Manufacturing Progress with Embodied Technological Change

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Introduction

The learning curve characterizes the reduction in unit costs as manufacturing experience accumulates. The following form is frequently used:

$$x = KY^{-a} \qquad (1)$$

where x is the cost of the Y'th item produced and K and a are positive constants. K is also the initial cost. The rate of reduction in costs is often expressed by the improvement ratio p, which is the relative cost after every doubling of output. From Equation 1,

$$p = 2^{-a}, \text{ so that } a = -\log p / \log 2.$$

However, several other functional forms have been proposed to deal with one or more of the following phenomena:

1) An initial downward concavity of the relationship may be found (Garg & Milliman 1961);
2) A "plateau effect," the eventual lack of any improvement with additional output, has also been observed (Conway & Schultz 1959; Baloff 1966, 1971);
3) Sudden reductions in labor hours may occur after significant periods of no improvement at all (Abernathy & Wayne 1974; Bright 1958).

Search Explanations of Learning

A model proposed by Muth (1986) implies the power function rela- tion, and is consistent with certain deviations from it, such as the initial concavity, the plateau effect, and irregularity of improve- ments. The hypotheses of the model are:

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1) Cost reductions are realized through independent random sampling (search) in a space of [technological, managerial, or behavioral] alternatives. The cumulative distribution of hours, or costs, is denoted by $F(x)$;

2) Low cost techniques for each manufacturing operation are adopted when discovered. A manufacturing process consists of one or more independent operations;

3) The distribution of unit costs approaches a power function at a lower bound (denoted by x_0). That is:

$$\lim_{x \to x_0} \frac{F(x)}{(x - x_0)^k} = c, \text{ a constant.} \tag{2}$$

Furthermore, the lower limit on x is zero ($x_0 = 0$);

4) Search is prompted by production activity. Hence the sample size n is proportional to cumulative output Y, subject to two qualifications: Sampling (1) may be carried out before actual production and (2) may terminate completely when the rate of improvement becomes sufficiently small.

Search may be terminated if the expected return from search is less than its cost. The decision to continue or abandon search is based on the dynamic programming model:

$$\phi_n(x) = \min \begin{cases} x + \beta\phi_{n+1}(x) \\ s + min(x, z) + \beta E_z\phi_{n+1}(\min(x, z)) \end{cases} \tag{3}$$

where x is the random variable denoting hours or costs;

s is the cost of a unit of search activity after n units have been produced;

ϕ_n is the minimum present value of the sum of labor and search costs from n+1 units to the end of the planning horizon; and

β is the discount factor.

This model assumes that any improvement technology is adopted as soon as it is found. The model indicates at each period whether to continue or abandon search. In this respect it resembles certain em- ployment search models (see Lippman & McCall 1976). The primary con- cern of such models is the stop rule indicating when the individual stops searching and accepts an employment offer. For learning curves the primary concern is the rate of improvement during the search pro- cess, while the plateau of the learning curve, characterized by the stop rule, is a secondary concern.

Three problems with explanations of learning curves based on search are addressed in a previous paper (Muth 1988):

1) Hypothesis 3 of the search model comes dangerously close to assuming the answer;
2) Independent random search (according to Hypothesis 1) in the space of options is unlikely. Certain deterministic strategies (local search, top-down search) appear to be used;
3) Models of learning curves exhibit very strong decreasing returns to search. This fact is not consistent with the historical pattern of invention and innovation (something like exponential growth).

Objectives of Present Paper

The search model (Equation 3) is consistent with all the empiri- cally observed properties of the learning curve phenomenon, and also very robust under various alternate assumptions. The drawback of this model is that it asserts that a better technology is adopted as soon as it is found. This assumption is not empirically supported.

Quite extensive empirical studies have shown that new technolo- gies or new production methods are not adopted immediately when they are discovered, as the second hypothesis asserts (Denslow & Schulze 1974; Enos 1958; Griliches 1957; Karlson 1986; Rosenberg 1963, 1972, 1976; Williamson 1971).

The rate of adoption may be influenced by many factors, such as expectations of future technological change, limited possibilities of obtaining or using information about new processes, uncertainty con- cerning profitability or the value of the information collected, in- vestment requirements, attitudes of management, competition and market structure, and the legislation and administrative regulations, can discourage the prompt adoption of new technologies (Balcer & Lippman 1984; Barzel 1968; Kamien & Schwartz 1972, 1982; Lippman & McCardle 1987; Mamer & McCardle 1987; Mansfield 1961; McCardle 1985; Nabseth & Ray 1974).

