"STRATEGIC ASPECTS OF FLEXIBLE PRODUCTION TECHNOLOGIES"

by

Lars-Hendrik ROLLER*
and
Mihkel TOMBAK**

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* Assistant Professor of Economics, INSEAD, Boulevard de Constance, 77305 Fontainebleau, France

** Assistant Professor of Production and Operations Management, INSEAD, Boulevard de Constance, 77305 Fontainebleau, France

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Lars-Hendrik Röller and Mihkel M. Tombak*

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Abstract

In this paper we examine the innovative manufacturing technologies known as "Flexible Manufacturing Systems". We begin with a description of these systems and then develop a simple strategic model of the decision process to invest in either FMS or in more traditional, product-dedicated equipment. Our model illustrates the importance of such market factors as product differentiation, difference in cost and market size in the decision process. We then discuss several extensions of our model to include the effects of competition and market growth on technology choice. Empirical evidence is shown to correspond with the theory.

*European Institute of Business Administration (INSEAD), Blvd. de Constance, 77305 Fontainebleau Cedex, France. This research has been financially supported by INSEAD research grant no. 2172 R.

I. Introduction

In a time of increasing internationalization of business large manufacturing firms face demands for a growing array of product designs necessary to satisfy diverse markets across borders and cultures. To further confound this problem management is confronted with escalating changes in the level of output and rising uncertainty in the competitive environment and in the manufacturing process itself. In this dynamic environment the term "flexibility" is heard more and more in defining the competitive edge (see Dertouzos, Lester and Solow, 1989). The strategic value of flexibility - the ability to adapt and survive under different market scenarios - should not be underestimated in the decision to acquire production technology.

The pursuit of flexibility has led many large firms to invest in sophisticated plants known as Flexible Manufacturing Systems (FMS) to the tune of 10 to 12 million dollars apiece (Krouse, 1986). These new manufacturing systems with their distinctive "high tech" characteristics are changing the face of the manufacturing world and have widespread implications for market structure, international competitiveness, and labour markets. An investment in a large hi-tech system such as an FMS is, however, a costly venture and can result in wideranging organizational changes (see Milgrom and Roberts, 1988). The manager is faced a difficult decision: whether to make the large investment in an FMS or to turn to more static, less expensive machines dedicated to certain, fixed types of products. The odern manufacturer must consider the intricate problem of future production system needs.

In this paper we examine what these new manufacturing technologies are and where they are presently in use. We then present a simple economic model, the analysis of which provides us with a number of insights into the market conditions which encourage firms to invest in FMS. Extensions of the basic model further our understanding of the factors affecting the timing of the investment. Finally, we present some empirical evidence which is consistent with the theoretical findings.

II. Flexible Manufacturing Systems - Small Wonders of Technology

A series of innovations have played a crucial role in the development of flexibility in automated production systems. At the machine level the introduction of numerical controlled machine tools and automatic tool changers has resulted in a dramatic drop in the set-up times required to produce different products. System, or factory level flexibility has been enhanced through automated materials handling systems and, most importantly, through centralized computer control. This has improved shop floor control and decreased throughput times. It is essential for the centralized computer control to communicate with and effectively manage all the other parts and microprocessors in the system, such as production scheduling, traffic control for the materials transfer line, production monitoring, tool control, and the automated guided vehicles. As a result, a considerable amount of effort has been put forth to develop a standard interface, namely, the Manufacturing Automated Protocol (MAP). Since its development by General Motors MAP has been accepted by a number of vendors (i.e. IBM, Allen-Bradley, Gould, Honeywell, Hewlett-Packard) as a standard protocol.

Attempts at developing FMS in the 1970's were to a large degree experimental. Many such attempts met with failure. As a result of the apparent risk and the large capital expenditures necessary, FMS was slow in being adopted by firms. A number of technological breakthroughs, starting with the development of the numerically controlled machine tools, computer controlled industrial robots, and the advent of the microprocessor in the 1970's brightened the prospects in terms of feasibility of such systems. With improving price/performance of microprocessors, with some of the software and systems level (i.e. MAP) problems gradually being solved, and with a larger number of firms having gained experience with smaller scale automation, the population of FMS showed a relatively strong rate of growth in the early to mid-1980's. Table 1 depicts the population distribution of FMS and how it evolved between 1980 and 1987.

