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**CAPACITY COMMITMENT
VERSUS FLEXIBILITY:
THE TECHNOLOGICAL CHOICE
NEXUS IN A STRATEGIC CONTEXT**

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Capacity Commitment Versus Flexibility: The Technological Choice Nexus in a Strategic Context*

Marcel Boyer[†], Michel Moreaux[‡]

Résumé / Abstract

Nous considérons le “fait stylisé” voulant les investissements dans les technologies flexibles de production soient beaucoup plus importants au Japon qu’aux États-Unis et en Europe. Nous montrons *comment* les choix et équilibres de flexibilité (simultanés ou séquentiels) dépendent de six caractéristiques de l’industrie et *comment* ils sont susceptibles d’être affectés par des changements dans ces caractéristiques. Les industries de faible volatilité et de taille intermédiaire favorisent les technologies inflexibles; celles de volatilité ou de taille élevée favorisent les technologies flexibles; celles de volatilité et de taille faibles ou moyennes favorisent la coexistence de technologies flexibles et inflexibles. La possibilité d’une trappe de flexibilité existe lorsque la volatilité est faible et la taille est intermédiaire. Enfin, la flexibilité pourra servir de barrière à l’entrée dans certaines industries alors que l’inflexibilité le pourra dans d’autres industries.

This paper deals with the underlying factors explaining the “stylized fact” that Japan invests significantly more in flexible manufacturing technologies than the United States and Europe. We show how technological flexibility choices and equilibrium (both simultaneous and sequential) configurations in different industries depend on six industry characteristics and how changes in those characteristics are likely to affect the technological flexibility configuration observed. Low market volatility combined with intermediate market size will favor inflexible technologies; large values of either volatility or size will favor flexible and inflexible technologies. The possibility of a flexibility trap exists in industries characterized by low market volatility and intermediate market size. Finally, inflexible technologies can be part of an entry preventing strategy in some industries while flexible technologies can be in other industries.

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**CAPACITY COMMITMENT VERSUS FLEXIBILITY:
THE TECHNOLOGICAL CHOICE NEXUS
IN A STRATEGIC CONTEXT [‡]**

by

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Figure 1
The Nash $(\gamma^{1*}, \gamma^{2*})$ and Stackelberg $(\gamma^{L*}, \gamma^{F*})$ Equilibria
in (μ, σ) -space
[for $\beta = x = 1$, $s = 0.2$, $H = .05$]

$$\begin{aligned}
\text{in domain I} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) = (i, i) \\ (\gamma^{L*}, \gamma^{F*}) = (i, i) \end{cases} \\
\text{in domain II} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) = (f, f) \\ (\gamma^{L*}, \gamma^{F*}) = (f, f) \end{cases} \\
\text{in domain III.A} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(i, f), (f, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (f, i) \end{cases} \\
\text{in domain III.B} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(i, f), (f, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (i, f) \end{cases} \\
\text{in domain IV} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(f, f), (i, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (i, i) \end{cases}
\end{aligned}$$

Figure 1'
**The Nash $(\gamma^{1*}, \gamma^{2*})$ and Stackelberg $(\gamma^{L*}, \gamma^{F*})$ Equilibria
 in (δ, H) -space**
 [for $\mu = 5$, $\sigma = 0.7$, $\beta = 1$, $s = 0.2$]

$$\begin{aligned}
 & \text{in domain I} \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) = (i, i) \\ (\gamma^{L*}, \gamma^{F*}) = (i, i) \end{cases} \\
 & \text{in domain II} \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) = (f, f) \\ (\gamma^{L*}, \gamma^{F*}) = (f, f) \end{cases} \\
 & \text{in domain III.A} \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(i, f), (f, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (f, i) \end{cases} \\
 & \text{in domain III.B} \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(i, f), (f, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (i, f) \end{cases} \\
 & \text{in domain IV} \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(f, f), (i, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (i, i) \end{cases}
 \end{aligned}$$

