Flexible Manufacturing Technology and Product-Market Competition

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WP #3135-90-MSA March 1990

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ABSTRACT

This paper presents a game-theoretic model to analyze how the existence of product-flexible manufacturing technology can affect the technology and market strategies of competing firms. Our two-firm, two-market model allows each firm to invest in a technology dedicated to its home market or a flexible technology that also can be used to invade its rival's market and/or provide a credible threat to retaliate if its own market is invaded. In contrast to single-firm models in which the availability of a flexible technology at a low cost makes firms better off, we find that unless several restrictive conditions are met, the existence of flexible technology (at a reasonable cost) can intensify competition; firms would be better off if the flexible technology did not exist. Depending on the nature of the competition, consumers may or may not benefit from its existence.

The authors gratefully acknowledge helpful comments from Garth Saloner, Mihkel Tombak, and seminar participants at MIT, Stanford, Columbia, and ORSA/TIMS.

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1. Introduction

The increasingly volatile and competitive business environment faced by American manufacturing firms has generated considerable interest in the deployment of flexible manufacturing systems (FMSs). In addition to its use as a tactical tool to respond quickly to variations in demand within a market (Fine and Freund 1990), or to reduce inventory requirements (Graves 1988; Caulkins and Fine 1990), flexible technology may also be employed strategically by the firm both to defend its own markets and to enter the markets of its less flexible competitors. In this paper, we focus on this strategic function of flexible technology. We present a competitive model which describes the impact of product-flexible manufacturing systems on firms' output and technology investment decisions.

As used here, flexibility refers to a production technology that can be modified, with little or no cost, to produce a variety of different goods. (See Piore (1986) for a useful flexibility taxonomy.) Many of the recent developments in the FMS investment evaluation literature (surveyed by Fine 1989) address some aspect of this feature of flexibility. See, for example, Fine and Freund (1990), Fine and Li (1988), Karmarkar and Kekre (1987), Kulatilaka (1988), and Vander Veen and Jordan (1989), each of which addresses some aspect of flexibility, but none of which considers interfirm competition. With respect to the explicit modeling of competition, the papers most closely related to ours are Gaimon (1989) and Roller and Tombak (1990). Gaimon uses a two-firm, continuous-time model to compare how firms' technology acquisition strategies compare under the assumptions of open-loop or closed-loop dynamics. The decision variables for each firm are the price charged, the rate of acquisition of new technology, and total capacity from old and new technology. Although her model of new manufacturing technology captures important correlates of flexibility, such as improved market share and lower variable costs, flexibility is not modeled explicitly. The results show that firms charge higher prices, acquire less new technology, buy less total capacity, and earn higher profits in the closed-loop game.

Roller and Tombak (1989) present a two-firm technology acquisition model with two differentiated products, each characterized by linear demand function, with a positive cross-price effect. Their results show (1) when products are highly differentiated, industry is driven to adopt FMS, (2) as markets become larger and as the difference between fixed costs of the two technologies diminishes, incentives to invest in FMS increase, and (3) the introduction of FMS improves economic welfare.

In our two-firm, repeated-game model, each firm may find it desireable to forego entry into the other's primary market, even if each has the technology to produce for both markets. Flexible capacity serves as a mechanism to prevent such entry. Entry by one firm into its rival's market may trigger a retaliatory punishment strategy ("grim" strategy) that leads both firms to achieve a mutually less profitable equilibrium path. In our model flexible capacity provides a credible threat to enter its rival's market in retaliation, if necessary.

Our purpose is to illustrate the strategic dynamics that can result among firms due to the availability of product-flexible manufacturing technologies. As a result, we present a very simple model that highlights the increased competition that may be fueled by the existence of flexible technology. In particular, we show how the existence of flexible technology can make firms worse off. To incorporate the concepts discussed here into a credible decision support system to aid managers in technology investment decisions would be a formidable task. However, managers who use decision support models to aid technology investment decisions without considering the issues highlighted here could estimate incorrectly the benefits and strategic implications of such investments.

The next section describes the models to be considered, including a formulation of the problem and assumptions about the timing of actions and cost structure of the different technologies available. Model I, presented in Section 3, examines the competitive interaction of firms in a duopolistic market when the game permits only a one-time purchase of technology before production. Model II, considered in Section 4, relaxes the restriction on technology purchase and permits firms to acquire technology before each period of production. In both sections, we show how the existence of flexible technology can intensify competition and make firms worse off. We conclude in Section 5 with a discussion of results and directions for future research.

2. Model Formulation

We want to evaluate the impact of flexible manufacturing systems and competition on firms' technology investment decisions. We use a two-firm, two-product model with three types of technology available. The first technology type represents a flexible system that may be employed in production of goods for either market. The other two technologies are dedicated--each restricted to manufacture of one product.

To simplify the analysis, we assume that when the firm purchases a technology, flexible or dedicated, it acquires sufficient capacity of that technology to satisfy all demand in the market(s) it is capable of serving. That is, the minimum efficient scale of each technology is sufficient to satisfy the market demand. This assumption enables us to concentrate on the decision to invest in a particular type of technology independent of the complicating issue of capacity quantity, which is addressed by Fine and Freund (1990) in the single-firm, stochastic-demand version of this model.

In Model I (Section 3), to reflect the long lead times associated with investment decisions, as compared to those for production, we permit the acquisition of capacity only once prior to the start of the T-period production horizon. In contrast, the timing in Model II (Section 4) allows firms to acquire additional technology before each of the production periods. In this latter model, a firm may choose to adopt a "wait and see" attitude, postponing some investment until after observing its rival's earlier actions.