The prevalent model of technological change is the logistic curve, which is ordinarily based on a model of contagion. The process of the spread of information concerning technology is viewed as being from a central source and other users. While this may be an adequate explanation for some consumer nondurables, it is not adequate for in- dustrial processes.

The displacement of sail by steam took more than a century (see Figure 1). Such a slow displacement could not possibly be explained by information transfer. In addition, steam never took over the entire market, because motor propulsion became important before sail was completely displaced, with an irregularity during World War II be- cause Liberty Ships were powered by steam.

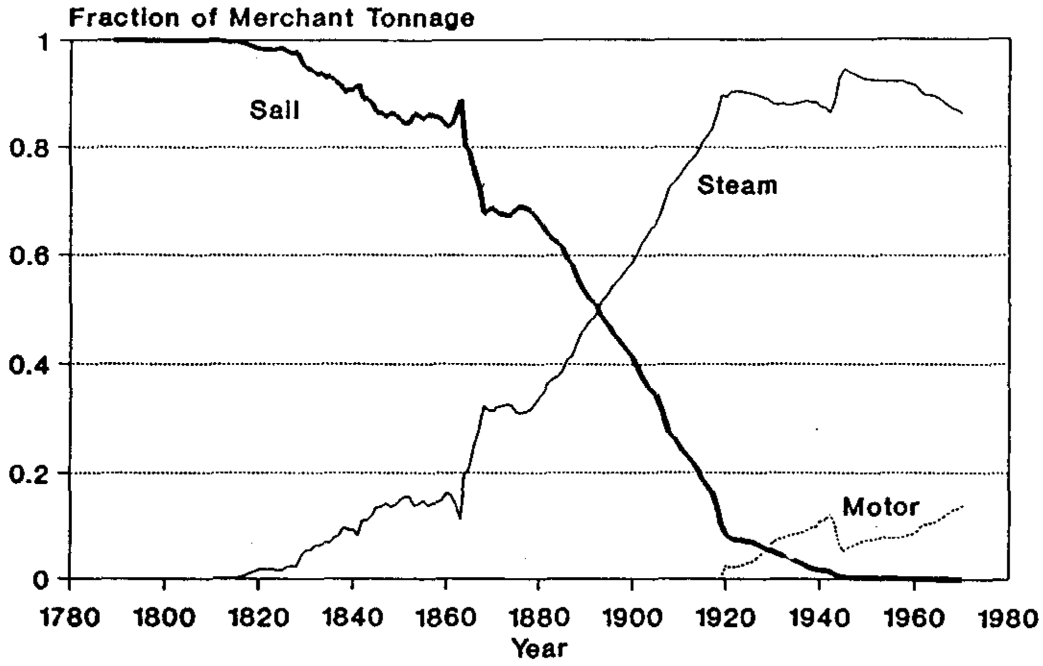

Figure 1. Fraction of Merchant Tonnage by Type of Propulsion
Source: *Historical Statistics of the U.S.*

The data of Figure 1 conceal the fact that both sail and steam were undergoing significant developments throughout this time period. In addition, designs were specialized according to the type of trade the vessel was engaged in and the cargo carried (see Chapelle 1935).

The variety of substitution curves in the steel industry is de- picted by Figure 2. Growth in the relative importance of the Bessemer process was quite rapid, in part because the suitability of the output for railroads. The crucible process did not die out completely for some time because its output was well adapted to cutlery and tools. The rise of the open hearth process was quite slow, but its demise was quite rapid. The basic oxygen and electric processes now coexist in different segments of the steel industry (primary producers and minimills, respectively). An electric process was more significant than the open hearth for a short time in the 19th century.