Table 1: Installed FMS*

	1980	1987
Japan	40	115
United States	25	72
Eastern Europe	25	41
Western Europe	25	141
Other countries	10	36
TOTAL	125	405

*Source: Tombak, 1988

Despite some of the more recent technological successes of FMS, firms are still wary of the large investment. This explains why the use of smaller scale flexible manufacturing cells (FMC) is more widespread and has outstripped investment in FMS in the U.S. In 1985, according to the Yankee Group, a market research group in Boston, FMS vendors earned $143 million, based on 12 new units sold and revenues derived from customer services. In contrast, a total of 250 FMCs were installed in 1985 and vendor revenues were $300 million (Krouse, 1986).

Most of these FMS implementations have occurred in the metalworking sector with some notable exceptions, for example, in the clothing industry. Table 2 shows the implementation of FMS by industry. It is interesting to note that FMS are found primarily in five industries, all characterized by intense competition and a need for large-scale modification of their manufacturing infrastructure. To survive in their market, they have had to acquire the capability of introducing new product designs more rapidly.

Table 2

Distribution of FMS by industry sector in 1987*

Industry Sector	Percentage of FMS by Sector		
	W. Europe	United States	Japan
Light automotive (cars, motor cycles)..	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

*Source: Tombak, 1988

But is flexibility always beneficial, and if so under what circumstances? What are the strategic forces and market fundamentals that drive firms into FMS investment? Under what situations does the outcome of this strategic technology game coincide with the firm's best interests? We plan to address these issues in the next section using a simple game-theoretic model to analyze the strategic interaction among firms.

III. The Strategic Value of Flexibility: A Simple Model

We model the technology-quantity choice as a two-stage sequential duopoly game of complete information (see Röller and Tombak, 1988). In the first stage, firms simultaneously choose between a flexible production technology (denoted FMS) and a less flexible (and less expensive) product dedicated technology (denoted DE). Two markets exist, one for product A, and another for product B. The flexible manufacturing technology allows a firm to participate in both markets (i.e. the equipment is capable of producing both product A and product B) whereas the inflexible technology limits the firm to producing either product A or B. Given a set of technologies chosen by the firms, a second stage game of Cournot quantity competition in each of the product markets completes the model. We seek a subgame-perfect equilibrium in such a game (Selten, 1975).

Demand for each market is given by the following linear, symmetric system,

$$P^A = a - Q^A - \lambda Q^B$$
$$P^B = a - Q^B - \lambda Q^A,$$

where Q^A and Q^B (P^A and P^B) are the total quantities (prices) for products A and B, respectively. We interpret λ as a measure of substitutability between products A and B. We assume that the two products are gross substitutes and that the own price effect dominates the cross price effect, i.e. $1 \leq \lambda \leq 0$. In other words, as λ approaches 1 the products become closer substitutes.

Given the firm's technology choices of FMS or DE in the first stage, firms have the following second stage payoff functions,

$$\pi_i^{FMS,T} = P^A Q_i^A + P^B Q_i^B - F^{FMS} - c(Q_i^A + Q_i^B), \quad \text{if firm i invests in FMS,}$$

$$\pi_i^{DE,T} = P^A Q_i^A - F^{DE} - c(Q_i^A), \quad \text{if firm i invests in DE,}$$

where $\pi_i^{FMS,T}$ is firm i's second stage payoff given that firm i chooses technology FMS and the rival firm chooses technology T=FMS,DE. Also, Q_i^A and Q_i^B are the quantities produced by firm i (i=1 or 2) in markets A and B respectively, F^{FMS} or F^{DE} are the fixed costs of the firm associated with the chosen technology FMS or DE, such that $F^{FMS} \geq F^{DE}$, and c is the marginal production cost. If both firms choose DE then one firm will enter market A and the other will enter market B.