We denote the two firms as 1 and 2, and the two markets as A and B. Let K^A and K^B, respectively, denote the dedicated technology that can only manufacture products for markets A and B, and let K^{AB} denote the flexible technology that can produce for both markets. These decision variables are indicator variables that represent the choice to purchase or not purchase each technology for a fixed one-time investment cost. We denote by C^A, C^B, C^{AB}, respectively, the investment and installation costs of acquiring technologies K^A, K^B, and K^{AB}.

Let $\pi_i^{M_m}$ ($\pi_i^{D_m}$) denote the per-period monopoly (duopoly) profits, net of operating costs, for firm i in market m, for i=1,2; m=A,B. We assume that operating profits for each firm in each market are independent of the technology used. This assumption could hold, for example, if the variable cost of producing one unit of product A is the same whether it is produced with the flexible technology or with the dedicated A-technology. For highly automated (flexible or dedicated) manufacturing systems, where most of the variable costs are material costs, this assumption seems reasonable. Both firms use a per-period discount factor of δ ($0<\delta<1$) over an industry horizon of length T.

We make the following assumptions about the cost and profit parameters:

ASSUMPTION 2.0: $\pi_i^{M_m} > \pi_i^{D_m}$ for i=1, 2, m=A, B,

ASSUMPTION 2.1: $C^{AB} > C^A$ and $C^{AB} > C^B$,

ASSUMPTION 2.2: $C^A + C^B > C^{AB}$,

ASSUMPTION 2.3a: $C^A < \sum_{t=1}^{T} \delta^t \pi_1^{D_A}$,

ASSUMPTION 2.3b: $C^B < \sum_{t=1}^{T} \delta^t \pi_2^{D_B}$.

The first assumption states the elementary result from microeconomics that profit levels are higher when a firm operates alone in a market than when there is duopolistic competition in that same market. The second assumption says that the more complex flexible technology costs more to acquire than either type of dedicated system. That is, there is some cost associated with the benefits that the flexible capacity provides. The third assumption indicates that it is more economical to purchase a flexible system than two dedicated systems if the firm is going to operate in both markets. Thus, if a firm desires the capability to operate in both markets, the lowest cost technology purchase decision results in the firm only buying a flexible system. The last pair of assumptions ensures that each firm will find it profitable to enter at least one market even if it will only earn duopoly profits in that market. In particular, Assumption 2.3 suggests the allocation of market A to firm 1 and market B to firm 2.

We also assume, for each market, that the monopoly profits accrued to a single firm in that market exceed the sum of the duopoly profits available to two firms in that market. This assumption holds, for example, under Cournot-Nash competition with linear demand curves and many other common models. Formally, we have

ASSUMPTION 2.4: $\pi_i^{M_m} > \pi_i^{D_m} + \pi_j^{D_m}$ $i=1,2,\ j\neq i,\ \ m=A,B.$

In essence, this assumption states that the two firms cannot costlessly enforce a cartel-like agreement to split up the monopoly profits in a single market. That is, if a market is split up and no cartel enforcement mechanism exists, the firms' best response duopoly strategies will yield less profit than if they could enforce a joint restriction to the monopoly output. See, for example, Rotemberg and Saloner (1986) for more on the costs of enforcing collusive agreements.

We assume that the firms have an opportunity to discuss possible collusive agreements before the start of the technology purchase and output production game. Any such agreement would have to be self-enforcing because such agreements are not enforceable in court. By self-enforcing, we mean that each firm finds it in its own best interest to abide by the terms. One possible collusive agreement is to have firm 1 assigned market A and firm 2 to market B. In the subsequent sections, we discuss the conditions that are conducive to the firms abiding by such an agreement and we describe the environment that encourages investment in flexible technology as a strategic weapon to enforce or undermine such agreements.

In effect, we assume that firms can observe compliance to an agreement that specifies which market(s) to enter, but cannot observe compliance for an agreement that specifies precise output levels in a market for each firm. When a cartel assigns either all or none of a specific market to a specific firm, cheating on the agreement is easier to observe than if it specifies the level of output to be produced in each market or if it specifies the equipment to be put inside each firm's factories. One might reasonably assume that firms could agree not to acquire a certain technology, but to be effective, each firm would need to have a retaliation mechanism to enforce the agreement. This type of agreement is discussed towards the end of Section 4

Finally, we assume that the two markets, A and B, are roughly comparable in size. Formally, we assume

ASSUMPTION 2.5: $\pi_i^{M_m} > \pi_i^{D_m} + \pi_i^{D_{m'}}$ for i=1, 2; m, m' = A, B; m≠m'.

This assumption assures that each firm would prefer a monopoly position in one market to a duopoly position in both.

3. Model I: One-Time Technology Acquisition

We analyze a two-stage game in which firms simultaneously and independently acquire production technology in period 0 (first stage), after which follows a T-period production horizon (second stage) for which we consider three cases: (1) T=1, (2) $1<T<\infty$, and (3) $T=\infty$. In stage two, in each period, the firms learn of the previous-period decisions made by each other and then simultaneously and independently make their production decisions. Profits accrue in each period according to the different monopoly and duopoly profit levels described above.

By assumptions 2.4 and 2.5, each firm would prefer to restrict each firm to a single market rather than engage in competition in both markets. We assume that the firms begin with the following (efficient) agreement, preceding the technology acquisition and production stages: Firm 1 agrees to produce only for market A and firm 2 agrees to produce only for market B. This agreement serves only as a tentative pact or focal point (Schelling, 1960); if collusion occurs, this is the form it will take. Also, we use this focal point to choose among the multiplicity of equilibria that exist in this game. The existence of the above agreement does not guarantee compliance; each firm will only adhere to it (and only credibly agree to it) if doing so is in its best interest.

