Working Paper

THE ECONOMIC BENEFITS OF
COMPUTER-INTEGRATED MANUFACTURING
(PAPER I)

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May 1987

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International Institute for Applied Systems Analysis
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FOREWORD

Two papers are presented here together in one package. The first which follows, is a general introductory and theoretical discussion of the problem of economic benefits estimation for CIM technologies. It was written by Robert U. Ayres, leader of the CIM project and Jeffrey L. Funk, now at Westinghouse R&D center. The second paper presents a particular (macroeconometric) methodology as applied to the benefits of robots and NC machine tools for a single country: Japan. It was written by Shunsuke Mori, a member of the CIM project team at IIASA. It is hoped that the results will be of considerable interest in themselves, as well as providing a viable model for future extension to other countries.

Two earlier CIM Working Papers are relevant to the approaches discussed here, namely [Ayres 86f] and [Ayres 87b].

Thomas H. Lee
Program Leader
Technology, Economy, Society

The Economic Benefit of Computer-Integrated Manufacturing[1]

Introduction[2]

The evolution of manufacturing technology from the 1820's until after World War II can be characterized broadly as exploiting economies of mechanization, specialization, standardization, and scale. On an aggregate level, the productivity of workers was enormously increased by mechanization, subdividing, and rationalizing complex non-repetitive tasks into a sequence of simpler repetitive ones, higher precision, and higher operating rates of machine tools, mass production of truly interchangeable standard parts, use of dedicated automatic machines to maximize parts output rates, and mechanical assistance for parts handling and assembly. Labor productivity improvements from the 1820's to the 1950's vary from one product to another, but in many cases the overall improvement was several orders of magnitude. Metal cutting rates, for example, increased by over 100 times from 1890 to 1970. However, by 1970 the potential for further improvements along the same lines was far more modest in most cases. Since 1950, the emphasis has shifted toward programmability and flexibility. The driving force for this shift arises out of the growing complexity and

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[1]Computer Integrated Manufacturing (CIM) refers to the use of computers to control the manufacture of discrete items. It covers, therefore, materials handling and storage, cutting, forming and shaping, parts, heat treating, surface finishing, joining (e.g. welding), assembly, and inspection. It also covers associated "overhead" activities such as design, production, engineering, quality control, plant operation, and internal maintenance, and packing and shipping.

[2]This section has been taken from the prospectus for the CIM project (IIASA, September 30, 1986).

diversity of the modern industrial economy.[3]

Increasingly, the problem of production is a problem of resource planning (i.e. coordinating suppliers and optimizing materials handling) and of inventory management. From another perspective, the problem of manufacturing is inherently information-intensive, involving many tens of thousands of binary go/no (yes/no) decisions based on sensory data gathered at many points in space and time about the state of each tool, each component, each subsystem, and the production environment. Historically, only human workers have had the sensory capability to acquire and interpret the data needed to make these binary go/no decisions. However, since the early 1980's manufacturing firms have begun to have an available alternative to humans: the machine or robot controlled by a "smart sensor".

The accumulation of technological changes in solid-state electronics and computer science since the mid-20th century seems to have finally reached a critical point. Solid-state microprocessors linked to solid-state sensory devices will soon begin to offer more accurate and reliable means of coordinating the complex processes required in modern manufacturing. "Smart sensors" are critical building blocks of the foreseeable computer-integrated, unmanned manufacturing plant of the future.[4]

It is one primary hypothesis of the CIM study that the driving force behind this change is not a wish to avoid high

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[3]For a more extended discussion of these issues in the CIM Working Paper series see [Ayres 86f, Ayres 87b].

[4]See Ayres [Ayres & Funk 85, Ayres 86c], articles forthcoming in <u>Robotics Journal</u> and <u>Prometeus</u>.

labor costs per se, but the need to escape from the bureaucratic inflexibility of organizations and the physical inflexiblity of mechanisms that were the price of relying on error-prone human workers for all of the micro-scale information processing functions in the conventional factory. Ultimately, it may be the desire to continually increase reliability and quality without sacrificing flexiblity that is the chief driving force behind the trend toward computer integrated manufacturing.

In addition, we hope to test several subsidiary hypotheses:

- that flexiblity to respond quickly to market changes is at best a secondary motivation for most early users in the first tier (systems integrators) and third tier suppliers (job shops), but may become a strong motivation for second-tier suppliers currently dependent on "Detroit Automation".
- that, currently, CIM is not needed by large-scale producers (systems integrators) to achieve major inventory savings and faster turnaround, and that CIM will get increased attention by these manufacturers only after the "easy" savings from statistical quality control, `just-in-time' methods (kan-ban), or materials-resource planning (MRP) have already been achieved. CIM may offer more immediate benefits to second tier suppliers who are under increasing pressure from their customers to meet more exacting delivery schedules, with shorter production runs.

- that economies of scale will have a decreasing influence in coming decades, whereas economies of scope (i.e. capital sharing facilitated by increased flexibility) will have an increasing influence.
- that, as a consequence of increasing flexiblity of major second-tier suppliers, the traditional niche for specialty subcontractors and suppliers will erode.

