nt.k
          ntr    - returns (%/yr)
          ntre   - residual earnings ($/yr)
          ntli   - last investment (ru)
          nt     - real production capacity (ru)

0111  r nti.kl=ntqi.k
          nti    - investment as a rate (ru/yr)
          ntli   - last investment (ru)

0112  expnd delay3(ntim,nti,ntid) investment maturation (ru/yr)
0113+ l $117.k=intgrl(nti.jk-$r17.jk)
0114+ n $117=nti*ntid/3
0115+ r $r17.kl=$117.k/(ntid/3)
0116+ l $127.k=intgrl($r17.jk-$r27.jk)
0117+ n $127=nti*ntid/3
0118+ r $r27.kl=$127.k/(ntid/3)
0119+ l $137.k=intgrl($r27.jk-ntim.jk)
0120+ n $137=nti*ntid/3
0121+ r ntim.kl=$137.k/(ntid/3)
0122+ mend

0123  n nti=ntiz
          nti    - investment as a rate (ru/yr)
          ntiz   - initial investment ($/yr)
```

```
0124  c ntid=5
        ntid    - maturation delay time (yrs)

0125  a ntre.k=ntqd.k*nt$.k-ntc.k
        ntre    - residual earnings ($/yr)
        esnto   - expected sales (ru/yr)
        nt$     - price ($/ru)
        ntc     - costs ($/yr)

0126  a ntc.k=ntfc*nt.k+ntvc.k*nto.k+ntrd.k
        ntc     - costs ($/yr)
        ntfc    - fixed costs ($,yr)
        nt      - real production capacity (ru)
        ntvc    - variable costs ($/ru)
        nto     - output (ru/yr)
        ntrd    - real depreciation (ru/yr)

0127  c ntfc=.5
        ntfc    - fixed costs ($,yr)

0128  a ntvc.k=tabhl(ntvcc,time.k,0,60,15)
        ntvc    - variable costs ($/ru)
        ntvcc   - variable costs ($/ru)

0129  t ntvcc=.3,.3,.3,.3,.3
        ntvcc   - variable costs ($/ru)

0130  a nto.k=ntef.k*nt.k*ntcu.k
        nto     - output (ru/yr)
        ntef    - experience factor (%)
        nt      - real production capacity (ru)
        ntcu    - capacity utilization (%)

0131  a ntcu.k=tabhl(cuc,into.k/esnto.k,0,2,.5)
        ntcu    - capacity utilization (%)
        cuc     - capacity utilization (%)
        into    - inventory output (ru)
        esnto   - expected sales (ru/yr)

0132  expnd dlinfl(esnto,ntqd,seft) expected sales (ru/yr)
0133+ r $r18.kl=(ntqd.k-$118.k)/seft
0134+ l $118.k=intgrl($r18.jk)
0135+ n $118=ntqd
0136+ a esnto.k=$118.k
0137+ mend

0138  n ntqd=1 initial sales (ru)
        esnto   - expected sales (ru/yr)

0139  a ntef.k=tabhl(nefc,log(ntco.k),0,12,2)*.1
        ntef    - experience factor (%)
        nefc    - experience factor (%)
        ntco    - cumulative output (ru)

0140  t nefc=3,5,7,8,9,10,10
        nefc    - experience factor (%)

0141  l ntco.k=intgrl(ntoa.jk)
        ntco    - cumulative output (ru)
        ntoa    - output accumulation (ru/yr)

0142  n ntco=ntcoz
        ntco    - cumulative output (ru)
        ntcoz   - initial cumulative output (ru)

0143  c ntcoz=1
        ntcoz   - initial cumulative output (ru)

0144  r ntoa.kl=nto.k
        ntoa    - output accumulation (ru/yr)
        nto     - output (ru/yr)

0145  l fmnt.k=intgrl(ms.jk)
        fmnt    - fraction of market to nt (%)
        ms      - market switching (%/%/yr)

0146  n fmnt=fmntz
        fmnt    - fraction of market to nt (%)
        fmntz   - initial % market to nt (%)

0147  c fmntz=0.0000129
        fmntz   - initial % market to nt (%)

0148  r ms.kl=(afms.k+pfms.k)*(sg.k)
        ms      - market switching (%/%/yr)
        afms    - attractiveness factor in switching
        pfms    - price factor market switching
        sg      - switching group (%)

0149  a sg.k=clip(fmnt.k,(1-fmnt.k),nt$.k/ot$.k,1)
        sg      - switching group (%)
        fmnt    - fraction of market to nt (%)
        fmnt    - fraction of market to nt (%)
        nt$     - price ($/ru)
        ot$     - price ($/ru)

0150  a pfms.k=tabhl(pmmsc,nt$.k/ot$.k,0,3,.5)*.01
        pfms    - price factor market switching
        pmmsc   - price factor market switching (%)
        nt$     - price ($/ru)
        ot$     - price ($/ru)

0151  t pmmsc=25,10,0,-5,-10,-13,-15
        pmmsc   - price factor market switching (%)
```

```
0152  a afms.k=tabhl(afmsc,time.k,0,60,15)*.01
          afms    - attractiveness factor in switch
          afmsc   - attractiveness factor in switching (%)

0153  t afmsc=0,0,0,0,0
          afmsc   - attractiveness factor in switching (%)

0154  a mkt.k=5000*exp(mgr*time.k)
          mkt     - market size (ru/yr at price=$1)
          mgr     - market growth (%/yr)

0155  c mgr=0
          mgr     - market growth (%/yr)

0156  l into.k=intgrl(ntoa.jk-ntqdr.jk)
          into    - inventory output (ru)
          ntoa    - output accumulation (ru/yr)
          ntqdr   - quantity demanded (ru)

