"A STRATEGIC ANALYSIS OF INVESTMENT IN FLEXIBLE MANUFACTURING SYSTEMS"

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A STRATEGIC ANALYSIS OF INVESTMENT IN FLEXIBLE MANUFACTURING SYSTEMS

ABSTRACT

In this paper we present a game theoretic model by which the investment in flexible manufacturing systems (FMS) can be analyzed. If the invesment in this innovative production system is viable (due to either revenue enhancements or cost reductions) the result is a competition for the first move among similar firms in an oligopolistic industry. As a result, the Schumpeterian hypothesis of investment in a technological innovation occurring within an industry by "swarms" appears to apply to FMS diffusion. Empirical evidence supporting the results of the theoretical analysis is presented.

(FLEXIBLE MANUFACTURING SYSTEMS; GAME THEORY; TECHNOLOGICAL INNOVATION DIFFUSION)

INTRODUCTION

In this paper we show that the investment in FMS could occur by what is described in the Schumpeterian hypothesis as a "swarm". Initially, the simplest variant of the model is described, that being a single period two-firm model. That model is then extended to include multiple periods (first in discrete time, then continuous time), and also multiple (greater than 2) firms.

A game theoretic model is chosen since it captures the strategic interdependence between firms. This is thought to be an important factor since the primary industries where FMS has made significant inroads are the aerospace, automobile, machine tool, heavy machinery, and electronics industries (see Table 1). All of these industries significantly exhibit strategic interdependence between competitors.

TABLE 1

Distribution of FMS by Industry Sector in 1987

Industry Sector	Percentage by number* W. Europe	U.S.A.	Japan
Light Automotive (cars, motorcycles)....	27	9	8
Heavy automotive/Heavy Machinery	21	28	21
Aerospace	15	33	0
Machine Tools	16	12	38
Electronics	6	6	22
Other sectors	15	12	11

* Compiled from Tombak (1988)

A large part of Schumpeter's work was devoted to the area of business cycles. He believed that technological innovation was one of the main vehicles of economic growth. As a consequence, it is not surprising that he would offer this explanation for the phenomena of business cycles:

> "Why is it that economic development in our sense does not proceed evenly ... ;why does it display those characteristic ups and downs? The answer cannot be short and precise enough: exclusively <u>because the new combinations"</u> [read technological innovations] "<u>are not as one would expect according to general principles of probability, evenly distributed through time ... but appear, if at all, discontinuously in groups or swarms"</u>

J. A. Schumpeter 1939, Pg. 223

In this paper we will examine an application of the above hypothesis, that being that the FMS innovation is adopted in "swarms" in a particular industry.

The particular type of flexibility concerning us is product flexibility, by which we mean the ability to change product designs with a standard set up time and cost (for a review of the different types of manufacturing flexibility see Tombak, 1988). FMS technologies are more product flexible than transfer line technologies but less flexible than their job shop counterparts. This is illustrated in Figure 1 which shows the appropriate technology for each job variety/volume mix.

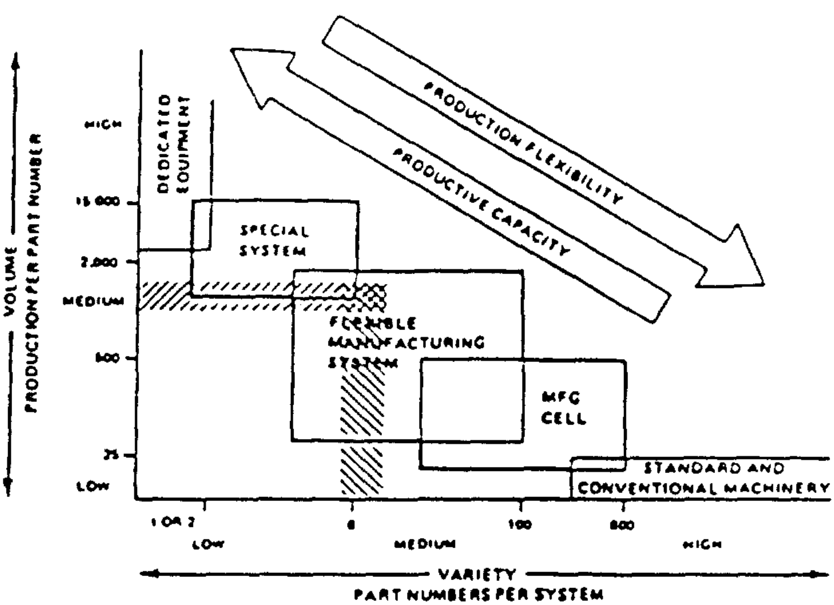

FIGURE 1. APPROPRIATE TECHNOLOGY FOR JOB VARIETY/VOLUME

Adapted from: Groover (1980, Pg. 566), and Wood (1982)

Since we are examining product flexibility, this paper will concentrate on the analysis of FMS vs. the more "hard" automation transfer line technologies (i.e. firms in the upper left area of the above figure). These transfer lines are made up of specialized machines which are difficult or impossible to reprogram. The materials flow is typically linear and constant as opposed to the random flow of an FMS. Transfer lines are used extensively in the automobile industry, electronics industry (both of which have many implementors of FMS), food processing industry, petroleum industry, and many others.

This study examines the driving forces for adopting the FMS innovation, lending insight into the decision processes of firms, valuable not only to firms in the adopting industries and machine tool manufacturers, but also to economic policy makers.

In this paper we initially present a survey of related literature in the areas of FMS and industrial economics. The simplest variant of the model, the duopoly model, is then described and a more complex, dynamic, model is depicted. The dynamic model is shown to exhibit a competition for the first move and hence the "swarming" effect of FMS diffusion in particular industries.

1. SURVEY OF LITERATURE

> "The fundamental impulse that sets and keeps the capitalist engine in motion comes from the new consumers' goods, the new methods of production or transportation, the new markets, the new forms of industrial organization that the capitalist enterprise creates"

Schumpeter (1983), Pg. 83.