Benefits Measurement

The various hypotheses stated above imply that improved product quality and increased flexibility in the use of capital are beneficial to users of CIM. However the argument thus far is only qualitative. To carry it a step further one must define quality and flexibility more precisely and formulate them in terms of conventional economic variables and models. This is the next task to be undertaken, and it is a vital one.

To organize the discussion, it is helpful to consider five possible kinds of economic benefit. The list follows:

1. Labor saving. Some CIM technologies (most notably robots) can be regarded as direct substitutes for semi-skilled human labor. This means that robots (sometimes called "steel collar workers") can also be regarded as additions to the labor force, although their `wages' are partly operating costs and partly costs of capital.
2. Capacity augmenting. Some CIM technologies, such as scheduling systems and programmable controllers (PC's) with sensory feedback, can be regarded as creating additions to capacity. This is the case to the extent

that they increase the effective utilization of existing machine tools and other capital equipment (e.g. by permitting unmanned operation at night) or permit faster turnarounds and reductions in the inventory of work-in-progress. The productivity of capital is thus increased.

3. Capital-sharing. The major benefit of "flexibility", as the concept is normally understood, is that it permits faster response to changing market conditions, or superior ability to differentiate products.[5] The major reason for slow response is the widespread use of dedicated, specialized ("Detroit") automation in mass production. Here, the lowest possible marginal unit cost is achieved at the expense of very high fixed capital investment and large write-offs in case the product becomes obsolete and cannot be sold. Flexibility in this context is the ability to adapt (or switch) capital equipment from one generation of a product to the next. The term flexibility is also widely used in a rather different context, to describe a futuristic concept analogous to an automated job shop, capable of producing "parts on demand". In either case, capital is shared among several products rather than dedicated to a single one. Evidently capital-sharing is practically indistinguishable from capacity augmentation. However it is perhaps slightly preferable

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[5]A more extended discussion of the rfelationship between flexibility and product differentiability (i.e. via design change flexibility or "mix flexibility") can be found in Boyer and Coriat (1987).

to model it as an extension of the lifetime of existing capital or (in some cases) as credit for capital recovery.

4. Product quality improvement. The term `quality' is not very precise, since it comprises at least two aspects; (1) product reliability (defect reduction), and (2) product performance. The latter can be disregarded, here, as being an aspect of product change (discussed next). It is postulated that several CIM technologies, especially the use of "smart sensors" in conjunction with programmable controllers, will eventually reduce the in-process error/defect rate. Moreover, these technologies will also permit more complete and more accurate testing and inspection of workpieces and final products. A quantitative measure of product reliablility is needed, if possible, better than the simple `percentage of time operating' measure that appears throughout the human factors literature [e.g. McCormick & Sanders 82].

5. Acceleration of product performance improvement. As noted above in connection with quality, improved product performance can be distinguished in principle from improved product reliability through reduced error/defect rates. The latter is a function of the manufacturing process only, whereas the former requires changes in the actual design of the product. It was pointed out that one benefit of flexiblity is that it reduces the cost of each product change. A further benefit is that, as a result, product redesigns are

likely to be more frequent. The problem, for an economist, is to find empircal evidence of a relationship between the cost of product redesign and retooling and the rate of product performance improvement. This appears to be a relatively unplowed field of research, to date.

Static vs. Dynamic Approaches to Benefits Measurement

Up to this point, we have not attempted to consider the question: benefits to whom? In fact, this is a critical issue because short-run benefits are likely to be appropriated mainly by producers (as profits), whereas in the long run in a competitive economy essentially all of the benefits will be passed on to consumers through product price reductions, performance improvements, and wage increases.[6]

More important for our purposes, it is only the short-term benefits appropriable as profit by producers that can directly motivate innovation and technological diffusion [Mansfield 61, 68]. In this context, it is clear that in a static environment, labor saving, capacity augmentation and capital sharing may contribute immediately to profitability. On the other hand, product quality and performance improvements may have a less direct impact on profitability in the short run, except to the extent that error/defect control has a direct effect on costs.

In a static world of competitive `price-takers', and given `fixed' and `variable' costs, the optimum (short-run

[6]This effect is reflected in the long-term rise in "labor share" of output.

profit maximizing) production level is determined by the shape of the variable cost curve. Assuming the usual U-shaped variable cost curve, the optimum production level is found by equating marginal revenue and marginal cost. If demand increases, but total capacity remains fixed, prices and profits will rise, and vice versa. If the industry is profitable, any existing (or new) producer can increase his capacity, thus reducing his average costs and breakeven point and he can increase market share by price cutting. But if several producers do this, the result is overcapacity and losses. Moreover, assuming non-convertible (inflexible) capital, the effective marginal cost now becomes the marginal <u>variable</u> cost and each competitor will go on producing even if it earns no net return on capital. In fact, the static competitive market is inherently unstable (and therefore not static) at any finite profit level.