Figure 2
The Nash $(\gamma^{1*}, \gamma^{2*})$ and Stackelberg $(\gamma^{L*}, \gamma^{F*})$ Equilibria
in (μ, σ) -space
[for $\beta = x = 1$, $s = 0.2$, $H = 3$]

$$\begin{aligned}
\text{in domain I} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) = (i, i) \\ (\gamma^{L*}, \gamma^{F*}) = (i, i) \end{cases} \\
\text{in domain II} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) = (f, f) \\ (\gamma^{L*}, \gamma^{F*}) = (f, f) \end{cases} \\
\text{in domain III.A} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(i, f), (f, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (f, i) \end{cases} \\
\text{in domain III.B} & \quad \begin{cases} (\gamma^{1*}, \gamma^{2*}) \in \{(i, f), (f, i)\} \\ (\gamma^{L*}, \gamma^{F*}) = (i, f) \end{cases}
\end{aligned}$$

1. Introduction

We are concerned in this paper with the emergence of new technologies commonly referred to as *Flexible Manufacturing Systems* (FMS)¹ and in particular with the ‘stylized fact’ that Japan seems to be investing in such technologies almost *four times more* than the United States per dollar of GNP. According to Tchijov (1992), Japan has about 24% of FMS in operation around the world and the United States 16%; the ratio of the Japanese GNP over the American GNP is about 40%. The FMS production systems being adopted at an increasing rate throughout the world have the following main economic characteristics: they require a relatively higher investment cost than conventional technologies but they allow for significant reductions in setup costs allowing more product flexibility and more volume flexibility (reduced minimum production runs), in lead time, in unit variable cost, in average batch size.² These new technologies are likely to lead not only to very different competitive environments but also to significant modifications of growth patterns.³ FMS are indeed changing dramatically the production process and

¹ They are also referred to as Computer Controlled (or Integrated) Manufacturing CAM/CIM.

² On the basis of the relatively restrictive criteria of the International Institute for Applied Systems Analysis in Austria (see Tchijov 1992), there were in 1989 about 800 FMS in operation in 26 countries: among others, Japan has about 24% of those, the United States 16%, the U.K. 11%, France 9.7% and Canada 0.5%; in terms of number of products, 30% of those FMS are used to produce no more than 10 products, 48% between 11 and 100, 19% between 100 and 1000, and 3% are used to produce over 1000 products; in terms of batch size, 32% are used to produce batches which are on average smaller than 10 units, 34% between 11 and 50, 29% between 50 and 1000, and 5% for batches of over 1000 units on average. Prudent estimates indicate that the introduction of a FMS has allowed an average reduction in lead time (lag between order and delivery) by a factor of 2 to 3, an average reduction in set-up time (the time spent to reset the equipment for a product change) by a factor of 10, an average reduction in personnel by a factor of 2 to 3, and a reduction in unit cost by a factor of 1.25 to 1.5. More recent developments in FMS increase those factors. Milgrom and Roberts (1990) provide other examples of the impact of the adoption of these modern technologies: a survey of the aerospace and other high precision industries revealed that 8.2% of all batches were of size 1 and 38% of size 16 and less; an Allen-Bradley plant producing electric controls can now switch production among its 725 products with an average set-up time of 6 seconds and it usually fills orders the day after they are received and ships products the same day by air express; General Motors engineers could in 1988 set a plant equipment to produce pilots of the 1989 models during the weekend and reset the equipment in time for the Monday morning production of the 1988 models while the same operation used to take weeks; General Electric has reduced the lead time for circuit-breaker boxes from three weeks to three days, which allowed a reduction in back orders from 60 days to 2 days; Caterpillar’s modernization program has been accompanied by a doubling of its product line.

³ See Boyer (1991): Growth patterns in the future are likely to be based on a *better matching* between products and preferences rather than on more units per capita because of the relative shift from economies

the internal organization of firms as well as their market environment and their relations with suppliers and customers. Given the major changes that a FMS represents, the evaluation process of such investments has been less than well understood by the engineering, finance and accounting personnel of the typical firm.⁴ The main difficulties in evaluating FMS projects revolve around the proper identification of the determinants of the value of more flexibility, of better quality control and better product reliability and of reduced lead time in production, incorporating in particular the value of organizational (incentives) restructuring possibilities, and the value the strategic advantages (and disadvantages) of an investment in FMS. A leitmotif of the engineering literature on the subject is that this state of affairs generates a bias towards rejecting such investments because major potentially favorable elements are either misunderstood or simply left out in the profitability evaluation, in particular the *strategic* impact of more flexibility and the change in the firm's cost of capital and capital structure.⁵

Different theories or models have been proposed to explain, more or less convincingly and more or less directly, the above 'stylized fact' regarding the relative FMS investment levels in Japan and the United States.⁶ In one such model, the working of financial markets differs in such a way that the level of monitoring of entrepreneurs by financiers is higher in Japan; given the presence of adverse selection and moral hazard features in financial markets, this allows for a lower cost of capital in Japan; since technological investments in FMS are typically long term investments, the model predicts that the level of such investments will be relatively larger in Japan. A related model makes the

of scale towards economies of scope allowed by FMS. Eaton and Schmitt (1993) have shown that this switch from scale to scope has also important implications for market structure and competition policy.