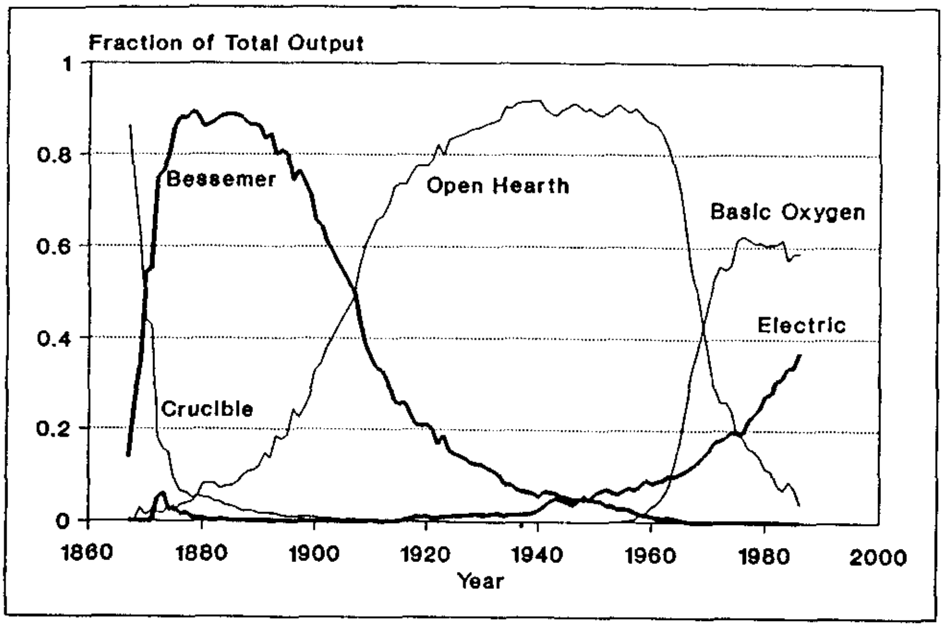

Figure 2. Fraction of Total U.S. Steel Output by Type of Process
Sources: *Historical Statistics of the U.S.*, and
American Iron and Steel Institute, *Annual Statistical Report*

It is interesting to note that Bessemer was aware of the advan- tages of the oxygen process, but it could not be economical until an inexpensive means of producing oxygen by the fractional distillation of liquid air was developed in the late 1920's (Rosegger 1986). The basic oxygen process was not developed until 1952, however, and was not important in the U.S. until the 1960's.

Not only is the information transfer model inadequate to explain these phenomena, but the logistic curve is sometimes a poor empirical fit.

Deterministic Models for the Adoption of New Technology

The models proposed here are based on Bellman (1955), especially the second model, which takes obsolescence as well as deterioration into account. One difference is Bellman's model is deterministic be- cause it assumes that the decision maker has full knowledge of the timing and quality of new machines.

The model is rephrased in cost minimization form as follows:

$$\phi_n(x, x^*) = \min \begin{cases} x + \beta\phi_{n+1}(x, x^{**}) \\ x^{**} + I + \beta\phi_{n+1}(x^{**}, x^{**}) \end{cases} \quad (4)$$

where $\phi_n(x, x^*)$ is the minimum present value of the sum of operating costs from n+1 to the end of the planning horizon when the current cost is x, and the best known cost is x^*;

$x^{**} = \min(x^*, z)$;

x^* is the annual operating cost of the best known technology;

z is the annual operating cost of the new technology (which may change with each time period); and

I is the investment outlay for new technology.

The deterministic technological change model suffers from a very unrealistic assumption that the technological environment surrounding a manufacturing concern is predictable.

Stochastic Technological Change Model

In order to overcome the weakness of the deterministic model, let us now assume that the adoption of new technology can be delayed and the future is uncertain. To accommodate the possible delayed adoption of new technologies, the best known technology may be recalled at a later time period and adopted, and this recall process can be incorpo- rated into the model by providing an additional state variable, x^*. Furthermore, to circumvent the apparent ignorance of precise cause and effect of the internal and external forces affecting to the discovery of new technologies, stochastic influence on the timing and the cost of the emerging new technologies is incorporated by introducing random variables with known distributions. The random variables, in this case the cost of the different technologies, are assumed to be inde- pendent of each other, but they share the same distribution. In such a stochastic system the expected cost is the criterion function, pre- suming that the system will converge to the expected value in the long-run.

The first model is for the case where the search activity for better production methods is never terminated regardless of the changing economic environment. The second model is for the case where the search activity may be terminated altogether at some point of time when it is considered uneconomical and then renewed after a while, in an on and off fashion, depending upon the changing economic variables. Since the impact of the search term on the new technology adoption behavior has been discussed (Muth 1986), this paper is primarily con- cerned with the first model.