In other words (as Schumpeter pointed out long ago), profits in a competitive market are inherently a dynamic phenomenon reflecting an exploitable temporary cost or price advantage. The advantage at any moment in time may be due to superior brand-name recognition, cheaper labor or energy sources, better location vis a vis markets, more efficient production technology or better product design. But unless one or more of these advantages is protected, e.g. by brand-name copyright (e.g. `Coke'), a monopoly franchise (CBS), an impenetrable secret or a set of interlocking patents, profitability will last just as long as it takes for a competitor to imitate or improve on the product and/or build a larger or newer plant.

It follows, therefore, that continuous long-term profitablity for a firm can only be assured by a continuous process of creating and exploiting new advantages (of some kind) to replace the older, dissipating ones. Opening new markets, advertising, product improvment, process improvement -- all are means of creating competitive advantages. Forward motion is essential: to be stationary is to sink and be overwhelmed. A moving bicycle, a lasso, a `hula-hoop', a child's top or a water ski are dynamically stable; but when the motion stops the system collapses. The same thing holds true for species in an ecosystem or firm in a competitive market. There is no safe place to hide indefinitely from hungry predators seeking a meal or hungry competitors seeking a market.

In short, only a dynamic model firm behavior has any value in assessing the benefits of CIM technologies (or, indeed, any other technologies provided exogenously). Furthermore, it is essential to view the firm in its competitive environment. Most simple models of the behavior of the firm assume a static environment (e.g. an exogenous demand schedule or market price and neglect the realities of competitive response. If all competing firms adopted a more efficient production technology simultaneously, none would gain any special advantage over the others but all would bear the cost of the necessary investment. To the extent that the adoption of more efficient production processes (CIM) results in lower costs and these are subsequently passed on to consumers as lower prices, the market for each product might (or might not) grow enough to result in increased profitability for the producer, ceteris paribus.

A Simple Dynamic Model for Estimating Private Benefits (Profitability) of an Innovative Production Technique

Suppose, for a moment, that each CIM adopter is a monopolist in its market 'niche'[7] and that this market is characterized by a constant price elasticity[8]

$$\sigma = \frac{PdQ}{QdP} \qquad (1)$$

where P is the product price and Q is the physical output (= demand) level. The producers profit (per unit time) can be defined

$$\pi = (P - C)Q \qquad (2)$$

where C is a cost function. One commonly assumed simple cost function is the so-called 'experience curve'[9]

$$C = C_0 N^{-b} \qquad (3)$$

[7]At first glance this is a very heroic assumption, but it is consistent with the notion that firms with similar production technologies can compete by product differentiation. This formulation was introduced by Chamberlin (1933, 1953).

[8]This assumption is also moderately heroic, though widely used in macroeconomic models. See, e.g. Houthakker & Taylor 1970.

[9]The experience curve is often parametrized in terms of the ratio s of end-of-period costs to beginning-of-period costs, after each doubling of cumulative output. Typical values of s range from 0.9 to 0.6. The lower the value of s, the faster costs are declining. For a recent survey of the microeconomic literature relating experience curves and cost functions, see [Gulledge and Womer 86].

where N(t) is cumulative output up to time t

$$N = \int_{0}^{t} Q(t')dt' \tag{4}$$

or

$$\frac{dN}{dt} = Q \tag{5}$$

and b is a parameter characteristic of the industry (see Figure 1). If the market demand Q is growing exponentially at a rate K