⁴ For quick but convincing overviews of the problems, see Gerwin (1982), Lederer and Singhal (1988) who provide an extensive list of references to the engineering literature, and Mensah and Miranti (1989).

⁵ Although this paper is a paper on technological flexibility, much of its content can be applied *mutatis mutandis* to organizational flexibility. Similarly, the negotiation strategy of brinkmanship, when feasible, can be understood as evolving from a relatively flexible position to positions which become "in a credible way" more and more inflexible.

⁶ Some of those were not developed with reference to the above 'stylized' fact but they may be reinterpreted in this context.

case that for cultural reasons Japanese managers and stockholders take a longer run approach (longer payback periods) in evaluating technological investments; since many of the benefits of FMS are long term benefits, the prediction follows. A third model rests on the belief or fact that successful investments in FMS require not only a concerted organizational transformation of the firm itself but also coordinated technological investments and organizational changes by suppliers and by clients; since this coordination is more easily reached in the well integrated Japanese industrial groups, the keiretsus using a kanban system,⁷ than in the more loosely integrated American industrial clusters, the model predicts larger FMS investments in Japan.

Our results suggest a different explanation based on the strategic interactions between the firms combined with the specific characteristics of an industry. Given that technology decisions are typically longer term decisions than production ones, we propose a two stage duopoly model in which firms choose in stage one their respective levels of technological flexibility and choose in stage two their production levels. We show that there exist very reasonable cases, which we characterize, in which the Nash equilibrium in technology is asymmetric, one firm being flexible and the other inflexible, even if both firms are completely symmetric: they have the same information and the same financial, cultural and coordination possibilities. We also show that there exist very reasonable cases, which we characterize, for which the firms suffers in equilibrium from too much flexibility: they experience a flexibility trap, a form of prisoner dilemma situation. We then introduce a variant of the above model by assuming that the long term technology choices are made sequentially with the second-mover (follower) firm observing the first-mover's (leader) choice before deciding on its own technology. We characterize the conditions or industry characteristics under which different asymmetric equilibrium configurations will emerge: a (f, i) -configuration with the first-mover flexible (f) and the second-mover inflexible (i) or a (i, f) -configuration. The stylized observation that Japanese are investing sig-

⁷ See Aoki (1988), pp. 208–223.

nificantly more in FMS than the Americans is consistent with the following assertion: American firms have typically been the first-movers in industries whose characteristics are such that the industry equilibrium is of the (i, f) type while the Japanese firms have typically been the first-movers in industries whose characteristics are such that the industry equilibrium is of the (f, i) type. We show also that being the first-mover is at least as profitable as being the second-mover. It follows that the relative positioning of the Japanese and American firms in different industries could explain the above ‘stylized fact’ in the absence of different levels of managers’ rationality or competence, different capital markets or different information structures.

Our results lead also to the following predictions. In both the Nash and the Stackelberg market structures, the value of flexibility *for a given firm* increases with market volatility σ ; it also increases eventually (not always) with increases in the size of the market μ . However, the effects of those exogenous changes on the equilibrium technological configuration in an industry may differ significantly from their effect at the firm’s level. In some particular contexts which we do characterize, an increase in market size may induce a firm to switch from a flexible technology to an inflexible one because the increased market size will in some contexts increase the commitment value of inflexibility. In some Stackelberg contexts which we also characterize, an increase in market size or in demand volatility will induce the two firms to *trade* their technological flexibility level; this surprising result is directly due to the strategic interactions between the firms. Moreover, increases in exogenous competitive pressures, measured either as an increase in demand elasticity or as a decrease in the minimum efficiency scale of production, will induce firms to switch, *one at a time*, from an inflexible technology to a flexible one. In general the leader will adopt the flexible technology first but again there are cases where it is the follower who adopts it first; in those latter cases, a further increase in competitive pressures will induce the firms to trade their technologies, from (i, f) to (f, i) , before further increases make it profitable again for the follower to adopt a flexible

technology ! Again, this surprising result is directly due to the strategic interactions between the firms. Finally, we show that the impact of a reduction in the investment cost of flexible technologies is favorable to the adoption of those technologies but that its specific impact on the probability of observing asymmetric equilibria (f, i) and (i, f) depends on the distribution of industries in (μ, σ) -space.