The assumptions made for both of these models are:

1) *Divisibility of innovation*: due to economies of scale, only some larger producers can afford to some innovations and take advantage of them. However, it is assumed here that any innovation can be adopted in a reduced scale for a proportionate price;
2) *Constant discount rate*;
3) *Infinite service life*: once adopted, the service life of an innovation is assumed to last forever;
4) *Innovations available forever*: once an innovation becomes available it will be available forever thereafter;
5) *Sampling from a stationary distribution*: productivity improvements are realized through independent sampling (search) from a space of [technological, managerial, or behavioral] alternatives, and the distribution function of profitability of the different alternatives does not change through time;
6) *Risk neutrality*: decision makers are assumed to be risk-neutral.

Stochastic Technological Change Model

In this model there are two decision options: Compare the best known technology so far, x^*, and the newly found one at the beginning of the current period, z, and adopt whichever the better one, x^{**}, or update the incumbent and do nothing. Define $\phi_n(x, x^*)$ as in the de- terministic technological change model. Then the optimum follows from the equation:

$$\phi_n(x, x^*) = \min \begin{cases} x + \beta E_z\phi_{n+1}(x, x^{**}) \\ E_z x^{**} + I + \beta E_z\phi_{n+1}(x^{**}, x^{**}) \end{cases} \tag{5}$$

where E_z is the operator signifying the expectations with respect to z.

Stochastic Technological Change with Search Model

In this model there are three decision options: Search for a new technology and then compare the newly found one, z, with the best known one, x^*, and adopt whichever is better; search for a new technology and update incumbent but keep the current one which costs x, and finally, do nothing but keep the current one. The optimum follows from the equation:

$$\phi_n(x, x^*) = \min \begin{cases} x + \beta E_z\phi_{n+1}(x, x^{**}) \\ s + \min \begin{cases} x + \beta E_z\phi_{n+1}(x, x^{**}) \\ E_z x^{**} + I + \beta E_z\phi_{n+1}(x^{**}, x^{**}) \end{cases} \end{cases} \qquad (6)$$

where s is the search cost.

Regions for Adoption and Search

The nature of the decision to invest in new technology or not is illustrated in Figure 3, which gives the choice regions for retaining the existing technology or replacing with the best found one as a function of the costs of the best known and the already utilized tech- nologies. The dotted line, which is the asymptote of the boundary, has the equation $x^* = x - rI/(1 + r)$.