$$Q = Q_0 \exp(Kt) \tag{6}$$

then it follows from (1) that

$$P = P_0 \exp(-Kt/\sigma) \tag{7}$$

and from (5) and (6) that

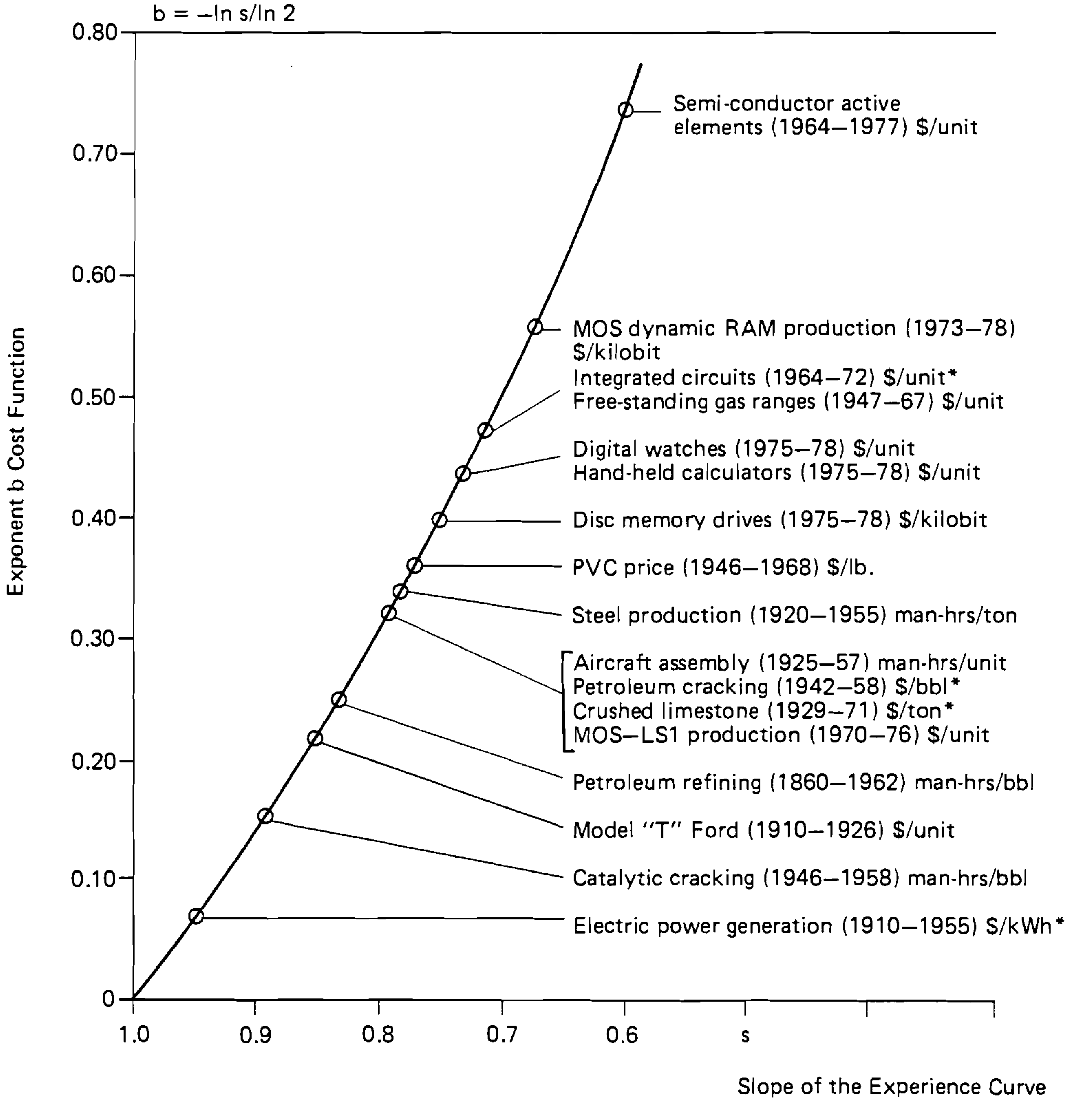
$$N = 1 + (Q_0/K)(\exp Kt - 1) \tag{8}$$

whence

$$\pi(t) = Q_0\{P_0 e^{-K/\sigma} - C_0[1 + (Q_0/K)(\exp Kt - 1)]^{-b}\}e^{Kt} \tag{9}$$

where

$$\pi(0) = Q_0(P_0 - C_0) \tag{10}$$



Source: Ayres, 1985 c.

*Constant $

Figure 1. Experience curve parameters for various industries.

For $Kt >> 1$ (9) reduces to

$$\pi(t) \cong Q_0\{P_0 e^{-Kt/\sigma} - C_0(Q_0/K)^{-b} e^{-bKt}\} e^{Kt} \qquad (11)$$

In this case it can be shown easily [Ayres 85c] that the condition for <u>growing</u> profitability is

$$b\sigma > 1 \qquad (12)$$

Condition (12) therefore requires $\sigma > 2$ if $b = 0.5$ and $\sigma > 10$ if $b = 0.1$. The condition is relatively easily met for fast gowing industries with large values of b (such as semiconductors) but it cannot be satisfied by more mature industries with small values of b.

One obvious implication of the above result is that true monopolists, who are fairly rare, -- in contrast to Chamberlinian monopolists -- are likely to have less incentive to adopt new production technologies than actively competing firms. In practice, oligopolists in mature, slow-growing industries (small b) do apparently have rather little incentive to innovate. Among a number of competing firms, however, the earlier adopter of a more efficient production technology is the one who will gain a <u>temporary</u> advantage and increase his profitability, market share or both. (Here long-term growth in profitability is not at issue). On the other hand, if the innovation is unsuccessful, the early adopter is worse off than the non-adopter. The choice, -- to adopt, or not -- is then made on the basis of failure risk vís à vís perceived benefits in case of success [Ayres & Mori 86]. It is important to realize, however, that the "game" in slow-growth industries is likely to be even less favorable than "zero sum". In fact, if the innovation is a success early adopters probably gain less than late adopters will lose. The problem is that nobody can opt out of the game (prisoners dilemma), so that change of any kind is risky.

The simple model above explicitly assumes that the benefits to CIM adopters are reflected in lower costs, rather than increased demand due (for instance) to superior product differentiability resulting in faster adaptation to market changes.

However, the apparent limitation can be partially overcome by adopting a Lancastrian point of view, namely that product services are, in fact, differentiated bundles of characteristics. A shift in demand function due to product "improvement" is practically indistinguishable from a shift in supply function due to process improvement. Either the firm can provide more "utiles" per unit cost, or a given number of "utiles" at less cost. The experience curve is likely to be as applicable to the one case as to the other.[10]

The analytical problem we must now face is as follows: given a competitive market and a risky innovation of uncertain success, how should a rational management play the game? And, given evidence of success by some early adopters, how can "followers" be expected to react? These are some key issues for future research.