Although the literature on technological flexibility is rather large and covers many fields from engineering, operations research, optimal control and production management to economics and game theory, few authors have explicitly considered and studied the strategic aspects of technological flexibility choices and nobody, to our knowledge, has directly tried to explain in an explicit model of strategic behavior the ‘stylized’ fact at the root of the present paper. See Kulitilaka and Marks (1988), Vives (1989), Röller and Tombak (1990, 1993), Fine and Pappu (1990), Milgrom and Roberts (1990) and Gerwin (1993) for the more significant contributions. The papers more related to the present one are those of Röller and Tombak (1990, 1993) and Fine and Pappu (1990). Those authors have attempted to model technological choices in an explicit strategic competition context. Röller and Tombak (1990) consider product flexibility in a differentiated product model in which firms move simultaneously in choosing under perfect information (no uncertainty) their respective technology and output. Two types of technologies are feasible, a dedicated technology which can be used to produce a single product and a flexible technology which can be used to produce multiple products. They characterize the sub-game perfect equilibria and show that flexible technologies are more valuable the larger the size of the market is, the smaller the differential investment cost is between a flexible and an inflexible technology, and the more differentiated the products are.⁸ In that

⁸ The last effect may be interpreted as follows: consider a firm with a dedicated technology in market A; if products A and B are relatively bad substitutes, the firm may switch to a flexible technology allowing it to enter into market B, therefore increasing competition in B, without affecting too much the market conditions in A; if the products are relatively good substitutes, the increased competition in market B will reduce the possible profits in market A. This is likely to develop into a prisoner dilemma kind of situation for the firms in the industry and therefore lead to the emergence of inefficient equilibria with too much investment in flexible technologies.

context, flexible technologies are never adopted if the products are perfect substitutes; but casual observation of markets or industries in which FMS investments have been undertaken indicates that many of those markets and industries are quite competitive with relatively similar product lines (for instance electronics, machine tools, heavy machinery). By introducing uncertainty in demand, we will characterize the subgame perfect equilibria with homogeneous products in which flexible technologies are present and play a major strategic role. Röller and Tombak (1993) show that a larger proportion of FMS firms in an industry is associated with more concentrated markets, larger markets and more differentiated products, results supported by an econometric analysis of Japanese and American data. Fine and Pappu (1990) consider retaliatory punishment strategies which firms can deploy when a competitor enters their home market. These strategies are made “credible” by investing in product-flexible technologies. Clearly, the existence of such technologies may increase competition and reduce the firms’ profits unless punitive strategies can be enforced (in a repeated game fashion): the firms may be caught in a prisoner dilemma situation and therefore could be better off without those flexible technologies. We will develop a model with two stage non repeated competition with volume-flexible technologies, show the existence of a flexibility trap and characterize the whole map of technological flexibility equilibria as a function of industry characteristics.

More flexibility means in our model a reduction in set-up costs, in minimum production runs, in inventories, in variable production costs at all production levels, speedier adjustments to changing market conditions (modeled through a random market demand), but requires a higher investment cost. We take also into account that in a *strategic* context, more flexibility *may* come at the expense of a commitment and preemption strategy whose credibility could rely on the inflexibility to adapt to changing market conditions. We analyze the balancing act between the two strategies and determine the factors which will tilt the balance one way or another. Our results show quite clearly that a decision on technological flexibility has not only decision-theoretic aspects but also important

strategic aspects.⁹

The paper is organized as follows. In section 2, we introduce the basic model and we discuss the related literature on the subject. Section 3 is devoted to the characterization of the best reply functions to flexibility and inflexibility. We characterize in section 4 both the Nash and Stackelberg equilibria and perform some comparative statics exercises on the impact of different changes in the industry parameters on the nature of the equilibrium. In section 5, we look at technological flexibility and inflexibility as means to deter entry when such deterrence is possible. In the conclusion, we come back to the stylized fact mentioned at the beginning and discuss the empirical implications of our results, both the lessons learned and the predictions made.