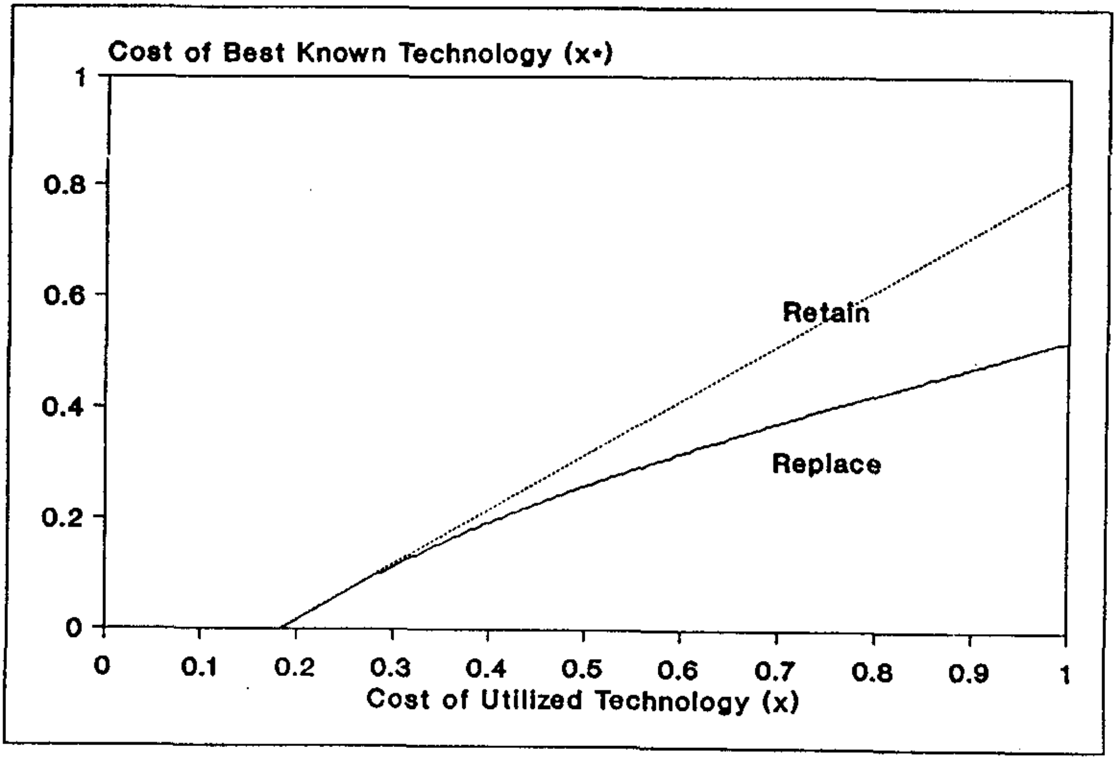

Figure 3. Decision to Replace or Retain as a Function of the Best known and Already Utilized Technologies.

Value iteration was used on Equation 5 with a planning horizon of 150 time periods. The continuous values of x and x^* were approximated by a discrete grid of 250 values. The distribution of z follows Equation 2 with c = 1, x_0 = 0, and k = 2, which corresponds to a 71% improvement rate. The investment outlay, I, was taken at a constant value of 2 and the interest rate, r, was 0.1.

This illustration provides insights about the properties of the optimal solution of the stochastic technological change model when the planning horizon is infinite. The first is the downward concavity of the adoption curve where the cost is around 1.

Another interesting observation is the convergence of adoption curve to $rI/(1 + r)$. Given the assumption of infinite service life of a piece of machine embodying an innovation, in the long run, the mini- mum allowable return of adopting one (marginal return) should be equal to the current operating cost (marginal cost).

Evolution of Technology

In this section the optimal paths of new technology adoption are examined, and the timing of adoption and the lags involved for the first model proposed. The time paths of technological change were calculated with simulation techniques. With a high initial cost of one, new values were sampled for 200 simulated time periods. The decision to replace or retain was then made on the basis of the regions given in Figure 3.

Learning Curve

The first result is the cost for a single simulated firm as a function of time, equated with the number of observations, as in Figure 4. This is the learning curve with an investment cost. Also plotted as a dotted line is the time path of the best technology known to the firm. Although the best known technology continues irregularly throughout the observed period, a plateau is reached abruptly for the utilized technology around period 10. This shows that the model is sufficient to explain irregularity of improvement, as well as a plat- eau. This does not, however, rule out other explanations of these phenomena.