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[10]There is a considerable debate in the literature on the microeconomic foundations of 'experience curves' (e.g. Arrow, 1962, Alchian, 1963) but the empirical evidence is fairly convincing.

Profitability and Diffusion[11]

The rate at which new technologies substitute for established ones has often been found to follow an S curve [Fisher & Pry, 1971]. However, the underlying mechanisms for this have never been fully explained. The most widely accepted reason is that new technologies follow a first order diffusion process (demand proportional to fractional market penetration) and a second order saturation process. The solution to the differential equation ($df/dt = af - bf^2$) representing this situation, where f is the fractional market penetration and a and b are constants, is the simplest form of curve, known as a logistic function. While this model is analytically simple and fits a wide variety of ex post data [ibid], it offers no clues for ex ante prediction of the rate at which diffusion will occur. Much of the technological forecasting literature has used this model assuming a priori that an S curve will represent the rate of introduction. The usual procedure is to determine the parameters of the curve by curve-fitting. An ex ante methodology is greatly to be desired. Mansfield [Mansfield 61, 68] was the first to attempt this task using econometric methods. More recent efforts along these lines have been reported by Blackman [Blackman 74], Martino [Martino et al. 78] and others.

The rate at which initial diffusion occurs has been found to depend empirically on the expected profitability of the new technology, the absolute size of the investment, the tendency for the industry to innovate, and the time-

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[11]This section is based on a previously unpublished working paper by Jeffrey L. Funk and the author (dated January, 1983).

preference (or discount) factor. Profitablity can be represented by a firm producing the product or using the new technology at a rate that will maximize its present value over a planning horizon. The size of the investment and the industry will determine a firms's attitude towards risk and short-term losses. The industry's tendency to innovate should also affect the time horizon considered. These ideas are the basis for the model described hereafter.

The rate at which a new technology is introduced in a sector can be viewed as a summation of the rates at which individual firms introduce the new technology. Each firm will introduce the new technology in a way that will maximize its objective function. We will assume the firm's objective is to maximize the present value of future profits over some time horizon, subject to a constraint on cumulative losses allowed. The control variable for the problem is the price P(t) or the quantity Q(t), as a function of time. If the price is set below cost the firm sells temporarily at a loss but gains production experience permitting it to reduce its costs. The maximization problem is represented mathematically below:

$$\text{Max } W(t)$$

where

$$W(T) = \int_{\emptyset}^{T} \pi(t)\ \exp(-\delta t)dt$$

$$= \int_{\emptyset}^{T} [P(t) - C(t)]Q(t)\exp(-\delta t)dt \qquad (13)$$

and

P(t) = unit price at time t
C(t) = unit cost at time t
Q(t) = quantity produced per unit time
δ = discount rate

Before considering more complex cases, it is interesting to note that for the simple case of Chamberlinian monopolist in a 'niche', confronting a <u>fixed</u> price elasticity σ, and a given market price, the optimal rate of CIM adoption **k** has been shown (Ayres, 1985) to be as follows:

$$k = \sigma(r-\delta) \qquad (14)$$

where δ is the adopting firms effective discount rate, and **r** is its target rate of return on investments. Alternatively $(r-\delta)$ represents the `risk-premium' set by the firm, over and above the discount rate.

A more complex model results if one introduces a loss constraint. A constraint on the maximum loss per period can be expressed as:

$$\pi(t) > -D \qquad (15)$$

A total loss constraint could also be introduced. Firms may have different cost functions, discount rates, cumulative loss constraints, and demand curves. The cost function will vary for each firm depending on its existing capital stock and personnel but in general it will decline as a function of cumulative production experience [e.g. Cunningham 80]. The cost of equity and debt capital as well as management risk preferences and perceptions of future prospects can result in widely varying discount rates [Ayres & Mori 86]. The cumulative loss constraint will depend on a firm's liquidity and its management's attitude towards risk. The time horizon considered is also available. It probably depends on the rate of exogenous technological change, i.e. on the expected time before the existing technology becomes obsolete. Other differences between firms and their products will affect the demand for a product as a function of price and other attributes. These differences will result in each firm introducing the new technology at a different time and rate.

New technologies can be divided into new processes which produce old products and new products which are produced with existing or new processes. CIM is basically a set of process innovations. Old products produced by a new process will normally be marketed initially at the same price as the old process to prevent products from the same firm from competing with each other. Here the decision variable for the adopter is the quantity of products to be produced by CIM vís à vís the quantity produced by the old process. Thus, for the moment, we consider only the case of a product demand curve that is not changing over time.

Consider a (new) firm that wishes to adopt a new process (CIM) to produce an established product. The market price for the product is $\hat{P}$. The CIM-adopter has unit costs C that will decrease as a function of cumulative output by the new process. It is free to offer its product at a different price P that might be either higher or lower than $\hat{P}$. It confronts a constant demand function which is a function of both P and $\hat{P}$. For the CIM adopter, the problem is expressed by (13) above, where its cost function C is given by equation (3) and N is given by equation (4).