Analysis of Second-Stage Outcomes

To determine the payoff structure for the game described above, we first analyze the production stage of the game for all possible outcomes of the earlier, technology acquisition stage. First note that there are four possible outcomes for the technology investment stage of the game, depending on whether firm 1 acquires K^A or K^{AB} and on whether firm B acquires K^B or K^{AB}. (We note that it is also possible for firm 1 to acquire K^B or firm 2 to acquire K^A, but we rule out these possibilities with our focal point assumption.)

Given the above collusive agreement, one possible outcome is that each firm buys only the dedicated capacity relevant for its own assigned market. We denote this case by (K^A, K^B). In this case, each firm has locked itself into the production of one good for the entire horizon. Each reaps the monopoly profits, ($\pi_1^{M_A}$ and $\pi_2^{D_B}$, respectively, for firms 1 and 2) in one market and incurs investment costs of acquiring one dedicated technology (C^A and C^B, respectively). Since technology can be acquired only in period 0, this outcome obtains in the (K^A,K^B) case for all values of $T \geq 1$.

If, however, firm 1 acquired dedicated A technology at cost C^A, and firm 2 chose the flexible technology at cost C^{AB}, then firm 2 has incentive to cheat on the agreement: Not only does firm 2 have the physical capability to produce for both markets, but also firm 1 can offer no retaliation once it has made its one-time technology decision in period 1. Firm 2 establishes itself as an unchallenged monopolist in market B and as an invading duopolist in market A. Thus, the (K^A,K^{AB}) outcome results in operating profits of ($\pi_1^{D_A}$) in each period for firm 1 and ($\pi_2^{D_A}+\pi_2^{M_B}$) in each period for firm 2. This outcome also obtains for any $T\geq 1$. A symmetric outcome obtains for the (K^{AB},K^B) case.

Determining the production outcomes and payoffs when both firms purchase the flexible capacity in period 1 is more complex. In this

(K^{AB},K^{AB}) case, each firm has the ability to operate in both markets, but is, by assumption, better off if each produces, without competition, in a single market. If T=1, the production subgame for this outcome resembles the classic Prisoner's Dilemma problem (see Figure 1): If both firms adhere to the collusive agreement, then they will both earn monopoly profits; if firm 1 honors the agreement but firm 2 does not, then the profits for the two firms will be $(\pi_1^{D_A}, \pi_2^{D_A}+\pi_2^{M_B})$, likewise, if firm 2 honors the agreement and firm 1 does not, the symmetric result obtains. When neither firm honors the agreement, then the profit vector is $(\pi_1^{D_A}+\pi_1^{D_B}, \pi_2^{D_A}+\pi_2^{D_B})$. Thus, each firm prefers to produce for both markets regardless of what its rival does, so that the dominant strategy in the one period game is for each firm to produce in both markets. Thus, the unique equilibrium to this subgame has the characteristic that both firms can be made worse off by the existence of the flexible technology.

		FIRM 2	
		B	A & B
FIRM 1	A	$(\pi_1^{M_A},\pi_2^{M_B})$	$(\pi_1^{D_A},\pi_2^{M_B}+\pi_2^{D_A})$
	A & B	$(\pi_1^{M_A}+\pi_1^{D_B},\pi_2^{D_B})$	$(\pi_1^{D_A}+\pi_1^{D_B}, \pi_2^{D_A}+\pi_2^{D_B})$

Figure 1: Production subgame for the two firms when (K^{AB}, K^{AB}) is the period 0 technology choice and the length of the game is T=1. Both firms producing for both markets, i.e., (A&B, A&B) is the dominant strategy (Prisoners' Dilemma) solution.

Suppose now, in the (K^{AB},K^{AB}) case, that the production game is played for some finite number $(T\geq 1)$ of periods. We refer to this case as Scenario I. The argument here will follow the traditional analysis of a repeated prisoner's dilemma. In particular, we use backwards induction by examining the game in period T, and then inductively examining the game in each preceding period, conditioned upon the outcomes of the successive periods. Thus, in our game in period T, we have a one-period production game remaining, with the associated prisoners' dilemma situation. The dominant strategy in this case is for both players to produce for both markets. In period T-1, each firm knows that its rival will produce for both markets in the following period. Thus, in this period, both will again produce for both markets. Using backwards induction, we find that in a game played a finite number of times (with the length of this horizon known to both players), the equilibrium is that both firms will produce for both markets in each period. Each firm would prefer the cooperative outcome, but there is no equilibrium that achieves it.

The prisoners' dilemma outcome in the (K^{AB}, K^{AB}) case is driven primarily by the assumption that T is finite and deterministic. However, for alternate model formulation assumptions, this outcome can be reversed: In equilibrium, each firm may choose to produce only for the market specified in the initial collusive agreement even though both have acquired the flexible technology. We describe such settings below, and refer to them, collectively, as Scenario II.

Scenario II can be obtained in any of three ways: (1) if the game is played for an infinite number of periods, (2) if there is uncertainty about the length of the game, or (3) if the game is played for a finite number of periods with incomplete information about rivals' payoffs. For case (1), this result obtains via the Folk Theorem (Friedman (1977) or Tirole (1988)). This theorem illustrates how the mutual threat of infinite horizon retaliation for violating a collusive agreement can be used to enforce that agreement.