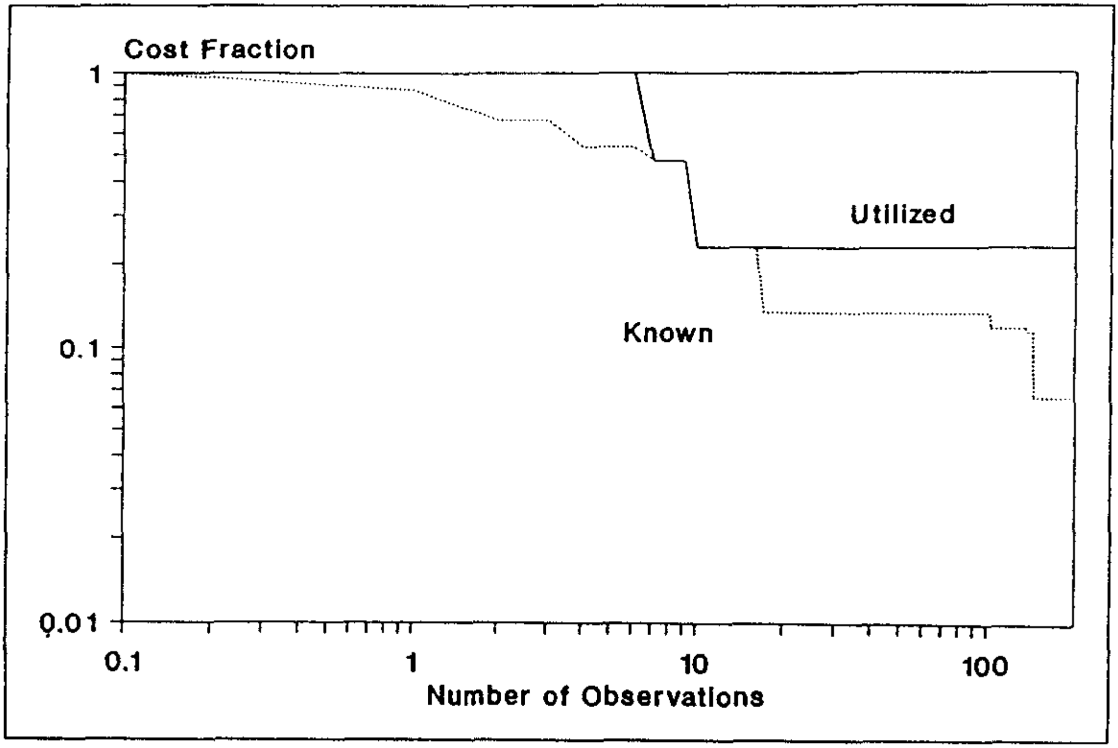

Figure 4. Learning Curve for a Single Firm

The average of the best known and utilized technologies for 1,000 simulated firms is given in Figure 5. The initial concavity of the learning curve shows up well, but the average of the plateaus is gradual. The initial concavity arises from deferring replacement in the expectation of further improvements to be found in the future. The plateau arises from improvements not being sufficiently large to exceed the rental price of the new equipment, namely $rI/(1 + r)$.

Number of Observations for a Cost Level

The distribution of the number of observations necessary to achieve reduced cost levels of 0.7, 0.5, and 0.3, respectively is drawn in Figure 6. It is somewhat different from the usual form of the substitution curve for new technologies, because it is for a value of a figure of merit and not a specific technology, such as the basic oxygen process. In this case, the curves are exponential in their general shape and do not have the initial "toe-in" that the logistic curve possesses. Some values of the parameters lead to such behavior, but do not appear to be the usual case.

Number of Observations for the Adoption Generation

The distribution of the number of observations necessary for the adoption of successive technologies is given in Figure 7. Note that the curve for the second innovation appears to be concave upwards initially and that very few of the firms adopt a third innovation, even after one hundred observations.