Let $\hat{Q}$ be the quantity by the old process produced and let f be the market penetration of the new process. It is reasonable to assume that the market share of Q is a function of the relative prices P and $\hat{P}$, but that -- for various reasons (including inertia and `intangibles') -- the market will tolerate some price differential ($P \neq \hat{P}$), even though the products produced by CIM technology are assumed to be identical to those produced by conventional technology. However the market responds to any differential by increasing demand for the lower priced source.

A mathematical relationship that satisfies this condition (while being less restrictive than the constant price elasticity assumption) is the following:

$$Q = ([P_t \lambda / P]^{\sigma} - 1)Q_o \qquad (16)$$

$$Q = (1 - [\hat{P} / \tau P]^{\sigma})\hat{Q}_o \qquad (17)$$

where $\hat{Q}$ is the quantity produced by conventional means

$$f = \frac{Q}{Q + \hat{Q}} \qquad (18)$$

The parameters λ, τ and σ (see equation 1) are all to be determined; P is a variable, while $\hat{P}$ is now assumed to be constant.

Thus the CIM adopter now sees the problem as:

$$W(T) = \int_{0}^{T} [P - C_0 N^{-b}]([\lambda\hat{P}/P]^{\sigma} - 1)Q_0 \exp(-\delta t)dt \qquad (19)$$

where

$$N = \int_{0}^{t} Q(dt') = ([\lambda\hat{P}/P(t')]^{\sigma} - 1)Q_0 dt' \qquad (20)$$

and (15) must be satisfied in all periods.
Taking the derivatives with respect to the time t:

$$dN/dt = ([\lambda\hat{P}/P]^{\sigma} - 1)Q_0 \qquad (21)$$

$$dW/dt = [P - C_0 N^{-b}]([\lambda\hat{P}/P]^{\sigma} - 1)Q_0 \exp(-\delta t) \qquad (22)$$

The mathematical complexity of this formulation conceals an essential tradeoff that the CIM adopter must face: Its costs will decrease with accumulating experience; and its costs will therefore fall faster if it sets its initial (entry) price P as low as possible, to gain the largest possible initial market share. On the other hand, its initial unit costs can be expected to be high, due to break-in problems and it will expect to lose money for a while. Therefore, the faster the intended penetration, the larger the initial loss. It follows that (in this model) the penetration rate is limited by the maximum annual startup loss that can be sustained.

This problem can be solved using Optimal Control Theory as described in the Appendix. When there isn't any constraint on the cumulative losses the diffusion process need not occur at a finite rate. Each curve is for a different initial cost. Numerical solutions are shown in Figure 2. The higher the initial cost the lower the final saturation level but the basic shape of the curve is not changed. Cumulative revenues are shown in Figure 3 for the same initial costs. Total profits (above an acceptable return on equity) over twenty-five years decrease with higher initial costs. If the initial cost was greater than C_{∞} = 23, no production should occur because it would result in negative profits. For lower initial costs the cumulative revenues early in the life of the project are negative, which requires liquid capital. The firm can go bankrupt if the pool of liquid capital dries up before profitability is achieved.

Because there is no penalty for decreasing output (thus resulting in unused capacity), a cumulative loss constraint causes the firm to have a discontinuous price path which results in a discontinuous output path. In real life a firm would not change its price instantaneously to eliminate excess capacity or to achieve better customer relations in the short run. This was resolved by assuming a constant initial price (close to prices satisfying the necessary conditions) until the costs were reduced to the initial price without violating the cumulative loss constraint. The solution then follows from the necessary conditions. This produced continuous solutions for price and output. Market penetration is shown in Figure 4 for price elasticities of .5 and 1. There is some resemblance to a traditional S curve, but the differences are significant.