In each period that both firms honor the agreement, the profits earned will be $(\pi_1^{M_A}, \pi_2^{M_B})$, which dominates the $(\pi_1^{D_A}+\pi_1^{D_B}, \pi_2^{D_A}+\pi_2^{D_B})$ payoffs that prevail without the agreement. Deviation from the agreement, by firm 2, for example, could yield one period of additional profits corresponding to the added duopoly profits from invading firm 1's market, but, in subsequent periods, each firm will earn only the "punishment" profits of $(\pi_1^{D_A}+\pi_1^{D_B}, \pi_2^{D_A}+\pi_2^{D_B})$ because firm 1 will revert to the prisoners' dilemma equilibrium (grim strategies) and begin producing output for both markets for the remainder of the infinite production horizon. This reaction by firm 1 constitutes a credible threat since firm 1 prefers the profits earned as a duopolist in two markets to the profits of a duopolist in a single market. Likewise, firm 2 can also maintain this sort of threat to keep firm 1 from entering market B. In the formal result (Freedman 1977; Tirole 1988), if the discount factor δ is not too small, such credible threats of infinite retaliation can sustain $(\pi_1^{M_A}, \pi_2^{M_B})$ profits in the game of infinite length.

For case (2), when the length of time that the markets will be profitable is stochastic, the form of the analysis is similar. Suppose there is a time-independent positive probability that the game could end after each period. A firm that considers violating the agreement must once again consider the losses it must suffer for the duration of the game after the period of deviation with the one period gain. However, because there is some probability each period that the game will end, the significance of the future losses is diminished. In effect, the firms discount the future more heavily than in the deterministic, infinite horizon case; the effective discount factor is the product of the original discount factor and the probability that the game continues for another period. The one-period gain sufficient for deviation is therefore smaller than in the deterministic, infinitely repeated game, i.e. where the probability that the game continues and is equal to one. However, the net effect of this assumption is to make the model more realistic (by acknowledging that an infinite horizon of production may not be realistic) while achieving the possibility that equilibrium behavior can still yield a result where firms who have both purchased flexible capacity do not invade each other's market.

For case (3), the Pareto-optimal stage outcome can be achieved in equilibrium (for a vast majority of the periods) when the industry horizon has a finite, fixed length, but each firm does not know with certainty the payoffs earned by its rival. The generalized model of this situation is formalized as a finitely repeated game with incomplete information by Kreps, Milgrom, Roberts, and Wilson (1984). We refer the reader to their results and only mention it to include it as a case within the set of games that have a solution that Pareto-dominates the Scenario I outcome.

Thus, in addition to the Scenario I situation where the industry horizon is finite and deterministic so that the prisoners' dilemma outcome obtains, there are also reasonable formulations such that each firm will choose to produce, in equilibrium, only in its own market even though both firms have purchased the flexible capacity. We group these three cases together and refer to them collectively as Scenario II. For the remainder of the paper, for ease of notation and calculation, we will focus our Scenario II analysis on case (1) above, when T is infinite.

Analysis of First-Stage Outcomes

Having discussed, for Scenarios I and II, the second-stage outcomes for each of the four possible investment pairs, we now consider the Period 0 investment decisions by comparing for each firm, the investment opportunity of acquiring the flexible technology versus acquiring only dedicated capacity. For Scenario I, the marginal profit available to each firm from buying the flexible technology is the additional duopoly profit stream from invading its rival's market, independent of which technology the rival has purchased. Consider the firm profits in Figure 2. First, suppose that firm 2 buys the dedicated technology. If firm 1 also buys dedicated technology, then it will earn monopoly profits from market A. However, if firm 1 buys the flexible technology then it will earn duopoly profits from market B in addition to the monopoly profits from market A.

	FIRM 2	
FIRM 1	K^B	K^{AB}
K^A	$-C^A + \sum_{t=1}^{T} \delta^t \pi_1^{M_A}$ $-C^B + \sum_{t=1}^{T} \delta^t \pi_2^{M_B}$	$-C^A + \sum_{t=1}^{T} \delta^t \pi_1^{D_A}$ $-C^{AB} + \sum_{t=1}^{T} \delta^t (\pi_2^{D_A} + \pi_2^{M_B})$
K^{AB}	$-C^{AB} + \sum_{t=1}^{T} \delta^t (\pi_1^{M_A} + \pi_1^{D_B})$ $-C^B + \sum_{t=1}^{T} \delta^t \pi_2^{D_B}$	$-C^{AB} + \sum_{t=1}^{T} \delta^t (\pi_2^{D_A} + \pi_2^{M_B})$ $-C^{AB} + \sum_{t=1}^{T} \delta^t (\pi_2^{D_A} + \pi_2^{D_B})$

Figure 2: Scenario I profit streams (In each of the four cells, Firm 1's payoffs appear above Firm 2's.)

Now suppose that firm 2 buys the flexible technology. If firm 1 buys only dedicated capacity then, because firm 2 will invade market A, firm 1 will only earn duopoly profits from market A. If firm 1 also purchases flexible technology then it will be able to retaliate and earn additional duopoly profits in market B. These observations yield the following proposition.

PROPOSITION 1: Under Scenario I (i.e., T is finite and deterministic) the following two conditions are sufficient for both firms to purchase the flexible technology:

$$C^{AB} - C^{A} < \sum_{t=1}^{T} \delta^{t} \pi_1^{D_B} \quad , \tag{3.1}$$

and

$$C^{AB} - C^{B} < \sum_{t=1}^{T} \delta^{t} \pi_2^{D_A} \quad . \tag{3.2}$$

PROOF: As can be seen from Figure 2, the marginal benefit to firm 1 of purchasing the flexible technology is $\sum_{t=1}^{T} \pi_1^{D_B}$, regardless of firm 2's decision. The marginal cost of purchasing K^{AB}, over purchasing K^{A} is $(C^{AB}-C^{A})$. Therefore firm 1 will purchase K^{AB} if condition (i) holds. The analysis for firm 2 is similar. ■

Now consider Scenario II, the case where threats of infinite horizon retaliation, made credible by holding the capability to produce for both markets, can deter each firm from invading its rival's market. Figure 3 illustrates the payoff matrix for Scenario II (for the case where $T=\infty$).