Since we wish to determine which market forces influence the adoption of FMS technologies and how they exert their influence we focus on three market fundamentals. In addition to λ, we define a measure of market size by $t = a - c$, where $t \geq 0$. The third determinant of market outcome is a measure of the difference in fixed costs between an FMS and a DE technology. We set $F^{FMS} = F^{DE} + s$, where $s \geq 0$ is the difference in fixed costs between the two technologies. As a result, our solutions emerge in terms of market size (t), the difference in fixed costs (s), and the market segmentation parameter λ.

In the first stage of the game the firms simultaneously choose the production technology. This stage of the game is illustrated in Figure 1.

FIGURE 1

The Production Technology Game

		FIRM 2	
		FMS	DE
FIRM 1	FMS	$\pi_1^{FMS,FMS}, \pi_2^{FMS,FMS}$	$\pi_1^{FMS,DE}, \pi_2^{DE,FMS}$
	DE	$\pi_1^{DE,FMS}, \pi_2^{FMS,DE}$	$\pi_1^{DE,DE}, \pi_2^{DE,DE}$

The equilibrium concept we use for the game in Figure 1 is subgame perfection (see Selten, 1975). In our analysis we will concentrate on three possible equilibria. First, (FMS, FMS) in which both firms choose flexible production technologies and enter both markets. Second (DE, DE) where both firms choose not to invest in flexible technologies and consequently enter separate markets. Third, the "mixed" case, where one firm chooses a flexible technology and the other firm does not. For each equilibrium we first solve the second stage Cournot quantity game for the two markets A and B. The solutions to the second stage Cournot game are then substituted into the payoff functions given in Figure 1. From Figure 1 we see that (FMS, FMS) is an equilibrium when,

$$\pi_i^{FMS,FMS} > \pi_i^{DE,FMS} \quad , \ i = 1,2.$$

For the model outlined in the previous section we can write the equilibrium conditions as,

$$t^2(1 - \lambda) - 9s(1 + \lambda) \geq 0.$$

From the above condition one can see that strategic incentives move the market to adopt FMS when t is high and when λ and s are low. One can interpret a low λ as the situation in which the two products are perceived by consumers as being highly differentiated. When this is the case any firm choosing DE automatically locks itself out of almost half of the market, hence the natural tendency to invest in an FMS. A high t represents large markets, encouraging more active participation in both markets. A high s is indicative of the fixed costs of the FMS being much greater than the fixed costs of the DE. This would discourage firms from investing in FMS. As discussed above, falling costs of FMS have been a big factor in the increase in implementations in the early to mid 1980's.

Similarly, the conditions for (DE, DE) to be an equilibrium for the game in Figure 1 are,

$$\pi_i^{DE,DE} > \pi_i^{FMS,DE} \quad , \quad i=1,2.$$

These conditions imply that,

$$t^2(1 - \lambda)(5\lambda^2 + 12\lambda + 16) - 36s(1 + \lambda)(2 + \lambda)^2 \geq 0.$$

As one would expect, these conditions yield market fundamentals λ's, t's, and s's that lie at opposite ends of their respective ranges from the conditions for (FMS, FMS). Consequently, for high λ's (products A and B being close substitutes), low t's, and high s's (DE, DE) will be the outcome. Finally, (FMS, DE) is an equilibrium when,

$$\pi_i^{FMS,DE} > \pi_i^{DE,DE} \quad , \; i=1,2,$$

and (DE, FMS) is an equilibrium when,

$$\pi_i^{DE,FMS} > \pi_i^{FMS,FMS} \quad , \; i=1,2.$$

By symmetry, both the conditions imply that,

$$t^2(1 - \lambda) - 9s(1 + \lambda) \geq 0 \text{ and}$$
$$t^2(1 - \lambda)(5\lambda^2 + 12\lambda + 16) - 36s(1 + \lambda)(2 + \lambda)^2 \geq 0.$$

These equilibria would result from our market fundamentals being in between the previous two cases. This confirms our intuition that asymmetric equilibria exist for intermediate values of t, λ, and s. In other words, the markets are too small, the products are too substitutable, and the fixed costs are too high for more than one firm to invest in FMS. It is interesting to note that asymmetric equilibria can emerge even though our model is completely symmetric. That is, even with identical firms we have one firm investing in the flexible production technology and the other not.