Since the release of the initial report on the implementation of a flexible manufacturing system (FMS) by Molins Machine Co. (Williamson 1968) the flurry of literary activity concerning the concept has been substantial. This section of the paper reviews the literature in this and related areas. We critically evaluate research attempting to mathematically model the economic aspects of these manufacturing systems. Thirdly, we discuss other economic models with aspects related to parts of the models employed here.

1.1 MATHEMATICAL MODELS OF FMS

This section of the literature review first scans the analytical models used in the designing of FMS. Three economic models are then critically evaluated.

There exists an extensive body of literature on the multitude of analytical techniques for FMS design. First there are the queueing network models CAN-Q (Solberg, 1978, Solberg and Nof, 1980) and MVAQ (Suri and Hildebrant, 1984) these methods have been used on a number of problems. Dubois and Stecke (1983) have extended the use of petri nets to analyze the problems of real-time control and performance measures of production systems. Simulation is probably the most popular method of analyzing the design decision of an FMS. A simulation model was successfully used by Denzler, Boe, and Dupalaga (1985) to emulate the Deere and Co. FMS in Waterloo, Iowa. A good review of this literature appears in Buzzacott and Yao (1986). This brief review shows that proven methods exist for demonstrating the technical feasibility of FMS. Yet, the problem of economic feasibility remains largely neglected in the modelling literature.

Three economic models have been proposed to assess the investment in flexible manufacturing processes. The first model examined is that of Fine and Freund (1986). It is a two-product model which assumes that firms must invest in plant and equipment before they receive their final information on product demand. The problem analyzed with this model is one of the firm choosing a portfolio of flexible and nonflexible capacity under uncertainty in the demand. The second model reviewed is that of Gaimon (1985). This model professes to determine the optimal timing of an investment in a FMS. The third economic model is that of Tombak and De Meyer (1988). This model analyzed the effects of uncertainty in the firm's inouts and outputs on the amount invested on flexibility.

Fine and Freund's (F&F) model begins with the assumption that a firm is uncertain as to whether it should be producing product A or product B. The firm must then make a decision as to whether or not it should invest in a manufacturing process that would produce only A, a technology that produces only B, a flexible technology that can produce both A and B, or some combination of the three. Their model concentrates on the benefits achieved by flexibility with uncertainty of product characteristics. Although they acknowledge that there would be benefits to flexibility in a world of certainty due to savings in equipment downtime with decreased set-up time, their model does not incorporate these benefits.

The F&F mathematical programming model is a static one, assuming there is only one period in which the firm makes production decisions. In contrast to this, the model we present in Section 2.2 is a dynamic one extending over multiple periods. Also assumed in the F&F model is that demand is a linear function of the amount produced and that the variable cost of producing a unit of product A is the same as producing a product B. Our models, however, can incorporate any demand or cost structure. Most importantly, in the F&F model there is little analysis of how competition affects the firm's investment in flexibility. Their model assumes that the firm is either a monopolist or exists in a perfectly competitive market, whereas we use a game theoretic approach, explicitly accounting for other forms of competition.

The F&F mathematical programming model assumes that a firm can purchase plant capacity in infinitesimally small amounts. What the problem formulation lacks is the large step function most firms face in their costs with the decision to purchase productive capacity. Also their model combines flexible and inflexible production capacities for the same product. However, Jaikumar's study (1986) reports that the management of an FMS is significantly different than that of the inflexible technology, and that different skills are required in the management of each.

Gaimon's (1985) model portrays a profit-maximizing firm that solves a mathematical programming problem to optimally derive its level of output, price, and productive capacity over time. The model assumes that the acquisition of flexible automation will reduce the firm's per unit production plus in-process inventory costs. Tombak (1988, pp. 103-107) shows that this is <u>not</u> a necessary condition for the firm to invest in FMS. The main problem with Gaimon's formulation lies in the manner in which the variables have been defined. In particular, it would be difficult to specify a per unit value for product-mix and volume flexibility, which the model would require.

The model exhibited in Tombak and De Meyer (1988) is one of pure competition, in which the decision of any one firm does not impact significantly on the market. In the model we present here strategic interdependence amoung firms is allowed. This encompasses the situation in oligopolistic industries in which the majority of FMS's are implemented (see Table 1).

1.2 OTHER RELATED ECONOMIC MODELS

In addition to the mathematical models discussed above, other more qualitative economic models point to the relevance of new technologies such as FMS. In the 1920's Schumpeter recognized the importance of technological innovation to economic growth, and as previously mentioned, FMS is innovative as a manufacturing technology. Schumpeter defined an "innovation" as being one of:

> "the following five cases: (1) The introduction of a new good - that is one with which consumers are not yet familiar - or of a new quality good. (2) The introduction of a new method of production, that is one not yet tested by experience in the branch of manufacture concerned, which need by no means be founded upon a discovery scientifically new, and can also exist in a new way of handling a commodity commercially. (3) The opening of a new market, that is a market into which the particular branch of manufacture of the country in question has not previously entered, whether or not this market has existed before. (4) The conquest of a new source of supply of raw materials or half-manufactured goods, again irrespective of whether this source already exists or whether it has first to be created. (5) The carrying out of a new organisation of any industry, like the creation of a monopoly position (for example through trustification) or the braking up of a monopoly position."
>
> Schumpeter (1983), Pg. 66.

An FMS most closely resembles Schumpeter's type (2) innovation. However, it may also lead to a type (5) innovation and would expedite any endeavor to pursue innovations of types (1) and (3).

Schumpeter developed two major hypotheses concerning technological innovation, (i) that technological innovation was more likely to be brought about by firms with a great deal of market power (i.e. a large market share) and, (ii) that innovations are more likely to occur during troughs of the business cycle (see Schumpeter 1939, 1983).