FIRM 2

FIRM 1	K^B	K^{AB}
K^A	$-C^A+\sum_{t=1}^{\infty}\delta^t\pi_1^{M_A}$ $-C^B+\sum_{t=1}^{\infty}\delta^t\pi_2^{M_B}$	$-C^A+\sum_{t=1}^{\infty}\delta^t\pi_1^{D_A}$ $-C^{AB}+\sum_{t=1}^{\infty}\delta^t(\pi_2^{D_A}+\pi_2^{M_B})$
K^{AB}	$-C^{AB}+\sum_{t=1}^{\infty}\delta^t(\pi_1^{M_A}+\pi_1^{D_B})$ $-C^B+\sum_{t=1}^{\infty}\delta^t\pi_2^{D_B}$	$-C^{AB}+\sum_{t=1}^{\infty}\delta^t\pi_1^{M_A}$ $-C^{AB}+\sum_{t=1}^{\infty}\delta^t\pi_2^{M_B}$

Figure 3: Scenario II profit streams

Consider the decision facing firm 1. (The analysis for firm 2 is analogous.) Purchase of the flexible system by firm 1 could be interpreted both as an "offensive" and a "defensive" strategic move. Firm 1 could use the flexible technology as an offensive tool to invade its competitor's market; this will happen if firm 2 cannot retaliate because it did not purchase the flexible technology. In particular, if firm 2 chose K^B, firm 1 would purchase K^{AB} if $C^{AB}-C^A < \sum_{t=1}^{T}\delta^t\pi_1^{D_B}$. (The analogous condition holds when the roles of the two firms are reversed.)

Firm 1's purchase of a flexible system may also be seen as a defensive or protective measure against the possibility that firm 2 might invade firm 1's market. If firm 2 purchased K^{AB}, then firm 1 can defend its monopoly in market A only by purchasing K^{AB} so that it has a credible retaliatory threat with which to deter firm 1 from entering. Otherwise, firm 2 will invade market A without fear of retaliation. Therefore, if firm 2 owned the flexible technology, then firm 1 would purchase K^{AB} if

$$C^{AB} - C^{A} < \sum_{t=1}^{T} \delta^{t} (\pi_1^{M_A} - \pi_1^{D_A}) .$$

These arguments demonstrate that under Scenario II (for T=∞), that firm 1 will acquire flexible capacity if and only if

$$C^{AB} - C^{A} < \min \left\{ \sum_{t=1}^{\infty} \delta^{t} (\pi_1^{M_A} - \pi_1^{D_A}),\ \sum_{t=1}^{\infty} \delta^{t} \pi_1^{D_B} \right\} , \tag{3.3}$$

and firm 2 will acquire flexible capacity if and only if

$$C^{AB} - C^{B} < \min \left\{ \sum_{t=1}^{\infty} \delta^{t} (\pi_2^{M_B} - \pi_2^{D_B}),\ \sum_{t=1}^{\infty} \delta^{t} \pi_2^{D_A} \right\} . \tag{3.4}$$

However, by Assumption 2.5, for both (3.3) and (3.4), the left hand term in the brackets is always the larger of the two, so this result can be expressed as:

PROPOSITION 2: Under Scenario II (T=∞), firm 1 will acquire the flexible technology if and only if

$$C^{AB} - C^{A} < \pi_1^{D_B} / (1-\delta),$$

and firm 2 will acquire the flexible technology if and only if

$$C^{AB} - C^{B} < \pi_2^{D_A} / (1-\delta).$$

Therefore, if flexible capacity is not too costly, then each firm will buy flexible capacity but produce only for its home market.

Three features of this result stand out. First, as expected in games of this type, the ability to credibly threaten retaliation by maintaining the capability to enter a rival's market, allows firms to achieve higher profits due to successful enforcement of collusive agreements.

Second, firms acquire flexible capacity for strategic considerations, and then use this flexible technology inflexibly, that is, to produce only one product. Flexible technology serves only as a deterrent which the owner hopes never to have to use. (Note the similarity with the nuclear arsenals held by the United States and the Soviet Union. Rotemberg and Saloner (1989) make the same point with respect to the use of strategic inventories to deter entry.) (In a somewhat different setting, Fine and Li (1988) provide an alternate reason why firms may sometimes use flexible technology inflexibly: Such an outcome may arise because, as products move through their respective life cycles, one product has sufficiently large volume to require the entire stock of flexible capacity, and the life cycles of all other products have either ended or have not yet begun.)

Third, in all of the cases examined, the existence of flexible capacity at a low cost makes both firms worse off because of the competitive market in which they must operate. This result contrasts sharply with the results of Fine and Freund (1990) and others, where a monopolist's profits increase as the cost of the flexible technology declines.

4. Model II: Dynamic Technology Acquisition Opportunities

In this section we modify the assumption that technology acquisition can occur only once. We assume that in each period (t=1,2,...,T) both firms simultaneously make technology decisions, then jointly observe the technologies chosen, and finally make production decisions. The assumptions about the relative costs of the different types of technology and the profits for each firm from each market are the same as given earlier. In addition, the focal point assumptions of the pregame agreement are the same: firm 1 gets market A as its home or base market, and firm 2 gets market B. Since the markets are assigned in this fashion, both firms prefer that each firm buys only the dedicated technology needed for its own market. Our intent is to analyze whether the ability to purchase, on short notice, the technology to invade one's rival's market, provides a sufficient threat to prevent competitive entry, while allowing each firm to avoid having to invest in capabilities for both markets. We find that this outcome obtains for some values of the model's parameters, but several other outcomes can also occur.