Next we analyze strategic incentives by examining the firms' payoffs for each equilibrium. It is clear that firms would prefer to be in the (DE, DE) equilibrium rather than the (FMS, FMS) equilibrium, since the DE technology is cheaper and competition is reduced. That is to say, they prefer to be monopolists, especially at a cheaper price. Thus, we have the following result:

> Producers' payoffs are highest in a (DE, DE) equilibrium and lowest in an (FMS, FMS) equilibrium.

The implication of the above statement is that when (FMS, FMS) is the strategic outcome of our game, the production technology game is a Prisoners' Dilemma. In other words, whenever market profitability is high (t is high), markets are highly differentiated (λ is low), and the new technology is relatively cheap (s is low) then firms tend to invest in FMS technology for <u>strategic</u> reasons, forsaking profits.

The questions then arise as to whether and how firms can break the Prisoner's Dilemma. One way would be through a change in λ. For example, if firms standardized their products, λ is increased and the payoff structure could be altered such that (DE, DE) becomes the equilibrium. Thus we have identified, in the context of our model, a strategic incentive for firms to standardize their products. This incentive to standardize comes from the fact that product differentiation leads to FMS investment and increases competition in each market.

IV. Extensions of the Basic Model

There are several ways in which the above model can be extended. We will discuss two additional important strategic dimensions. The first extension is the question of competition and how it effects the adoption of new multiproduct technologies. One way of modelling this is to introduce one more parameter, the number of firms playing the technology game (n). We denote the proportion of firms that invest in FMS by ρ. We then investigate the properties of the function $\rho(n)$, in particular what happens to $\rho(n)$ as n approaches infinity. This model is formalized in Röller and Tombak (1989). The basic conclusion is that as markets become perfectly competitive, fewer and fewer firms invest in FMS, i.e. $\rho(n)_{n\to\infty} = 0$. This suggests a basic Schumpeterian conclusion, namely that competitive forces drive firms away from multiproduct technology investments.

The second aspect, so far excluded from the basic model outlined above, is the crucial dynamic effect of investment decisions. In other words, when do firms invest in new production technologies and how is this timing decision influenced by what rival firms do? Is there a competitive race to adopt earlier than your competitor, and if so, does this lead to an adoption time which is too early in the social sense or even from the firm's point of view? One can easily see that these questions of strategic timing require the introduction of some dynamic element into our basic model. The literature on dynamic technology adoption is mostly concerned with the singleproduct case (see Reinganum (1981a,b), Fudenberg and Tirole (1985))). As already demonstrated in the above simple model, a multiproduct environment, such as FMS, is crucially dependent on the precise demand characteristics. In particular, the multiproduct technology game leads to fundamentally different strategic outcomes depending on whether markets are modelled as complementary or substitutable, or whether markets are in a growth phase or declining.

Take for example the case of growing markets with substitutable products. This may be modelled by allowing a(t), where da(t)/dt>0, in the above simple model, that is, the demand shifts up over time. It can be shown (see Kim, Röller, and Tombak, 1989)) that in this case firms adopt the new multiproduct technology simultaneously. Moreover, the comparative statics show that the more differentiated the markets are (low λ) the early the firms adopt. Higher production costs (c) and high costs of the new technology (F^{FMS}) delay the firms' simultaneous adoption decision. It can also be shown that the competitive nature of the game leads firms to adopt earlier than socially optimal.

We now compare this to the case of complementary products. Here we show that firms will never simultaneously adopt, but that there will be a leader and a follower. The reason for this is the noncompetitive nature of the complementary market game, namely the fact the production by a rival firm in other markets helps boost demand in all markets, thereby inducing more cooperative behavior[1]. Under this scenario, firms in effect behave more cooperatively: one firm adopts the new technology first and recovers its investment while the other firm saves on not

1. This is analogous to the concepts of strategic substitutability and complementarity, where strategic substitutability induces a more competitive outcome (see Bulow, Geanakoplos, and Klemperer, 1985).

having to invest in the expensive technology. Once markets have grown to be large enough to guarantee high payoffs for both firms (recall that we have indeed assumed markets are growing) the second firm follows. It is clear that demand characteristics play an important role.