Since the 1920's, there has been a significant influx of literature in the area of economics of innovation. Much of this work concentrates on product innovation eg. Scherer (1984), or on process innovations that reduce the unit costs of production, eg. Reinganum (1983), and Freeman (1982). However, this work examines the situation where an investment in process technology may increase the unit costs of production and simultaneously increase sales through providing consumers more of a customized product (proof that there can exist such situations is shown theoretically in Tombak, 1988).

Kamien and Schwartz (1982) have done a considerable amount of work in the empirical testing of the Schumpeterian hypothesis (hypothesis (i), above), but it is generally accepted (and they themselves admit) that the empirical tests were not definitive for the hypothesis. Mansfield, et.al. (1977) have done studies which concentrated on particular industries and the rates of technology innovation diffusion. One of those studies which is especially pertinent to this paper analyzed survey data from the machine tool industry. This is interesting since it is in the machine tool industry that one finds one of the largest concentrations of FMS implementations, and it is from this industry that the building blocks of FMS (numerically controlled machine tools) are produced.

An economic model that is made use of is that of equilibria in product characteristic space. In this approach firms choose points along the various dimensions of their product's characteristics (of which one would be price). This allows firms to compete on the basis of multiple dimensions of the their product. The increase in sales is modelled, in Section 2.2, through the use of a logit model in product characteristic space. The first use of the product characteristics framework should be accredited to Lancaster (1975). This allows us to cast the problem in a spatial setting and make use of the results of Hotelling's (1929) seminal work and of the more recent work of DePalma et.al. (1985).

The logit model along with the concept of consumer ideal (or "bliss") points we use in Section 2.2 has also been used by Schmalensee and Thisse (1985), and Choi, DeSarbo, and Harker (1987). Choi, et. al.'s purpose, however, was to find the optimal position in product characteristic space of a new entrant. Both these papers hint at there being some value of flexibility in product design. The new flexible manufacturing technologies examined in this study, however, would no longer make it necessary for the firm to specify a point in this space. Rather, a firm with an FMS has the capability to manufacture a broad set of characteristics, and with that to respond to changes in consumer tastes or the mix of products offered by the competition.

That this new process technology should affect economic theory is clear. For example, FMS challenges the belief that one must standardize products for cost effectiveness.

> "Fixed costs, therefore, force an economy to choose from the large set of all conceivable products"
>
> Spence (1976), pg. 217.

In the situation analyzed in this study the fixed cost in flexible manufacturing technology opens up the set of products.

1.3 ASSESSMENT

This survey of literature relating to FMS shows that much work has been done concerning the engineering issues of design and operation but many issues in the economics of these systems have not been adequated covered. It is shown that many of the existing economic models are unrealistic, and, as a result, do not provide much insight into the FMS acquisition process. Although there is a wealth of information from the economics of innovation area, it addresses innovations in process technologies broadly and does not examine FMS specifically.

2.0 DESCRIPTION OF THE OLIGOPOLISTIC MODEL

Due to the strategic interdependence of firms in an oligopoly the basic formulation used is that of a noncooperative game theoretic model. The strategy space for each firm consists solely of either continuing with a transfer line (the existing manufacturing system), or an investment in a flexible manufacturing system. A schematic of this game in its simplest form is shown in the following figure.

		FIRM A	
		TRANSFER LINE	FLEXIBLE MFG SYSTEM
FIRM B	TRANSFER LINE	I	II
	FLEXIBLE MFG SYSTEM	III	IV

FIGURE 2. THE MANUFACTURING TECHNOLOGY GAME

2.1 THE SINGLE PERIOD MODEL

Let us assume that a firm can produce only one product (product 1) with a transfer line (TL) and two products (products 1 and 2) with a FMS (this assumption will be relaxed later to allow multiple products with the FMS). If supplied only with product 1 consumers would demand an amount Q. However, if the consumers were supplied with both products 1 and 2 then they would demand those products in quantities Q_1 and Q_2, respectively. Furthermore let:

P = unit price for both products (exogenous variable)

C^{AF} = unit cost of firm A with an FMS where C incorporates the unit capital costs

C^{AT} = unit cost of firm A with a TL

π = profit

If we allow firm A the first move in a sequential move game then the game in extensive form is as follows.