In period 0, each firm chooses between buying the dedicated technology for its own market or buying the flexible technology. Subsequent to period 0, if a firm initially purchased only the dedicated technology for its own market and wants to enter its rival's market (or wants a more immediate threat to enter), it will purchase the other dedicated technology. (Since the flexible technology costs more to acquire than either dedicated technology, this is the least costly way to acquire, subsequent to period 0, the technology for one's rival's market (assuming, as we do, negligible salvage value of used equipment).) Once a firm owns the capability to produce for both markets, it no longer has any further technology acquisition decisions to make. We assume that technology investments are irreversible acquisitions of production capabilities.

As in the previous section, we first analyze Scenario I: the case where the time horizon T is finite and deterministic. Consider the start of period T. Four possible combinations of the two firms' technological capabilities are possible. These are: (1) each can only produce for its home market, (2) firm 1 has only A capacity and firm 2 has A and B capacity, (3) firm 1 has A and B capacity and firm 2 has only B capacity, and (4) both firms have A and B capacity. We denote these four states, respectively, as (A,B), (A,AB), (AB,A), and (AB,AB). Note that a firm can have capability to produce both products either from having acquired K^{AB} in period 0 or from having acquired K^A and K^B in different periods.

Consider first the (AB,AB) state. No further technology will be acquired in period T, and since this is the final period, the firms face a one-shot prisoners' dilemma-type game as discussed in the previous section. Therefore, each will produce for both markets and earn duopoly profits in both markets.

Consider next the (AB,B) state. If firm 2 purchases K^A at cost C^A, then each firm will earn duopoly profits in both markets in period T. If firm 2 does not purchase K^A, then it will earn $\pi_2^{D_B}$, whereas firm 1 will earn $\pi_1^{M_A}+\pi_1^{D_B}$. Firm 2 will therefore purchase K^A if and only if $\pi_2^{D_A}>C^A$.

Similarly, in the (A,AB) state, firm 1 will purchase K^B if and only if $\pi_1^{D_B} > C^B$.

In the (A,B) state the firms face the following game in period T:

FIRM 1	FIRM 2: No Purchase	FIRM 2: Purchase K_A
No Purchase	$(\pi_1^{M_A}, \pi_2^{M_B})$	$(\pi_1^{D_A}, \pi_2^{M_B} + \pi_2^{D_A} - C^A)$
Purchase K_B	$(\pi_1^{M_A} + \pi_1^{D_B} - C^B, \pi_2^{D_B})$	$(\pi_1^{D_A} + \pi_1^{D_B} - C^B, \pi_2^{D_A} + \pi_2^{D_B} - C^A)$

Figure 4: Technology acquisition subgame at the start of period T.

Independent of firm 2's action, firm 1's dominant choice is to purchase K^B if and only if $\pi_1^{D_B} > C^B$. Similarly, firm 2 will purchase K^A if and only if $\pi_2^{D_A} > C^A$. For each firm, regardless of its rival's choice, it only pays to purchase capacity to invade the rival's market if the duopoly profits from that market exceed the acquisition cost.

Now consider the subgame beginning at some time t ε {1, 2, ..., T-1}. Again, the four possible states are (A,B), (A,AB), (AB,B), (AB,AB). By our previous arguments, the last pair yields the outcome that each firm earns duopoly profits in both markets for the remainder of the finite time horizon. For the (AB, B) state, we first observe that if firm 2 finds it profitable to acquire K^A in period $t \geq 2$, then firm 2 will also find it profitable to acquire K^A in t-1, the previous period. That is, if a firm is ever going to acquire a retaliatory capability, it will do so sooner rather than later. Firm 2 will acquire K^A in period $t \geq 1$ if the state is (AB, B) and

$$\sum_{s=t}^{T} \delta^s (\pi_2^{D_A}) > C^A \qquad (4.1)$$

That is, if firm 1 has acquired the capability to produce for both markets, whereas firm 2 can only produce for market B, then if (4.1) holds firm 2 will acquire K^A to achieve duopoly profits in market A since it cannot keep firm 1 out of market B. The (A, AB) state is completely symmetric: firm 1 will purchase K^B in period t≥1 if the state is (A, AB) and

$$\sum_{s=t}^{T} \delta^{s} (\pi_1^{D_B}) > C^B \qquad (4.2)$$

The conditions (4.1) and (4.2) are more easily satisfied for smaller values of t. Therefore, if for some t>1, one or both of these conditions hold, then, because the payoff data is stationary and deterministic, the condition(s) would have held at t-1 and, inductively, at t=1. Therefore, in the (AB, B) and (A, AB) states, a firm will retaliate as soon as possible or not at all, depending, respectively, on whether (4.1) or (4.2) holds for t=1.

Finally, consider the (A, B) case. This situation will arise if each firm purchased only the dedicated technology for its home market in period 0 and neither firm has added any technology up until time t. At time t=T, as discussed earlier, each firm will follow its dominant strategy, independent of its rivals action. Therefore, any actions taken by firm i at t=T-1 will not affect the period T actions of firm j (j≠i). Therefore, by backward induction, for general t<T in the (A, B) state, firm 1 will acquire K^B if and only if (4.2) holds, and firm 2 will acquire K^A if and only if (4.1) holds. Again, (4.1) and (4.2) are more easily satisfied for smaller t's, so that if a firm is ever going to acquire the technology to invade its rival's market, it will do so at time 0. Furthermore, since at time 0 a firm may purchase K^{AB}, which is cheaper than acquiring K^A and K^B separately, the relevant conditions are weaker than (4.1) and (4.2) at t=0. For each firm, the discounted duopoly profit stream need only exceed the marginal cost of acquiring the dedicated technology for its own market. That is, firm 1 will purchase K^{AB} at time 0 if