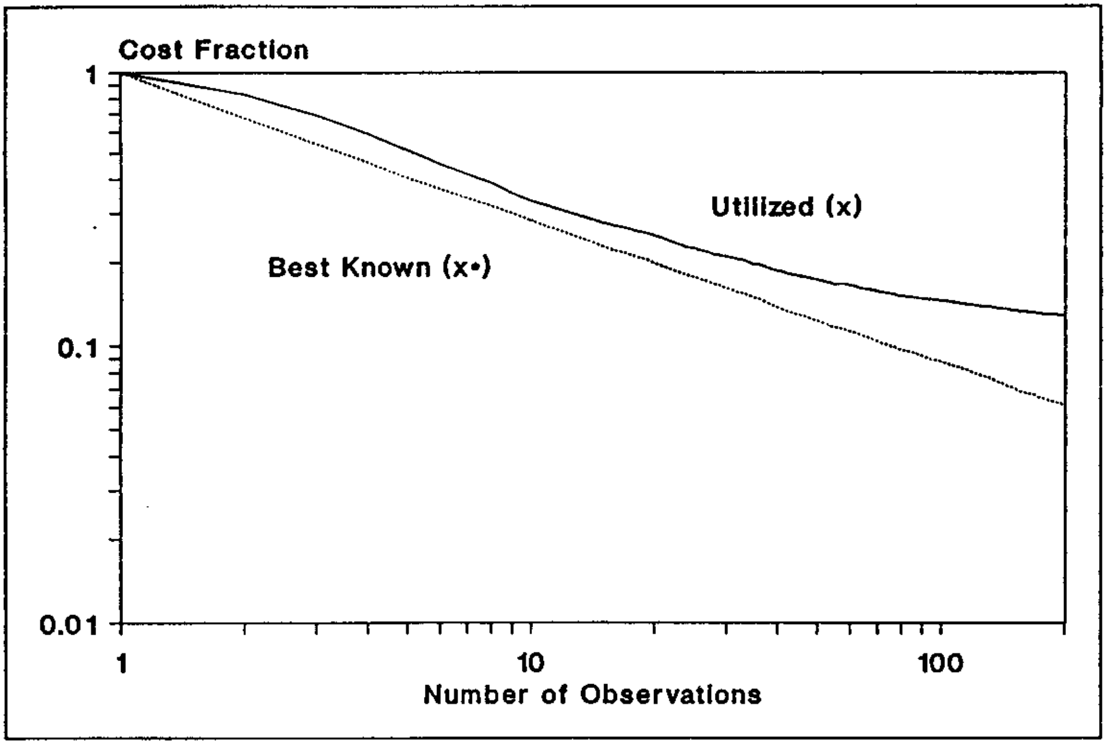

Figure 5. Learning Curves (Sample Size = 1,000)

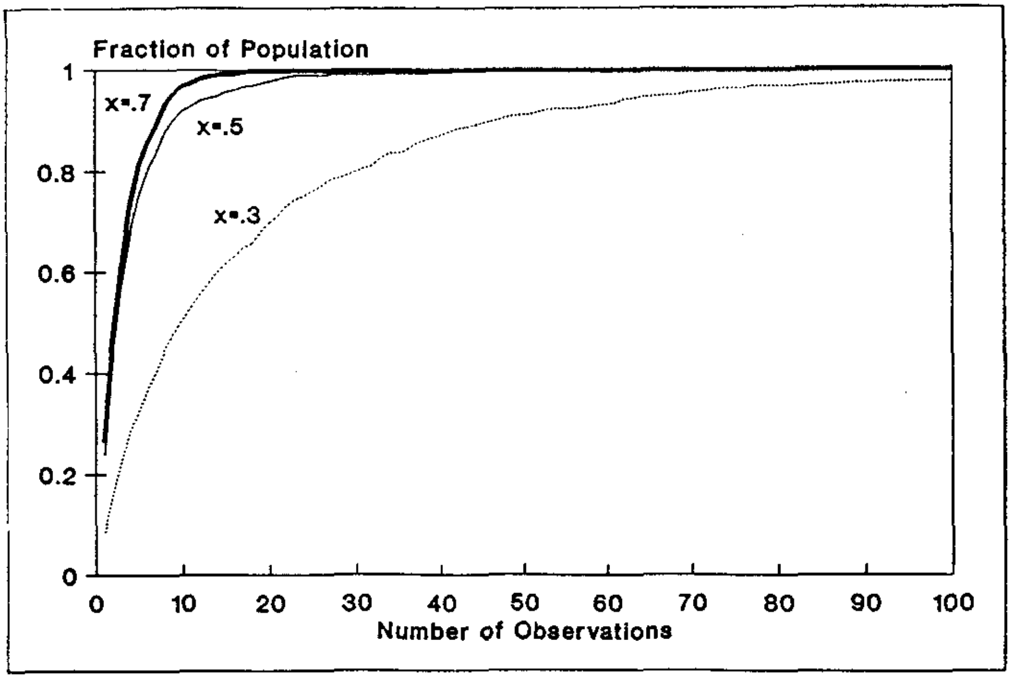

Figure 6. Distribution of the Number of Observations to Achieve a Given Cost Level