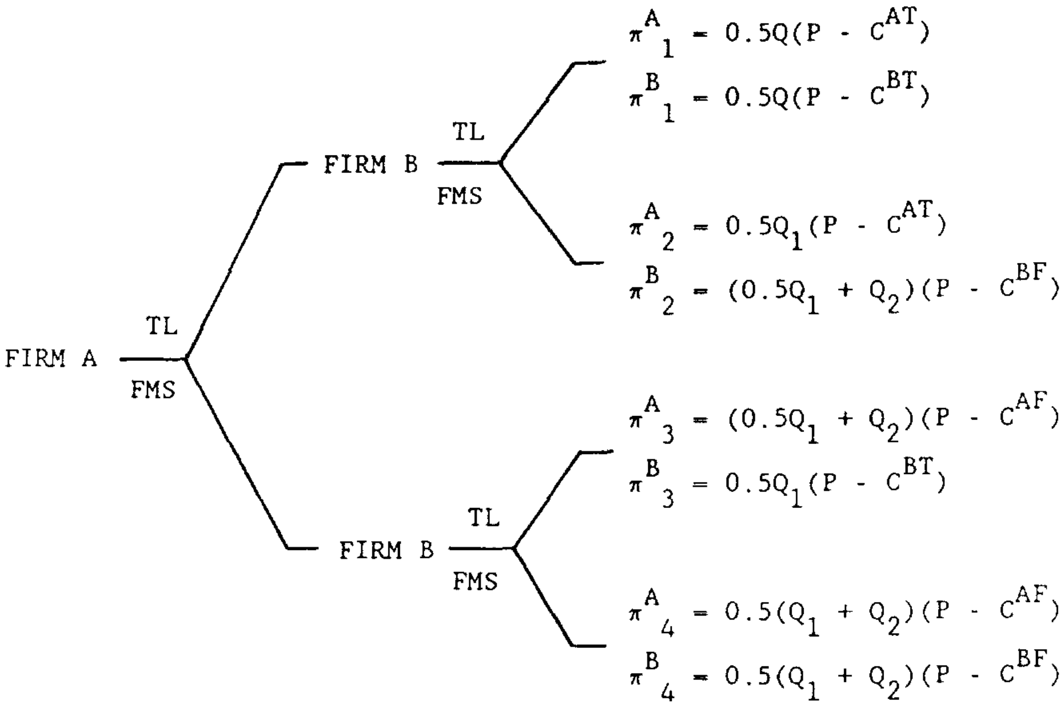

FIGURE 3. THE EXTENSIVE FORM OF THE MANUFACTURING TECHNOLOGY GAME

Note that in the above game we have assumed that the firms perform equally well with respect to the marketing of the products that they deliver (i.e. whenever both firms produce the same product they split the market for that product equally). Also note that,

$$Q = Q_1 + Q_2$$ (the original market size is not expanded with the introduction of new product).

Consequently,

$$\pi^A_4 = 0.5Q(P - C^{AF}) \quad \text{and}$$

$$\pi^B_4 = 0.5Q(P - C^{BF}).$$

2.2 THE MULTIPERIOD MODEL

In this section it will be shown that with all else being equal, and given that the market's profit is sufficiently large to cover the investment in FMS, firms would have an incentive to preempt their competitors. Here we make use of a logit model of consumer preferences since those preferences may change over time.

Let S_t be a state variable at time t defined as follows:

$$S_t = \begin{cases} 1 & 0 \le t < t^A,\ t^B \text{ quadrant I of Figure 2.} \\ 2 & t^A \le t < t^B \quad \text{quadrant II (firm A preempts B)} \\ 3 & t^B \le t < t^A \quad \text{quadrant III (firm B preempts A)} \\ 4 & t^A,\ t^B \le t < \infty \text{ quadrant IV} \end{cases}$$

where t^A and t^B denote the time period in which firm A and firm B, respectively, invest in a FMS. Furthermore let:

P = unit price for the product(s)

D_t = total demand in period t for the product(s)

C^{AF} = unit cost for firm A with a FMS

C^{AT} = unit cost for firm A with a TL

M^A, M^B = the market shares of firms A and B, respectively.

These market shares are defined by the logit model[1] (as it has been used by Schmalensee and Thisse 1985, and many others)

[1] This is the expression for the probability that an individual will purchase the good. For hetergeneous consumer groups the market share would be the integral over the range of product characteristics of this expression multiplied by the probability distribution function. It is assumed throughout the remainder of this paper that the consumer has homogeneous tastes.

as:

$$M^A = \frac{e^{-\beta d(x,y)}}{\sum_{i=1}^{n} e^{-\beta d(x,y_i)}}$$

In our situation these market shares become:

$$M^A{}_t(S_t) = \begin{cases} 1/2 & S_t = 1 \text{ or } 4 \\ 1/[1 + e^{-\beta d(x,z)}] & S_t = 2 \\ 1 - 1/[1 + e^{-\beta d(x,y)}] & S_t = 3 \end{cases}$$

$$M^B{}_t(S_t) = \begin{cases} 1/2 & S_t = 1 \text{ or } 4 \\ 1/[1 + e^{-\beta d(x,y)}] & S_t = 3 \\ 1 - 1/[1 + e^{-\beta d(x,z)}] & S_t = 2 \end{cases}$$

where: x = consumers' bliss points

y = firm A's product characteristic

z = firm B's product characteristic

$d(x,y)$ = the distance between x and y = $|x - y|$

β = parameter

Since in this case the industry is a duopoly,

$$M^A{}_0 + M^B{}_0 = M^A{}_t + M^B{}_t = 1 \qquad \text{for all } t.$$

One would expect the manufacturer with the TL system to produce a product of attributes at the initial bliss point (assuming he had no information about future shifts in this point). That the producer with the TL would position himself in such a way is a result of Hotelling's Principle of Minimum

Differentiation (Hotelling, 1929).[2] Suppose the path of the consumer bliss points drifted linearly over time from the TL's product attribute as shown in Figure 3.