2. A Model of Technological Flexibility

In the spirit of Stigler (1939),¹⁰ let us characterize a technology by the two parameters (γ, x) , where γ represents the degree of *inflexibility* and x is the level of capacity (average cost minimizing production level). The strategic value of technological flexibility comes from the possibility of influencing the behavior and choices of competitors, including eventually the decision to enter or not. We consider a duopoly (possibly with a competitive fringe), the simplest possible framework in which such strategic consider-

⁹ Technological flexibility is quite different from another concept of flexibility which we may call flexibility in timing. In the latter context, an agent remains flexible by postponing a decision in order to benefit from improved information over time. The strategic aspect of such flexibility in timing refers to two different phenomena. First, to the irreversibility occurring when a decision, taken with less than full information, nevertheless commits an agent or a society to an irreversible future set of actions (see Henry 1974 and Freixas and Laffont 1984). Second, to the relative value of commitment versus flexibility, the former corresponding to a decision taken before the uncertainty is levied and the latter to a decision taken after the resolution of uncertainty (see Spencer and Brander 1992, Sadanand and Green 1993). The present paper is somewhat related to the latter strand of the literature on flexibility in timing insofar as we consider at least implicitly the value of the commitment associated with inflexibility versus the value of easier adaptation to changing markets with flexibility.

¹⁰ George Stigler pioneered in his 1939 article the analysis of technological or cost flexibility. He stated that firms in general have to make a choice among different equipment giving rise to different cost configurations, for example a cost function which has a relatively wide flat bottom and a cost function which can attain a lower minimum average cost at the expense of steeply rising average cost as production moves away from the most efficient scale of production. See Boyer and Moreaux (1989) for a review of the general definitions of flexibility proposed by Stigler (1939), Marshak and Nelson (1962) and Jones and Ostroy (1984).

ations can be analyzed and also the competitive setting which is the most conducive to strategic interactions. To concentrate on these strategic aspects, we will assume that the level of capacity is exogenous. To make those strategic aspects as explicit as possible, we will consider two different market structures: a Nash setting in which the long run technological choices are made simultaneously and a Stackelberg setting in which they are made sequentially with the second-mover firm choosing its technology after observing the choice of the first-mover firm. In both cases, the short run decisions on production will be assumed to be made simultaneously once technological choices are determined and observed by both firms. Hence we have in mind a two stage model:

- long run stage 1: firms choose simultaneously or sequentially their technologies
- short run stage 2: firms choose simultaneously their marketed quantities.

This two stage formulation will in general give rise to multiple equilibria in stage 2 and discontinuities in profit functions; this reflects important underlying phenomena (shut-down of production, bankruptcy, etc.) but makes the analysis more intricate and the results, obtainable by numerical simulations, less intuitive. As a step towards avoiding those difficulties but without missing the basic intuitions and results on the flexibility versus inflexibility technological choice problem, we will assume in this paper that the firms can only choose between two levels of flexibility, either perfect flexibility ($\gamma = f$) or perfect inflexibility ($\gamma = i$). Let us explain what we mean by these two extreme possibilities.

The choice between a flexible technology and an inflexible technology rests in part on efficiency or cost-wise considerations and in part on strategic considerations. We can identify the fundamental cost-wise differences between flexibility and inflexibility as follows: flexible technologies require a larger investment cost; inflexible technologies are more efficient (lower average variable cost) for production levels close to capacity; flexible technologies have a lower set-up cost incurred when a new production run starts. In order to fully incorporate the important differences in terms of production costs and

to stress the commitment advantage an inflexible technology may confer, we will model an inflexible production process as a process which can be operated at a given fixed level (at capacity) to produce a given fixed quantity $q = x$ which is then sold by the firm.¹¹ The cost-wise trade-off between choosing a maximal flexibility level $\gamma = f$ and choosing a maximal inflexibility level $\gamma = i$ is captured by the following three characteristics which we will assume for the cost function. First, the investment cost H of a flexible technology is larger than that of an inflexible technology, the latter being set at 0. Second, a flexible technology has no set-up cost and a constant marginal cost of production c while an inflexible technology has a set-up cost equal to sx and an average direct cost of production equal to 0 for $q \in \{0, x\}$ but infinite otherwise. We will assume for matter of simplicity that both technologies attain the same minimum average variable cost, that is $c = s$.