We now consider declining markets, i.e. $da(t)/dt<0$. Intuitively, one may argue that in a world of falling demand one would either invest right away, or nobody would invest in an expensive new technology. This intuition is essentially correct. For the above model under declining demand, firms' dynamic maximization problem is convex. This implies that firms optimize by either adopting instantaneously or never, irrespective of the costs of the new technology. This result, even though perfectly plausible, is quite different from the growing market case.

Finally, what would be the prediction of the above models if we consider a product going through a life cycle? It is clear that firms would not invest in the new technology during the falling phase, since firms would have wanted to invest earlier (i.e. during the growth phase), or never. Thus, our model would predict that firms would invest during the growth phase. As we will see next, this prediction is empirically supported.

V. The Value of Flexibility: Some Empirical Evidence

A recent analysis (Tombak 1988) of approximately 2000 North American businesses reveals that there is indeed a strong positive correlation between the degree of flexibility in their manufacturing processes as well as in other aspects of their performance. Studies covering other parts of the world lead to similar conclusions. This would lend some empirical evidence to the fact that a profitable environment, be it through large demand (high t) or a lack of competition (small number of firms n), induces firms to invest in these expensive technologies.

The above study of 2000 businesses also found that manufacturing flexibility had a stronger correlation with firm performance in the consumer durable sector than in any other manufacturing sector tested. The theory suggest that this could be due to products being more differentiated in the consumer durable manufacturing sector. This also coincides with the data shown in Table 2 where most sectors exhibit a high degree of customization.

As can be seen in Table 2, over 85% of the FMS implementations have been in industry sectors characterized by large firms. Furthermore, many FMS adopters are in state subsidized markets, i.e. defence department contracts in the aerospace industry and several key European and Japanese industries. This corresponds with the Schumpeterian result found in our theoretical model that highly concentrated industries would foster the adoption of the new manufacturing technologies.

In the same study by Tombak (1988) manufacturing flexibility is seen to be more important in the growth phase of the product life cycle than in the mature phase. This is due to several factors. First, when a product is in its early stages, manufacturers often have to make frequent design changes as they learn about market demands for specific features. Second, because the volumes demanded are uncertain, manufacturers may find that frequent process changes are required. And third, during the growth phase, the rate of learning about the production process is greatest, leading again to more frequent process changes. In the mature phase, flexibility continues to be important, but to a lesser degree. This observation closely coincides with the prediction of the theoretical model, that is firms are more likely to invest during the growth phase of the product life cycle.

VI. Conclusion

This paper argues that it is not always an advantage to be flexible, because of the cost associated with each aspect of flexibility. In many instances it is not possible to recover the related investment in a competitive environment. For instance, we find that in some cases the benefit of flexibility can be completely eliminated if every (or most) competing firm(s) invest in a flexible technology. This well known strategic situation is called the "prisoner's dilemma". It depicts a situation where through mutual cooperation, a better outcome could be guaranteed, but where competitive forces drive the strategic game towards a less favorable solution. Under this scenario, firms are collectively better off by not investing in FMS. However, individual firms will still invest in FMS to ensure their survival.

We have determined a set of conditions under which we would expect firms to increasingly invest in flexible manufacturing technologies: declining costs of FMS systems, increasing market segmentation and product differentiation, products in the growth phase, uncertainties regarding market size and customer tastes, and increasing market power. The last one, market power, is worth a few comments. As global competition intensifies and markets open up to international competitors, it is important to ask whether FMS investment is vital to survival. We believe that FMS investment is not necessarily the answer to increased competition, for all firms. In fact, the advantages of flexibility may be diminishing as a greater number of firms "go flexible". A firm may very well perform best by catering to a particular segment of the market, using a less flexible and less expensive technology. We find that with intensifying competition, a large number of firms will not use flexible technologies. On the other hand, there will always be some firms that choose the flexible option, entering the whole spectrum of markets with a large variety of products produced by the flexible manufacturing system. Thus, we find that competition will yield a technology mix, with some firms opting for flexibility and others not, each operating in its strategic niche.

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