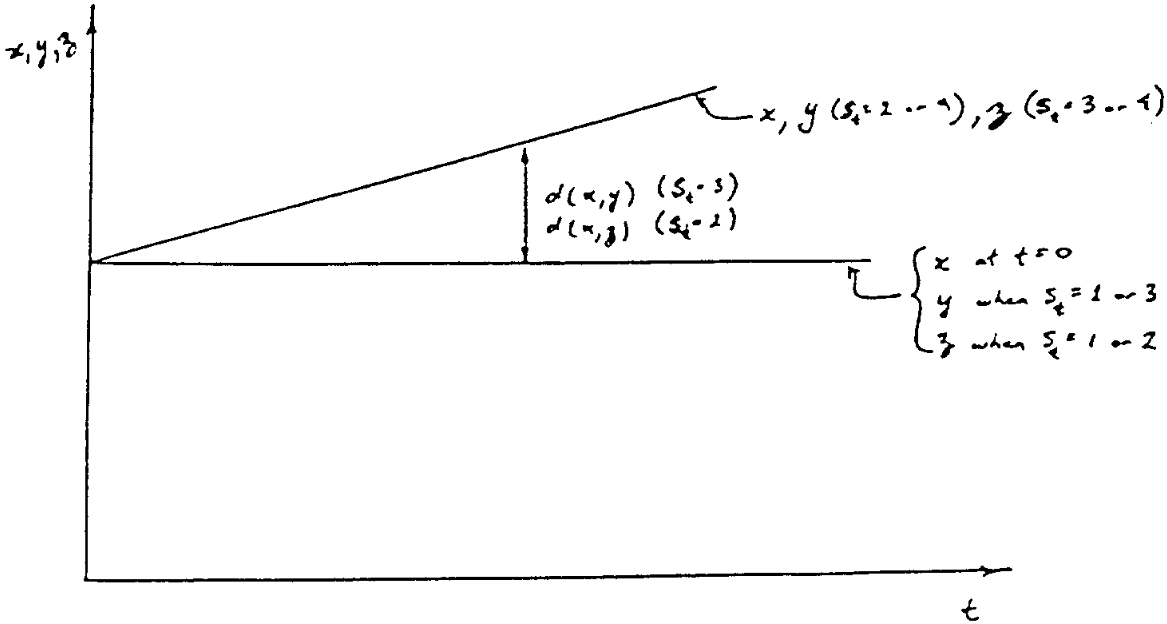

FIGURE 3. CONSUMER BLISS POINTS OVER TIME

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[2] Hotelling's Principle was shown to be invalid by Lerner and Singer (1937) when there were more than 2 firms, and by d'Aspremont, Gabszewicz, and Thisse (1979) when there exists pure competition. Both cases were considering the situation where the products and the consumers are homogeneous. DePalma, Ginsburgh, Papageoriou, and Thisse (1985), however, show that the principle is restored when products and consumers are sufficiently heterogeneous. We have allowed for the existence of heterogeneous products and strategic interdependence of firms.

The effect of such a drift in the consumer bliss point on the firms' market share, assuming firm A preempts B, is shown in the following figure.

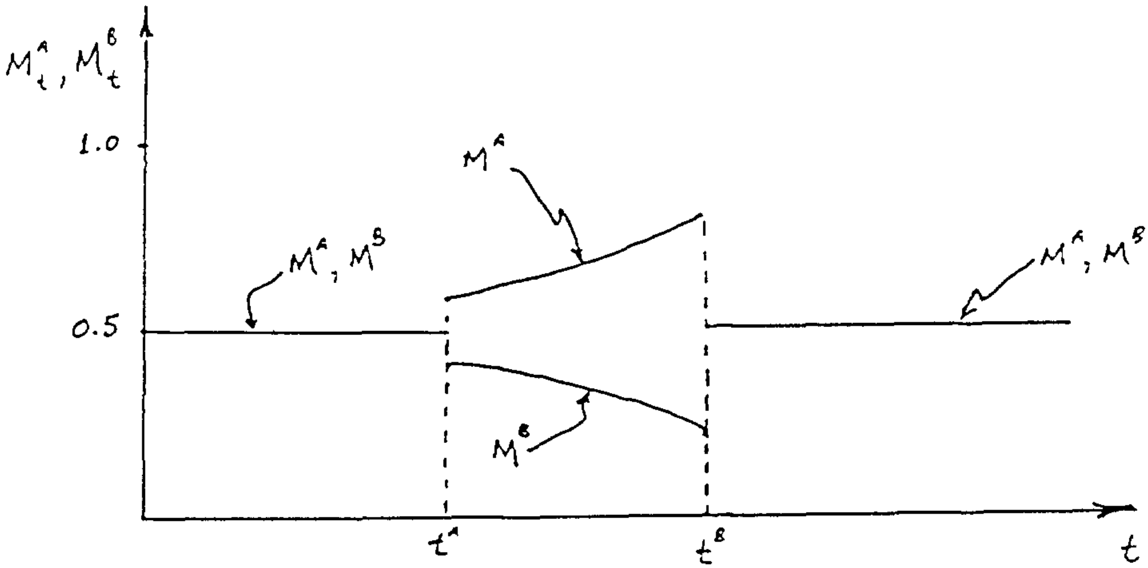


FIGURE 4. EFFECT OF BLISS POINT DRIFT

The net profit of firms A and B for the period t are π^A_t and π^B_t, respectively. They are computed as follows:

$$\pi^A_t(S_t) = \begin{cases} M^A(S_t)D_t(P - C^{AT}) & \text{for } S_t = 1 \text{ or } 3 \\ M^A(S_t)D_t(P - C^{AF}) & \text{for } S_t = 2 \text{ or } 4 \end{cases}$$

The cashflows are then the profits from each period less the capital costs (K) of an FMS of capacity $0.5D_\infty$ (assuming D_t is nondecreasing). These cashflows are then discounted for a net present value. Let ρ^A and ρ^B be the annual discount rates for the firms A and B, respectively. The net present value will be calculated for each of the firms in one of the following ways, depending on the strategy chosen.

<u>QUADRANT I</u> - $S_T = 1$, both firms have transfer lines

In the first period firm A can choose to either invest in FMS and preempt his competitor or to wait. If A preempts then he should expect firm B to make his best response to A's move. The players are assumed to be intelligent i.e. they can put themselves in their competitor's place, surmise what their reactions are likely to be, and gauge their own actions accordingly. The computation to be made in this situation is:

$$NPV^A_t(1) = MAX \begin{cases} \pi^A_t(1) + (1 + \rho^A)^{-1} NPV^A_{t+1}(1) \\ \\ \pi^A_t(1) - K + (1 + \rho^A)^{-1} NPV^A_{t+1}(3) \end{cases}$$

If A's maximum NPV comes from the top expression this implies that A's optimal decision at time t would be to retain its transfer line. However, if the bottom expression is the maximum then A's decision would be to implement a FMS.

If A chooses not to implement a FMS in the previous period B's optimal response is governed by:

$$NPV^B_t = \text{MAX} \begin{cases} \pi^B_t(1) + (1 + \rho^B)^{-1} NPV^B_{t+1}(1) \\ \\ \pi^B_t(1) - K + (1 + \rho^B)^{-1} NPV^B_{t+1}(2) \end{cases}$$

Again, if the top expression is the maximum the best decision of the firm is not to invest in FMS. Otherwise B should preempt A. If, on the other hand, A chooses to preempt B then we would move to the situation in quadrant II.