Hence:

$$H(i) = 0 \text{ and } H(f) = H > 0$$

$$C(q) = \begin{cases} cq & \text{if } \gamma = f \\ 0 & \text{if } \gamma = i \text{ and } q = 0 \\ sx & \text{if } \gamma = i \text{ and } q = x \\ \infty & \text{if } \gamma = i \text{ and } q \notin \{0, x\} \end{cases}$$

$$c = s.$$

We will assume that the firms produce an homogeneous product and that the demand is linear.

$$p = \max\{0, \alpha - \beta(q^L + q^F)\}.$$

Our model is therefore a model of volume flexibility rather than product flexibility; but the two are intimately related through the reduced fixed cost which FMS implies. We will assume that there is uncertainty in demand in the following sense:¹² although β

¹¹ Admittedly, this is an extreme assumption. It can be relaxed in different ways (see Boyer and Moreaux 1995) at the cost of blurring the argumentation but the main thrust of the results remains valid. For a study along these lines, see Lecostey (1994).

¹² If x were chosen endogenously, flexibility would be useless in the absence of some variability (either in the form of seasonal patterns in demand or of genuine uncertainty) in demand because firms would choose a

is assumed to be known with certainty, the parameter α (a measure of the size of the market) is assumed to be a random variable with probability distribution function $F(\alpha)$ known by both firms:

$$\underline{\alpha} \in [\underline{\alpha}, \bar{\alpha}], \text{ with variance } V \text{ and mean } \mu.$$

To stress even more the strategic character of technological flexibility choices, we will assume that the value of α becomes known at the beginning of every short run production period; in other words, the uncertainty of demand is levied after the long run decisions but before the short run decisions. The two firms, assumed to be risk neutral, will choose their flexibility levels to maximize their expected profits.

The relative advantages and disadvantages of flexibility and inflexibility stem here from three elements: *first*, a flexible technology requires a larger investment outlay; *second*, flexibility allows for an easier adaptation to changing levels of demand; *third*, inflexibility has a commitment value insofar as it means a smaller interval (a singleton here) in which the firm will select its quantity produced in stage 2, if it produces at all. In order that an inflexible firm be always better off producing and selling $q = x$ than shutting down, we will assume that:¹³

$$\underline{\alpha} \geq 2\beta x + s \text{ [which implies that } \mu \geq 2\beta x + s].$$

Hence, an inflexible firm will produce and sell the quantity $q = x$ (its reaction function is constant at x).

capacity giving the minimum average cost of production in stage 2. With x exogenous, flexibility may be profitable even without variability in demand because the flexible technology allows a lower production cost ex post for production levels away from x .

¹³ Suppose firm 1 is inflexible and firm 2 is flexible; then (recall that $c = s$) $q_2(q_1) = \frac{1}{2\beta}(\alpha - s - \beta q_1)$ and firm 1 will prefer to produce at capacity if in such a case the equilibrium price is above s rather than not produce and realize zero profits. Producing and selling at capacity x means a price of $p = \frac{1}{2}(\alpha + s - \beta x)$ which is larger than s if $\underline{\alpha} > \beta x + s$, in which case $q_2(x) > 0$. If both firms are inflexible, then producing and selling at capacity means a price of $p = \alpha - 2\beta x$ which is larger than s if $\alpha > 2\beta x + s$. If both firms are flexible, then the Cournot equilibrium price with both firms producing will be $p = \frac{1}{3}\alpha + \frac{2}{3}s$ which is larger than s if $\alpha > s$; hence our assumption. Moreover, the assumption on $\underline{\alpha}$ simplifies the analysis insofar as it implies that for any realization of demand (α), there is a *unique* Cournot Nash Equilibrium in stage 2 in which *both* firms produce.

This model representation will allow us to characterize in a relatively explicit way the *strategic* value of technological flexibility choices. The structure of the model is such that the solution of the competition game between the two firms can be obtained by solving first for the production choices of the firms given their respective technological choices, and then for the technological choices given their respective optimal production decision functions. We are therefore looking for a subgame perfect Nash or Stackelberg equilibrium in technological adoption as a function of the following six industry parameters:

μ , the average or expected size of the market

V , (or σ), the variability or volatility in the level of demand

H , the differential investment cost for a flexible technology

β , the slope of the demand function

x , the average cost minimizing level of production

s , the minimum level of average variable production cost for an inflexible technology which is equal, by assumption, to the constant marginal cost of production c for a flexible technology.