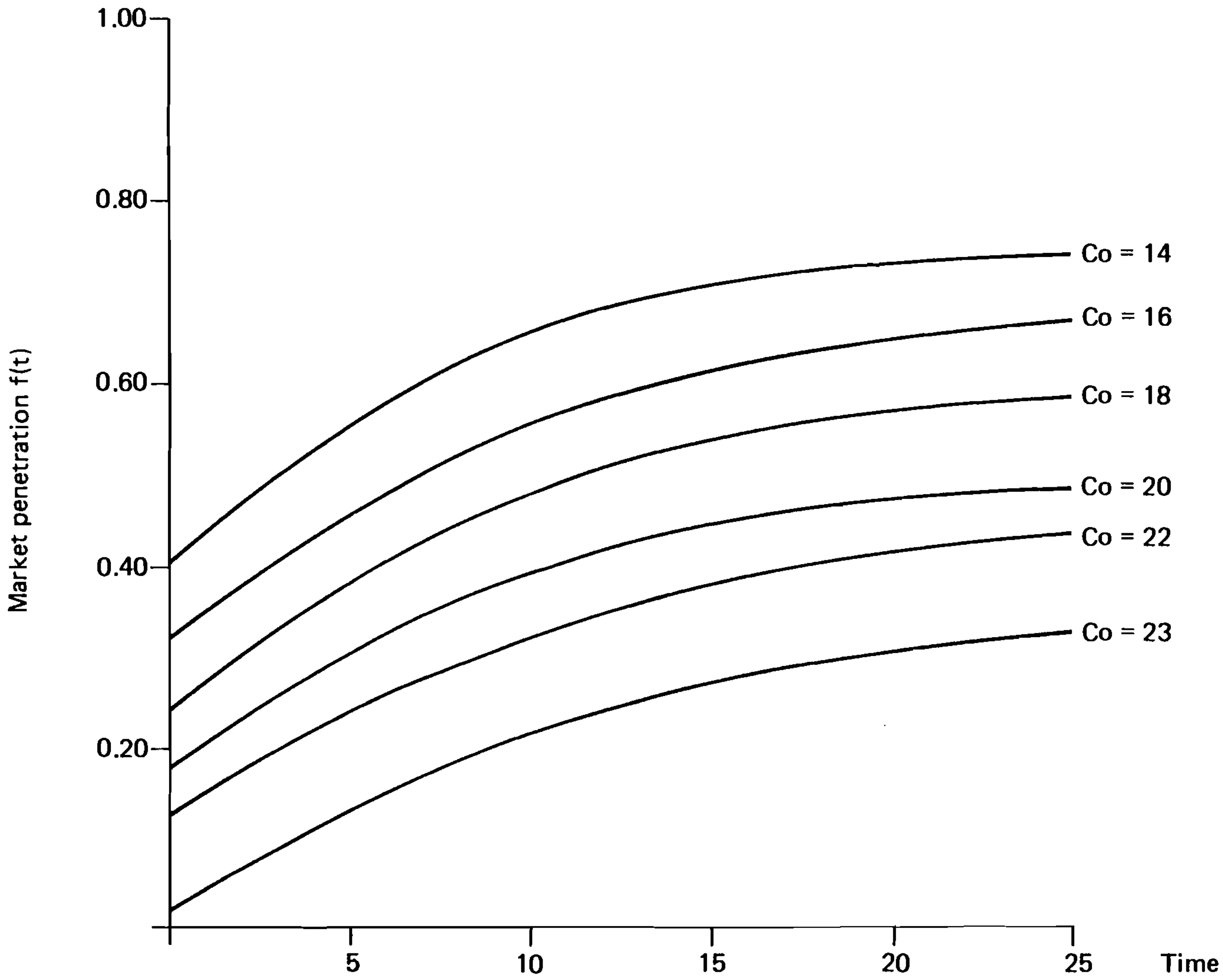

Figure 2. Market penetration vs. time for different initial costs.