<u>QUADRANT II</u> - $S_t = 2$, firm A has an FMS, firm B has a TL

In this situation firm B must decide when (or if) he is to respond with an investment in a FMS. The response period t^B is computed from the following objective function:

$$NPV^B_t = \underset{j}{\text{MAX}} \left[\sum_{i=t}^{j-1} \pi^B_i(2)(1 + \rho^B)^{i-t} - K(1 + \rho^B)^{j-t} + \sum_{i=j}^{k} \pi^B_i(4)(1 + \rho^B)^{i-t} \right]$$

where $j \in L$ (L is the set of all time periods t such that $t \geq t^A$).

Expressed within the first summation are the cashflows to B when A is able to produce on the bliss point and B is not. The second summation represents cashflows to B when both firms are able to produce at the bliss point.

If, in quadrant I, A chooses to wait and B chooses to preempt then the competitive situation is that of quadrant III.

QUADRANT III - $S_T = 3$, firm B has a FMS, firm A has a TL

This is the same situation as in quadrant II with the players reversed. The comments and the expressions now apply to firm A with

$j \varepsilon M$ (M = the set of all time periods $t \geq t^B$).

The solution procedure for such a game would be via dynamic programming using as functional equations those expressions given in quadrant I.

The problem is reduced down to finding optimal t^A and t^B. This was done for numerical examples by solving the following first order conditions of the continuous-time game. These results were confirmed through a complete enumeration of the discrete-time game NPV's and searching for the maximum. The game splits into two cases, (1) where firm A preempts B, (2) where firm B preempts firm A.

2.3 THE CONTINUOUS-TIME GAME

We now extend the game described in the previous section into continuous time (i.e. the time increments are made infinitesimally small). This way we can analytically get conditions for the optimal timing of an investment in FMS. First we examine the game in a duopoly setting, then we extend those conditions found to that of multiple (n > 2) firms. From the optimality conditions obtained, we go through a numerical example to illustrate under what conditions a competition for the first move would develop.

Let us assume that we have two equally well endowed firms and that firm A preempts firm B (the case of firm B preempting A will then be just the mirror image of the results of this case). In the continuous-time game the net present value for firm A as a function of its investment period is given by:

$$NPV^A(t^A, t^B) = \int_0^{t^A} \frac{D(t)}{2}(P - C^{AT})e^{-\rho t} dt + \int_{t^A}^{t^B} \frac{D(t)(P - C^{AF})e^{-\rho t}}{1 + e^{-\beta d(x(t),z)}} dt$$

$$+ \int_{t^B}^{\infty} \frac{D(t)}{2}(P - C^{AF})e^{-\rho t} dt - K e^{-\rho t^A}.$$

The first order condition for firm A is then:

(14)

$$\frac{\partial NPV^A}{\partial t^A} = (\frac{1}{2}D(t^A)(P - C^{AT}) - \frac{D(t^A)(P - C^{AF})}{1 + e^{-\beta d(x(t^A),z)}} + \rho K)e^{-\rho t^A}$$

$$= 0.$$

The sufficiency condition for optimality is:

$$\frac{\partial^2 NPV^A}{\partial t^{A^2}} = (\frac{1}{2}(P - C^{AT})(D'(t^A) - \rho D(t^A)) + \frac{(\rho D(t^A) - D'(t^A))(P - C^{AF})}{1 + e^{-\beta d(x(t^A),z)}}$$

$$- \frac{D(t^A)(P - C^{AF})\beta d'(x(t^A), z)e^{-\beta d(x(t^A),z)}}{(1 + e^{-\beta d(x(t^A),z)})^2} - K\rho^2)e^{-\rho t^A} < 0.$$

For firm B the net present value as a function of its response time is:

$$NPV^B(t^A, t^B) = \int_0^{t^A} \frac{D(t)}{2}(P - C^{BT})e^{-\rho}t dt$$

$$+ \int_{t^A}^{t^B} (1 - (\frac{1}{1 + e^{-\beta d(x(t),y)}}))D(t)(P - C^{BT})e^{-\rho t} dt$$

$$+ \int_{t^B}^{\infty} \frac{D(t)}{2}(P - C^{BF})e^{-\rho t} dt - Ke^{-\rho t^B}$$

For firm B the first order condition for optimal response is:

$$\frac{\partial NPV^B}{\partial t^B} = (\frac{(P - C^{BT})D(t^B)}{1 - (\frac{1}{1+e^{-\beta d(x(t^B),y)}})} \tag{15}$$

$$\frac{-1}{2}(P - C^{BT})D(t^B) + K\rho)e^{-\rho t^B} = 0.$$

The sufficiency condition for firm B's optimal response is:

$$\frac{\partial^2 NPV^B}{\partial t^{B^2}} = ((\frac{1}{2}(P - C^{BF}) - (1 - \frac{1}{1 + e^{-\beta d(x(t^B),y)}})(P - C^{BT})(\rho D(t^B) - D'(t^B))$$

$$-K\rho^2 - \frac{\beta d'(x(t^B), y)e^{-\beta d(x(t^B),y)}D(t^B)(P - C^{BT})}{(1 + e^{\beta d(x(t^B),y)})^2})e^{\rho t^B} < 0.$$

This analysis can be extended to the general n-firm case with the use of the following expression:

$$NPV^{A^n}(t^A, t^B, t^C, \ldots) = \int_0^{t^A} \frac{(P - c^{AT})D(t)}{n} e^{-\rho t} dt$$

$$+ \int_{t^A}^{t^B} (P - C^{AF}) \frac{D(t)}{1 + \sum_{i=2}^{n} e^{-\beta d(x(t), z_i)}} e^{-\rho t} dt$$

$$+ \int_{t^B}^{t^C} (P - C^{AF}) \frac{D(t)}{2 + \sum_{i=3}^{n} e^{-\beta d(x(t), z_i)}} e^{-\rho t} dt$$

$$+$$

$$\vdots$$

$$+ \int_{t^{n-1}}^{t^n} (P - C^{AF}) \frac{D(t)}{(n-1) + e^{-\beta d(x(t), z_n)}} e^{-\rho t} dt$$

$$- K e^{-\rho t^A}$$

where the order of the FMS investment is firm: A, B, C, ...