3. The Best Reply Functions at the Technological Choice Stage

We first characterize the second stage production equilibria given the technological choices made at the first stage and then characterize the best responses at the technological choice stage.

3.1 The Expected Profits given the Outcome of the Technological Choice Stage

Since the flexibility variable γ can take only two values, namely f and i , we must base our analysis on the explicit consideration of the four possible technological configurations which may arise at the end of the first stage of the game. Under our assumption on $\underline{\alpha}$, we can characterize the equilibrium at stage 2 by assuming that an inflexible firm does

produce and sell at capacity and that the competitor, if flexible, reacts optimally to it. It is in that sense and case that commitment, under inflexibility, is said to be ‘maximal’.

Suppose that at the end of stage 1, the technological choices results in (i, f) , that is one firm inflexible and the other flexible. The flexible firm’s profit function is given by

$$\Pi^f(\alpha; i, f) = [\alpha - s - \beta(q^i + q^f)]q^f - H \quad (3.1)$$

and the best response of the flexible firm is:

$$q^f(q^i) = \frac{1}{2\beta}(\alpha - s - \beta q^i). \quad (3.2)$$

The inflexible firm will produce and sell in stage 2 the quantity $q^i = x$. Hence the second stage equilibrium is

$$(q^i, q^f) = (x, \frac{1}{2\beta}(\alpha - s - \beta x)). \quad (3.3)$$

Substituting these values in the profit functions (3.1) and denoting by $E\Pi^\gamma(\gamma', \gamma'')$, $\gamma \in \{\gamma', \gamma''\}$, the expected profit of the firm with technology γ when the technological choices are (γ', γ'') , we get the reduced form profit functions:

$$E\Pi^f(i, f) = \frac{1}{4\beta}[V + (\mu - s - \beta x)^2] - H \quad (3.4)$$

$$E\Pi^i(i, f) = \frac{1}{2}x(\mu - s - \beta x) \quad (3.5)$$

Note that we can express x as

$$x = \frac{1}{3\beta}(\mu - s) + \delta, \quad (3.6)$$

that is to say the Cournot equilibrium quantity $\frac{1}{3\beta}(\mu - s)$ when both firms are flexible and α is equal to its expected value μ , plus some discrepancy term denoted by δ which may be either positive or negative according to the value of x . From the assumption on $\underline{\alpha}$, we must have $\frac{1}{6\beta}(\mu - s) \geq \delta$ so that:

$$\underline{\delta} \equiv -\frac{1}{3\beta}(\mu - s) \leq \delta \leq \frac{1}{6\beta}(\mu - s) \equiv \bar{\delta}. \quad (3.7)$$

Substituting x given by (3.6) into (3.4) and (3.5), we get:

$$E\Pi^f(i, f) = \frac{1}{9\beta}(\mu - s)^2 + \frac{1}{4\beta}V - \frac{1}{3}\delta(\mu - s) + \frac{1}{4}\beta\delta^2 - H \quad (3.4')$$

$$E\Pi^i(i, f) = \frac{1}{9\beta}(\mu - s)^2 + \frac{1}{6}\delta(\mu - s) - \frac{1}{2}\beta\delta^2 \quad (3.5')$$

where $\frac{1}{9\beta}(\mu - s)^2$ is the profit per firm (over variable costs) at the Cournot equilibrium when both firms are flexible and α is equal to its expected value μ .

Suppose that at the end of stage 1, the technological configuration is (i, i) , that is both firms are inflexible. Then both firms will produce and sell quantity $q = x$ for all values of α and we obtain

$$E\Pi^i(i, i) = x(\mu - s - 2\beta x), \quad (3.8)$$

that is, adopting the representation (3.6) for x :

$$E\Pi^i(i, i) = \frac{1}{9\beta}(\mu - s)^2 - \frac{1}{3}\delta(\mu - s) - 2\beta\delta^2. \quad (3.8')$$

Suppose finally that at the end of stage 1, the technological configuration is (f, f) , that is both firms are flexible. Then the second stage Cournot equilibrium will be the standard Cournot equilibrium with linear demand and constant marginal cost of production, that is $q^f = \frac{1}{3\beta}(\alpha - s)$. Therefore

$$E\Pi^f(f, f) = \frac{1}{9\beta}(\mu - s)^2 + \frac{1}{9\beta}V - H. \quad (3.9)$$

We can now go back to the technological choice stage and characterize the best response function $BR(\cdot)$ of a firm to different choices of technological flexibility by the other.