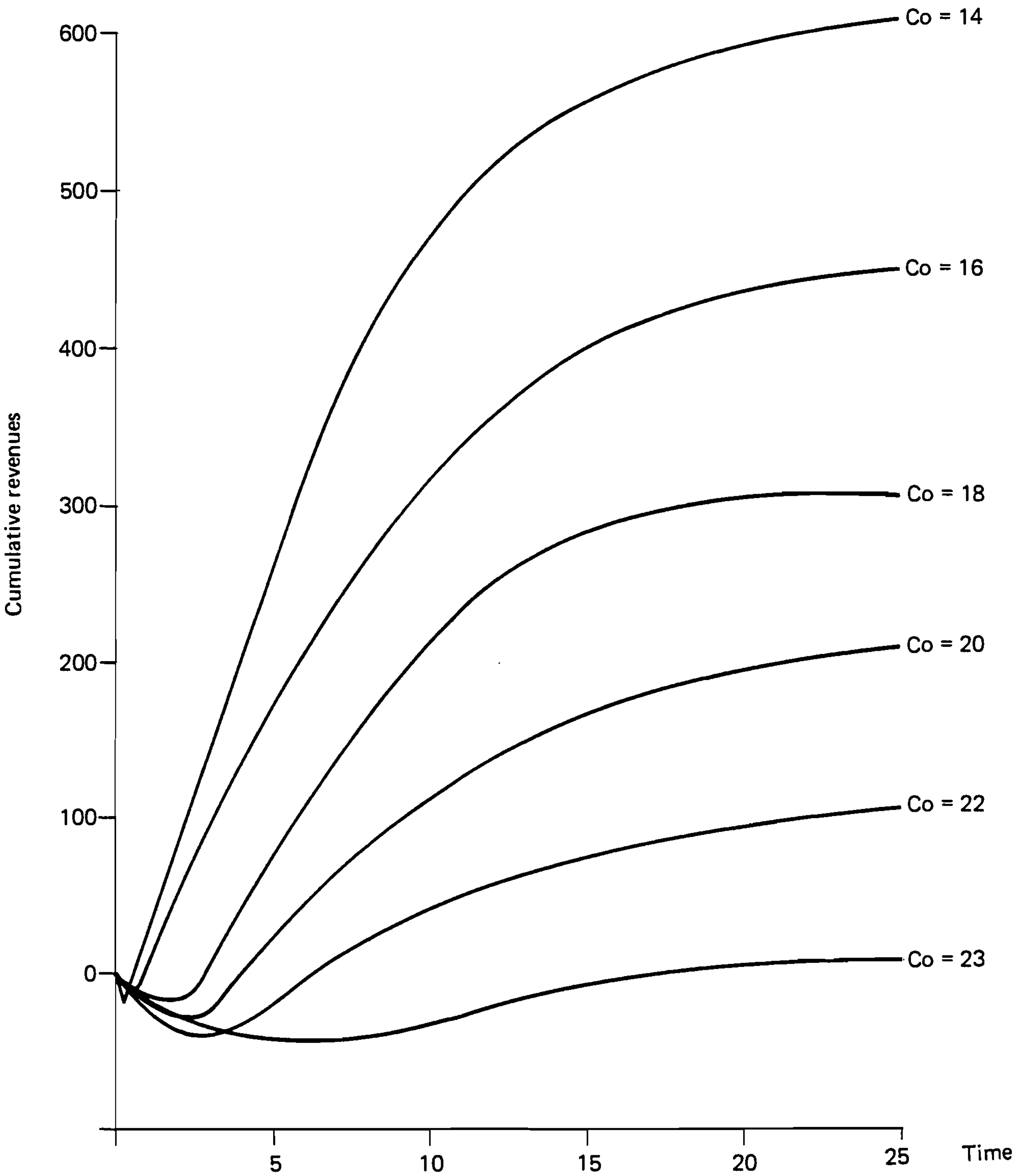

Figure 3. Cumulative revenues vs. time for different initial costs.

Conclusion

In this paper, a simple dynamic model based on the `experience curve' for estimating private benefits (to the firm) is briefly discussed and some possible directions for extension are indicated. An application of the model to predicting penetration (or diffusion) rates is discussed also.

It was pointed out that there is another dimension of the problem, viz. to estimate social benefits. To be sure, the likelihood of social benefits does not, in itself, provide a motivation for private firms to adopt a new technology. In a centrally planned socialist economy, of course, such a distinction should (in principle) be unnecessary. But quite apart from the motivational aspect, there is a very important methodological problem to be faced. As noted previously, we need a dynamic model for evaluating social benefits of CIM (or other new technologies). Such a model is suggested by Mori in the following paper and preliminary results are obtained for the Japanese economy.

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APPENDIX

Introducing the Hamiltonian function:

$$(1) \quad H = [P - C_0N^{-b}]([\lambda\hat{P}/P]^{a} - 1)Q_0 \exp(-\delta t)[1 + \mu] + \eta([\lambda\hat{P}/P]^{a} - 1)Q_0$$

where η and μ are adjoint variables for N and a respectively, and P, P, N, a, η and μ are all functions of time. The optimal time paths for N and P are determined by the necessary conditions of Pontryagin's maximum principle:

$$(2) \quad \partial H/\partial P = 0$$

$$(3) \quad \partial H/\partial N = -d\eta/dt$$

$$(4) \quad \partial H/\partial \pi = -d\mu/dt$$

$$(5) \quad \partial H/\partial \eta = dN/dt$$

$$(6) \quad \partial H/\partial \mu = d\pi/dt$$

$$(7) \quad \pi > -D$$

$$(8) \quad \eta(T) = 0$$

$$(9) \quad \mu(T) = 0$$

From (1), (2) = 0 and using (9):

$$(10) \quad \mu(t) = 0.$$

Applying the necessary conditions

$$(11) \quad \partial H/\partial P = Q_0 \exp(-\delta t)(1 - a)[\lambda\hat{P}/P]^{a} - 1 + aC_0\lambda\hat{P}N^{-b}P^{-a-1} - \eta\lambda\hat{P}aP^{-a-1} = 0$$

$$(12) \quad (1 - a)[\lambda\hat{P}/P]^{a} - 1 - \lambda\hat{P}aP^{-a-1}[\eta \exp(-t) - C_0N^{-b}] = 0$$

$$(13) \quad \partial H/\partial N = bCN^{-b-1}([\lambda\hat{P}/P]^{a} - 1)Q_0 \exp(-\delta t) = -d\eta/dt$$

$$(14) \quad \partial H/\partial \eta = ([\lambda\hat{P}/P]^{a} - 1)Q_0 = dN/dt$$

Solving for P leaves two differential equations (13 and 14) with two unknowns (N and η). When the cumulative loss constraint is not violated a numerical solution can be found by assuming $\eta(0)$ and solving difference equations iteratively until $\mu(T) = 0$

is satisfied. For portions of the solution that violate this constraint it is maintained by choosing P to keep $\pi(t) > -k$ [Bryson et al. 63]. This will require $P(t) = C_0 N(t)^{-e}$, when $k = 0$, until the necessary condition $dH/dP = 0$ produces a price greater than the costs. The rest of the solution follows from the necessary conditions as described earlier.