$$\sum_{t=0}^{T} \delta^{t} \pi_1^{D_B} > C^{AB} - C^{A}, \qquad (4.3)$$

and firm 2 will buy K^{AB} at time 0 if

$$\sum_{t=0}^{T}\delta^{t}\pi_2^{D_A} > C^{AB} - C^{A}. \tag{4.4}$$

Again, we observe that the existence of flexible capacity can make the firms worse off: If

$$C^{A} > \sum_{t=0}^{T}\delta^{t}\pi_1^{D_B} > C^{AB} - C^{A} \tag{4.5}$$

and

$$C^{B} > \sum_{t=0}^{T}\delta^{t}\pi_2^{D_A} > C^{AB} - C^{B}, \tag{4.6}$$

then the availability of the flexible technology at cost C^{AB} leads both firms to purchase it and earn duopoly profits over the T-period horizon. If K^{AB} did not exist, or if its cost, C^{AB} were high enough to reverse the direction of the second inequality in each of (4.5) and (4.6), then, provided that the discounted monopoly profits in each market exceeded the acquisition cost of the respective dedicated technology, each firm's dominant strategy would be to remain a dedicated monopolist in its own market.

We turn now to Scenario II, in which credible threats of retaliation can effectively deter each firm from invading its rival's market, allowing each firm to earn larger equilibrium profit rates than those achieved in the deterministic, finite horizon game. Again we focus our analysis on the deterministic case with $T=\infty$. In Section 3, where the one-time technology purchases occurred simultaneously, no retaliation was possible by a firm that chose to buy only dedicated capacity in period 0. Therefore, the need for retaliatory capability forced each firm to acquire flexible technology from the start. In the analysis that follows, a firm can adopt a "wait and see" technology adoption strategy: Begin by adopting the technology only for one's own market and then acquire technology for one's rival's market only if retaliatory capability becomes necessary.

In the analysis that follows, we assume that neither firm will ever find it profitable to invade its rival to earn only one period of duopoly profits if doing so triggers the infinite retaliation response. Let V_D^1 and V_D^2 represent, respectively, for firms 1 and 2, the value to that firm of defending its market from permanent incursion by its rival. That is, we let

$$V_D^1 = \sum_{t=1}^{\infty} \delta^t (\pi_1^{M_A} - \pi_1^{D_A}) = (\pi_1^{M_A} - \pi_1^{D_A})/(1-\delta)$$

and

$$V_D^2 = \sum_{t=1}^{\infty} \delta^t (\pi_2^{M_B} - \pi_2^{D_B}) = (\pi_2^{M_B} - \pi_2^{D_B})/(1-\delta)$$

.

Also, let V_O^1 and V_O^2 represent, respectively, for firms 1 and 2, the value to that firm of an offensive strategy, i.e., invading its rival's market and earning duopoly profits there. That is, we let

$$V_O^1 = \sum_{t=1}^{\infty} \delta^t (\pi_1^{D_B}) = \pi_1^{D_B}/(1-\delta)$$

and

$$V_O^2 = \sum_{t=1}^{\infty} \delta^t (\pi_2^{D_A}) = \pi_2^{D_A}/(1-\delta)$$

.

Recall from Assumptions 2.4 and 2.5 that the valuing of defending either market exceeds the value of invading either market. That is, $V_D^i > V_O^j$, for i, j=1, 2.

The equilibrium outcome(s) for this game depend(s) on the relative magnitudes of V_D^i and V_O^j, for i, j=1, 2, as well as the values of C^A, C^B, and C^{AB}. If $V_D^1 > C^B$, then firm 1 has a credible threat to acquire dedicated B technology to retaliate if firm 2 invaded its market. Therefore, if this condition holds, firm 2 would never acquire A capacity, either with flexible or dedicated technology, solely to invade its rival's market because the invasion would violate the collusive agreement and trigger retaliation, making firm 2 worse off. The symmetric statement (with the firm and market labels reversed) holds if $V_D^2 > C^A$. Therefore, if both of these conditions ($V_D^1 > C^B$ and $V_D^2 > C^A$) hold, then each firm will acquire dedicated capacity and stick to its own market.

If $V_O^1 < C^{AB} - C^A$, then the value of successfully invading market B is so small for firm 1 that it would never acquire the capability to do so even if it were certain that firm 2 would not retaliate. The symmetric statement holds for firm 2 if $V_O^2 < C^{AB} - C^B$. Therefore, if both of these conditions ($V_O^1 < C^{AB} - C^A$ and $V_O^2 < C^{AB} - C^B$) hold, then each firm will acquire dedicated capacity and stick to its own market. Clearly the most interesting cases lie between the extremes of this and the previous paragraphs.

In fact, there are 18 distinct cases that arise for this model. We describe these in the Appendix. The results described there show that a variety of equilibria are possible: Both firms may acquire dedicated capacity and stick to their own respective markets, both firms may buy K^{AB} but produce only for their own markets, or one firm may buy K^{AB} and invade its rival while the other resigns itself to such entry. The common thread here, however, as above, is that the existence of flexible capacity (especially at a low price) can make firms worse off: Flexible capacity may be purchased but used to produce only one product or its existence could cause mutual market invasions, lowering profitability for both firms.

5. Concluding Discussion

Our paper examines the strategic effects of flexible manufacturing systems on the technology investments of competing firms in an industry. We have developed a two-firm, two-market model in which each each firm has one of the markets as its base or home market. Our profit structure assumptions dictate (1) that the two markets are of comparable size, and (2) that each firm would prefer to function as a monopolist in only one market than to operate as a duopolist in both markets. We then use a game-theoretic analysis to derive equilibrium technology investments for this setting. We first allow a one-time technology acquisition opportunity before production is permitted (Section 3), and then relax this assumption to allow technology purchase before each production period (Section 4).