0157  n into=intoz
          into    - inventory output (ru)
          intoz   - initial inventory (ru)

0158  c intoz=1
          intoz   - initial inventory (ru)

0159  a ntqd.k=pmdnt.k*fmnt.k*mkt.k
          esnto   - expected sales (ru/yr)
          pmdnt   - price mult demand (%)
          fmnt    - fraction of mkt to nt (%)
          mkt     - market size (ru/yr at price=$1)

0160  r ntqdr.kl=ntqd.k
          ntqdr   - quantity demanded (ru)
          esnto   - expected sales (ru/yr)

0161  a pmdnt.k=tabhl(pmdc,nt$.k,0,3,.5)
          pmdnt   - price mult demand (%)
          pmdc    - price mult demand (%)
          nt$     - price ($/ru)

0162  t pmdc=2.5,1.5,1,.82,.7,.65,.60
          pmdc    - price mult demand (%)

0163  a nt$.k=tabhl(o$c,into.k/esnto.k,0,4.0,.5)
          nt$     - price ($/ru)
          o$c     - price ($/ru)
          into    - inventory output (ru)
          esnto   - expected sales (ru/yr)

0164  t o$c=10,3,1,.9,.82,.74,.7,.69
          o$c     - price ($/ru)
```

```
0165  l ioto.k=intgrl(otoa.jk-otqdr.jk)
          ioto    - inventory (ru)
          otoa    - output accumulation (ru/yr)
          otqdr   - quantity demanded (ru/yr)

0166  n ioto=iotoz
          ioto    - inventory (ru)
          iotoz   - initial inventory (ru)

0167  c iotoz=4500
          iotoz   - initial inventory (ru)

0168  a otqd.k=pmdot.k*(1-fmnt.k)*mkt.k
          esoto   - expected sales (ru/yr)
          pmdot   - price mult demand (%)
          fmnt    - fraction of mkt to nt (%)
          mkt     - market size (ru/yr at price=$1)

0169  r otqdr.kl=otqd.k
          otqdr   - quantity demanded (ru/yr)
          esoto   - expected sales (ru/yr)

0170  a pmdot.k=tabhl(pmdc,ot$.k,0,3,.5)
          pmdot   - price mult demand (%)
          pmdc    - price mult demand (%)
          ot$     - price ($/ru)

0171  a ot$.k=tabhl(o$c,ioto.k/esoto.k,0,4.0,.5)
          ot$     - price ($/ru)
          o$c     - price ($/ru)
          ioto    - inventory (ru)
          esoto   - expected sales (ru/yr)

0172  s ntei.k=log(ntco.k)
          ntei    - efficiency index (ln(ru))
          ntco    - cumulative output (ru)

0173  s otei.k=log(otco.k)
          otei    - efficiency index (ln(ru))
          otco    - cumulative output (ru)

0174  parm dt=.01
0175  parm start=0
0176  parm stop=60
0177  parm pltper=1.5
0178  parm prtper=5
```

## REFERENCES

Anderson, Oscar Edward Jr. (1953) Refrigeration in America: A History of a New Technology and Its Impact. Princeton N.J.: Princeton University Press.

Arrow, K.J (1962) The economic implications of learning by doing. Review of Economic Studies (29):155-173.

Bright, James R. (1958) Automation and Management. Cambridge, Massachusetts: Harvard University Press.

Davisson, William I. and John J. Uhran Jr. (1977) A Primer for NDTRAN: A Systems Dynamics Interpreter. Notre Dame, Indiana: University of Notre Dame plus draft of updated version of same. Due for publication in 1980.

Fisher, J.C. and R.H. Pry (1970) A simple substitution model of technological change. Report 70-C-215, General Electric Co. Research and Development Center, Schenectady, N.Y., Technical information series. See also Technological Forecasting and Social Change (3):75-88.

Forrester, Jay W. (1968) Industrial Dynamics. Cambridge, Massachusetts: M.I.T Press.

Galbraith, J.K. (1967) The New Industrial State. Boston: Houghton Miffin Co.

Giedion, Siegfried (1948) Mechanization Takes Command. New York: Oxford Universty Press.

Gold, Bela, William S. Pierce and Gerhard Rosegger (1975) Diffusion of major technological innovations. Pages 129-147, Technological Change: Economics, Management and Environment, edited by Bela Gold. Oxford: Pergammon.

Markowich, P. (1979) Sensitivity Analysis of TECH1--A Systems Dynamics Model for Technological Shift. WP-79-78. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Meadows, Dennis L. (1970) Dynamics of Commodity Production Cycles. Cambridge, Mass.: Wright Allen Press.

Peterka, V. (1977) Macrodynamics of Technological Change: Market Penetration by New Technologies. IIASA RR-77-22, International Institute for Applied System Analysis, Laxenburg, Austria.

Pugh, Alexander L. III (1970) DYNAMO II User's Manual. Cambridge, Massachusetts: M.I.T. Press.

Rademaker, O. (1973) On understanding complicated models: Simple methods. Presented to the American-Soviet Conference on Methodological Aspects of Social Systems Simulation, Sukhumi, U.S.S.R., Oct. 24-26/

Robinson, Jennifer (1979) Technological Shift as Related to Technological Learning and Technological Change. WP-79-106. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Smith, Adam (1776) The Wealth of Nations. Book I, Chapter 1: On the Division of Labor. Numerous publishers.

Steen, Herman (1963) Flour Milling in America. Minneapolis: T. Denison and Company.

Utterback, James M. (1979) Business invasion by innovation. Technology Review. (81): ??