The first order condition for the first firm being:

$$\frac{\partial NPV^{A^n}}{\partial(t^A)} = \quad K\rho e^{-\rho t^A}$$

$$-\frac{(P - C^{AF})D(t^A)e^{-\rho t^B}}{1 + \sum_{i=1}^{n} e^{-\beta d(x(t^A),z_i)}} = 0.$$

where $z_i = z_i(t^A)$.

The sufficiency condition for profit maximization by firm A is:

$$\frac{\partial^2 NPV^{A^n}}{\partial t^{A^2}} = (-K\rho^2$$

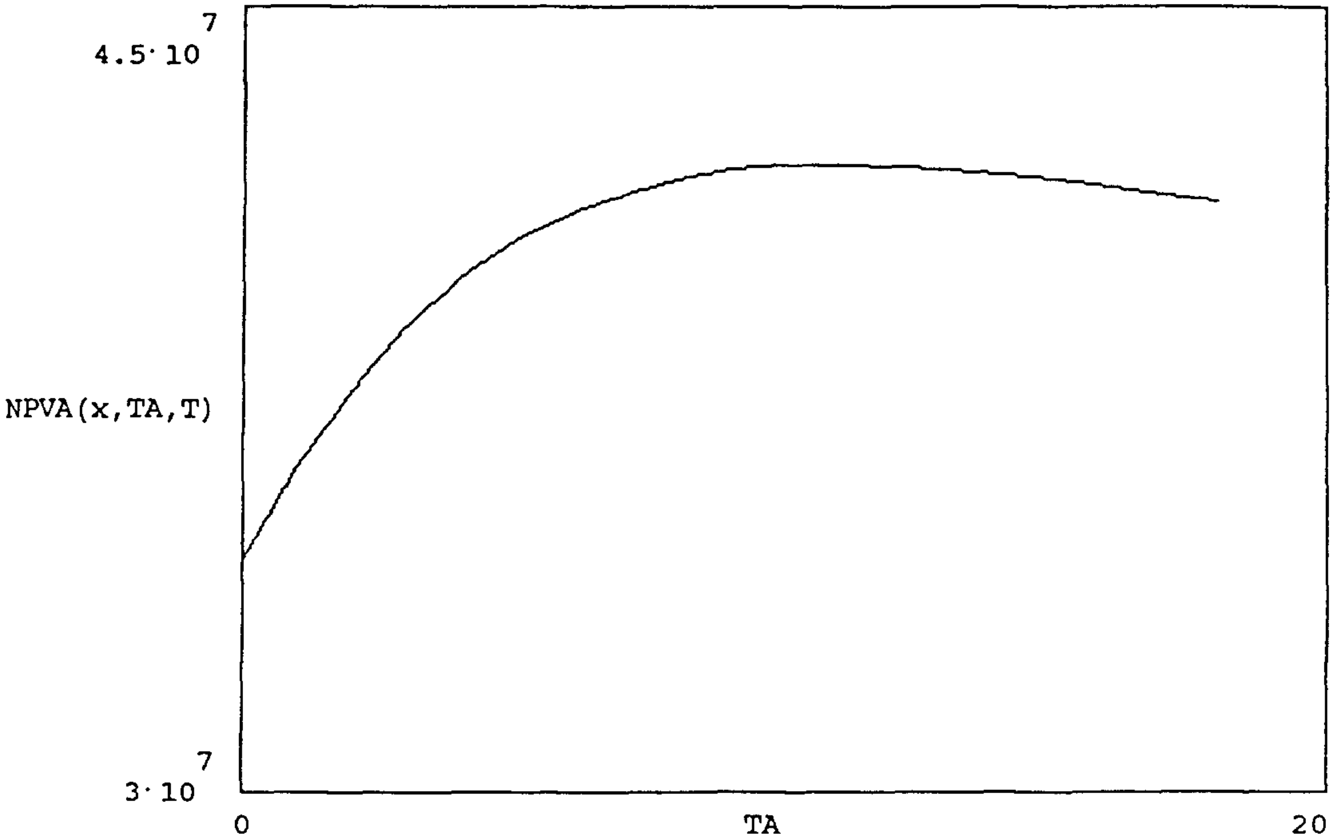
$$-\frac{(P - C^{AF})}{1 + \sum_{i=2}^{n} e^{-\beta d(x(t^A),z_i)}}(\rho D(t^A) - D'(t^A))$$

$$+\frac{(P - C^{AF})D(t^A)\sum_{i=2}^{n} -\beta d'(x(t^A), z_i)e^{\beta d(x(t^A),z_i)}}{(1 + \sum_{i=2}^{n} e^{-\beta d(x(t^A),z_i)})^2})e^{-\rho t^A}$$

$$< 0.$$

A numerical example of the net present value of firm A as a function of its timing of investment is given in the following figure.