Obviously, our model is very stylized and many of our assumptions may not hold in a particular industry. However, we believe that the model does capture some of the basic characteristics of product-flexible manufacturing systems and competitive interaction, so that the insights from the model can be useful for practitioners who must consider the strategic implications of their technology investment opportunities.

Our results suggest that unless (1) industry conditions allow collusive agreements that can be enforced by credible commitments to retaliate against entry and (2) firms can develop capabilities to produce for a rival's market on relatively short notice, then the existence of flexible technology will make firms worse off, providing the flexible technology is not too expensive. Condition (1) can be achieved in a repeated-game model if (i) the horizon is infinite, (ii) the horizon length is stochastic, or (iii) each firm has incomplete information about its rival's payoffs.

We note that in this analysis all of the outcomes are cast in terms of their impact on producers without considering consumer welfare. Clearly, there are some instances in which consumers benefit from the existence of a flexible technology. Specifically, these are the cases in which firms are unable to credibly threaten a retaliation to invasion and thus unable to sustain monopoly production in their assigned markets. However, in games whose outcome has both firms using flexible capacity inflexibly, consumers do not benefit from the existence of flexible technology and producers spend more on technology (for the same net revenues) than they would if the flexible technolgy did not exist. The winners in this case are the capital goods producers who supply the flexible technologies.

The results from explicit consideration of competition with flexible technology contrast sharply with the single-firm analysis of Fine and Freund (1990), in which a firm operating as a monopolist is unequivocally better off with a low-cost flexible manufacturing system investment option. This contrast suggests that the evaluation of flexible manufacturing system investment opportunities should take into account competitive interaction effects.

Appendix: Description of the 18 cases from Section 4, Scenario II

As discussed near the end of Section 4, the equilibrium outcome for Scenario II when investments may be made in any period depends on the relative magnitudes of V_D^i and V_O^j, for i, j=1, 2, and C^A, C^B, and C^{AB}. We list and discuss below ten mutually exclusive combinations of these parameters. Each of the other eight cases is symmetric to one of the cases numbered 2-9, with the roles of firms 1 and 2 reversed, and the market labels, A and B, reversed.

Note that in Section 3, to have a credible retaliation threat in the face of an invasion by its rival, a firm had to acquire K^{AB} in period 0 since no later purchase of capacity was possible. In this scenario, a firm has an additional means to credibly threaten its rival since it may purchase additional dedicated capacity at a later time if threatened by a market invasion. The conditions for this to occur require that $V_D^i > C^m$, i=1,2 and m corresponding to the dedicated technology used for production in the rival's market.

The equilibria for a given parameter relationship are given in terms of (i) the capacity acquisition outcome (ii) the existence of a credible threat to enter later if invaded if only dedicated capacity is purchased in period 0 (since purcahse of flexible capacity always constitutes a credible threat) and (iii) the resulting market production scheme.

Parameter Relationships	Equilibrium Outcome
1. $V_D^1 > C^B$ $V_D^2 > C^A$	(K^A, K^B) Each firm has a credible threat in later periods Each produces only for own market

Parameter Relationships	Equilibrium Outcome
2. $V_D^1 > C^B,\ V_O^1 > C^B$ $C^{AB} - C^B < V_D^2 < C^A$	(K^A, K^{AB}) Firm 1 has a credible threat for later Firm 2 buys K^{AB}, because of the value of V_O^1 No market invasion
3. $V_D^1 > C^B,\ C^{AB} - C^A < V_O^1 < C^B$ $C^{AB} - C^B < V_D^2 < C^A$	Two pure strategy equilibria arise: 1. (K^A, K^B) Firm 1 has credible threat, no value to immediate offensive Firm 2 has no credible threat later No market invasion 2. (K^{AB}, K^{AB}) Both immediately establish credible threats No market invasion
4. $V_D^1 > C^B,\ V_O^1 < C^{AB} - C^A$ $C^{AB} - C^B < V_D^2 < C^A$	(K^A, K^B) Firm 1 has credible threat, but will not invade Firm 2 has no credible threat for later invasions No market invasion

Parameter Relationships	Equilibrium Outcome
5. $V_D^1 > C^B$, $V_O^1 > C^{AB} - C^B$ $V_D^2 < C^{AB} - C^B$	(K^{AB}, K^B) Firm 1 has offensive value No credible threat for firm 2 Firm 1 invades market B
6. $V_D^1 > C^B$, $V_O^1 < C^{AB} - C^B$ $V_D^2 < C^{AB} - C^B$	(K^A, K^B) Firm 1 has credible threat no value to offense Firm 2 has no credible threat No market invasion
7. $C^{AB} - C^A < V_D^1 < C^B$, V_O^1 as in (2)-(4) $C^{AB} - C^B < V_D^2 < C^A$	Two pure strategy equilibria arise: 1. (K^A, K^B) Neither has credible threat for later No market invasion 2. (K^{AB}, K^{AB}) Both immediately establish credible threat No market invasion
8. $C^{AB} - C^A < V_D^1 < C^B$, $V_O^1 < C^{AB} - C^A$ $V_D^2 < C^A - C^{AB}$	(K^A, K^B) Firm 1 has credible threat no value to offense Firm 2 has no credible threat later No market invasion

Parameter Relationships	Equilibrium Outcome
9. $C^{AB} - C^{A} < V_D^1 < C^B, V_O^1 > C^{AB} - C^A$ $V_D^2 < C^A - C^{AB}$	(K^{AB}, K^B) Firm 1 values offense Firm 2 never has credible threat Firm 1 invades market B
10. $V_D^1 < C^{AB} - C^A$ $V_D^2 < C^{AB} - C^B$	(K^A, K^B) Neither offense nor defense pays No market invasion

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