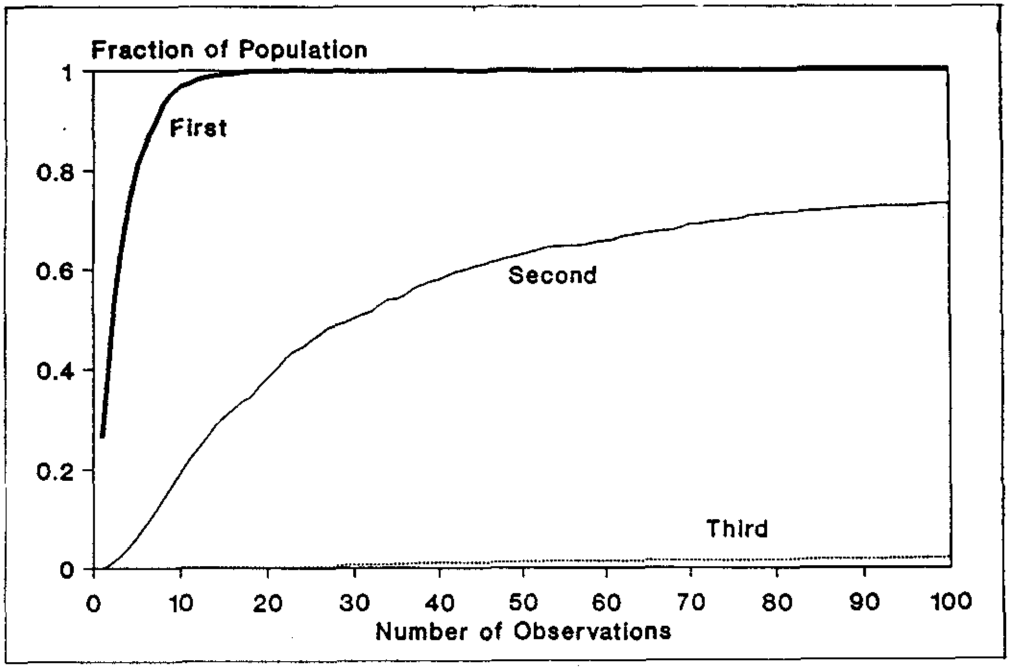

Figure 7. Distribution of the Number of Observations for Successive Adoptions

Conclusions

In order to explain certain improvement phenomena, this paper uses dynamic programming models in which the benefits of inventive ac- tivity are realized only after investment is made in equipment incor- porating the newly discovered technologies. The proposed models gen- eralize a hypothesis in a model of the learning curve asserting that process changes are introduced as soon as they are found. They pre- dict delayed investment in the expectation that something better comes available later. They thus provide an interpretation of technical in- efficiency. The models also explain initial non-linearities and plat- eaus in learning and substitution curves. Further experiments with different parameter values are reported in Shin (1990).

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국문요약 :

오래도록 生產性向上曲線 (또는 學習曲線), 生產函數, 그리고 代替曲線 등은, 서로 관련이 없는 別個의, 그리고 순전히 經驗的인 (empirical) 現象들인 것들로서 이해되어 왔었다. 그러나 1980년대 중반에 발표된 Muth 敎授의 探索理論 (Search Theory)이 생산성향상곡선에서 관찰된 諸般현상들을 모두 설명함으로써 이들 현상은 하나의 통합이론체계에 의하여 일관되게 설명되게 되었다. 이 理論의 초기형태는 그 普遍性을 구속하는 네가지 假說위에 설립되었었으나 점차적으로 이들 가설들이 완화되면서 (relaxed) 이 理論은 또한 解釋力에서 뿐만 아니라 一般性에 있어서도 계속 강화되어 왔다.

본 論文의 目的은, 이들 네가지 가설들 중 유일하게 아직 緩和되지 못하고 있는, 實際 현상과 다분히 遊離된, 두번째 假說, 즉 「생산성향상을 위한 탐색과정에서 새로이 발견된 개량 新技術 (또는 생산방식) 은 卽刻的으로 採擇될 것」이라는 가설을 緩和함으로써, 보다 현실에 대한 해석력과 일반성 면에서 개선된 모델을 제시하는데 있다. 이를 위하여 제시된 모델은 Muth 교수의 탐색이론모델에 두가지 변수를 더함으로써 擴張하여 만든 모델이다. 이 두 변수는 신기술의 채택 (또는 획득) 을 위하여 지불하여야 하는 投資費변수와 탐색과정을 통하여 발견은 되었으나 아직 채택은 되지 않은, 留保상태 신기술의 運營費用변수 (또는 收益性변수) 등이다.

이 모델의 內容은, 생산성향상은 신기술이 具現된 (embodied) 裝備 (equipment) 를 使用함으로써 실현되며, 따라서 創意的 活動의 利得은 이들 裝備에 대한 投資행위로서 실현된다는 것이다. 이 모델은 보다 나은 신기술이 또 발견될 것이라는 期待下에, 현재 발견된 最新技術을 채택하지 않는 投資遲延현상을 예측·설명해 주며 따라서 이로 인한 技術的 非效率性의 존재이유를 제시한다. 또한 이 모델은 생산성향상곡선의 初期屈曲현상, 停滯현상, 그리고 跳躍현상 등을 모두 설명해 준다.