FIGURE 4. THE NPV FOR FIRM A VS TIME OF INVESTMENT

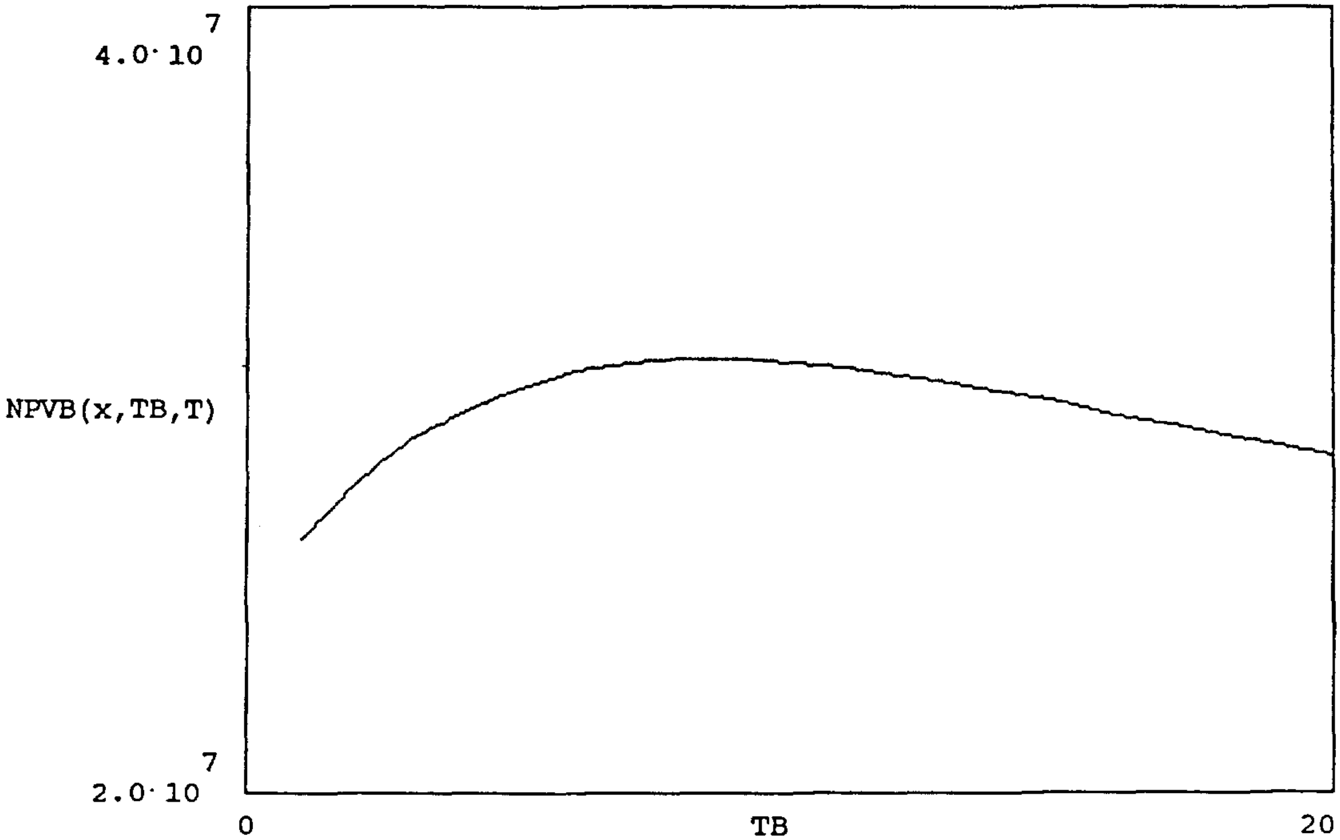


Given:
P := 100.0
cat := 90.0
caf := 92.0
T := 0 ..20
Row := 0.10
D(T) := 1000000
K := 10000000
TB := 18
TA := 0 ..TB
α := 1.0
y := 10
x(T) := 10 + 0.1 T
dist(x,T,y) := $|x(T) - y|$

The net present value for firm B as a function of its timing of response appears in the following figure.

FIGURE 5. THE NPV FOR FIRM B VS TIME OF INVESTMENT

Case where firm A preempts firm B



Given:
P := 100.0
cbt := 90.0
cbf := 92.0
T := 0 ..20
Row := 0.10
D(T) := 1000000
K := 10000000
TA := 1
TB := TA ..20
α := 1.0
z := 10
x(T) := 10 + 0.1·T
dist(x,T,z) := |x(T) - z|

From the above figures 4 and 5 we see that there exist optimal timings for the FMS investments. These optimal time periods t^{A*} and t^{B*} can be solved for analytically from the first order conditions given by the expressions (14) and (15). The optimal response was computed for each firm given the other firm's timing of the investment. Finding the points of maximum payoff we find the Nash equilibria at time periods (t^{A*}, t^{B*}) of (9, 9), (10, 10) and (11, 11) where (11, 11) Pareto dominates the other equilibria. These Nash equilibria are also subgame perfect.

It is interesting to note that, as B responds sooner, the NPV function for A shifts downward and as firm A preempts later, the NPV function for B shifts upward. The two NPV's correspond (give equal values) at their equilibrium points (9,9), (10,10) and, (11,11). The NPV for the preempting firm is always greater than or equal to that of the follower. This phenomenon is not affected by our earlier assumption of bliss points moving linearly over time. The bliss points can move in a random walk pattern and the NPV for the preempting firm is greater than or equal to the NPV of the follower so long as the bliss point strays from the initial bliss point sufficiently to create the incentive for the shift in technology. Thus, when firms have similar market positions and similar cost structures there exists an incentive to preempt and a competition for the first move. This supports the hypothesis that the diffusion of this technological innovation will occur in "swarms".

2.4 CONCLUSIONS

The analysis of the previous model shows that the Schumpeterian hypothesis that industries will invest in innovative technology in "swarms" may well hold in the case of FMS. An examination of the list of firms implementing FMS (shown in Tombak, 1988, Appendix D) gives credence to the hypothesis. There, it is exhibited that there are high concentrations of FMS implementors in the machine tool, automobile, aerospace, heavy machinery (agricultural and construction machinery), and electronics industries. This is summarized in Table 1 of the Introduction. It is interesting to note that many of the implementations were carried out during approximately the same time period (1982-1984) with the machine tool industry (understandably) being the earliest to make use of the technology. We know that the development of an FMS requires years of effort (Jaikumar, 1986). This appears to bear out the theory of implementations by "swarms".

It should be kept in mind, however, that niches may well exist where TL technology would be appropriate in industries which have adopted FMS. For example, if the TL were able to produce at a lower cost and the producer could thereby offer a lower price to the customer this would allow the producer with a TL to cater to consumers who are more price sensitive and less reactive to other product characteristics. The analysis of this situation would require higher dimension vectors of product characteristics used in the logit model in section 2.2.

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