3.2 The Best Response to Inflexibility

Suppose first that a firm has chosen an inflexible technology. Under our assumption on $\underline{\alpha}$, both $E\Pi^f(i, f)$ and $E\Pi^i(i, i)$ are positive and therefore a firm will never decide as

a best response to stay out of the market. It is evident that flexibility is for the other firm a best response iff $E\Pi^f(i, f) \geq E\Pi^i(i, i)$, that is to say, from (3.4) and (3.8), iff

$$f = BR(i) \iff \frac{1}{4\beta}[V + (\mu - s - 3\beta x)^2] - H \geq 0. \quad (3.10)$$

or equivalently from (3.4') and (3.8'), iff

$$f = BR(i) \iff \frac{1}{4\beta}V + \frac{9}{4}\beta\delta^2 - H \geq 0. \quad (3.10')$$

The first term of the above inequality (3.10') depends on the volatility of the market whereas the second term is an increasing function of the *absolute* value of δ , the gap (either positive or negative) between the Cournot equilibrium production level, when both firms are flexible and the size of the market is equal to its average size, and the capacity production level x . If the capacity production level x is equal to $\frac{1}{3\beta}(\mu - s)$ and the volatility of the market size V is equal to 0, then as far as the profit over variable costs is concerned, it would make no difference to adopt a flexible technology or an inflexible one. If the exogenous capacity x is equal to $\frac{1}{3\beta}(\mu - s)$, i.e. if $\delta = 0$, then the best second stage production level with a flexible technology is equal to $\frac{1}{3\beta}(\mu - s)$, the production level at which an inflexible firm would be committed, so that the flexible technology and the inflexible one are equivalent. As the volatility of the market increases, the flexible technology becomes relatively more profitable since it allows a finer tuning of the second stage production level. The term $\frac{1}{4\beta}V$ is the gain coming from this more adapted response when the market size is fluctuating around its average value. If the capacity level x is either higher or lower than the Cournot quantity without uncertainty $\frac{1}{3\beta}(\mu - s)$, then the best response to x is, for a flexible firm, equal to $[\frac{1}{2\beta}(\mu - s) - \frac{1}{2}x]$ so that the gap between this best response and the capacity commitment level amounts to:

$$\begin{aligned} x - \left(\frac{1}{2\beta}(\mu - s) - \frac{1}{2}x \right) &= \left(\frac{1}{3\beta}(\mu - s) + \delta \right) - \left(\frac{1}{2\beta}(\mu - s) - \frac{1}{2} \left(\frac{1}{3\beta}(\mu - s) + \delta \right) \right) \\ &= \frac{3}{2}\delta. \end{aligned}$$

Hence, except when $x = \frac{1}{3\beta}(\mu - s)$, i.e. when $\delta = 0$, inflexibility is never a best response to inflexibility when the differential fixed cost is neglected.

Noting that by assumption $\mu > s + 2\beta x$, we may characterize the conditions under which flexibility is a best response to inflexibility as follows:

Proposition 1: *Flexibility is a best response to inflexibility, $f = BR(i)$, when the sum of the volatility effect $\frac{1}{4\beta}V$, permitted by a better adjustment with a flexible technology, and the capacity effect $\frac{9}{4}\beta\delta^2$, which are both positive, is larger than the differential fixed cost H , a condition which is more likely satisfied:*

- the larger the variance of the market size V is,
- the further (smaller or larger) the expected size of the market μ is from $3\beta x + s$,
- the further the capacity production level x of an inflexible technology is from $\frac{1}{3\beta}(\mu - s)$,
- the smaller the differential cost H of the flexible technology is [for $H = 0$, flexibility is always a better response to inflexibility than inflexibility],
- the further the average variable cost s is from $\mu - 3\beta x$,
- either the further the absolute value of the slope of the inverse demand function β is from $\frac{1}{3x}(\mu - s) + \frac{1}{9\beta^2}(2H)$ when $H \leq \frac{3}{4}(\mu - s)x$, or the smaller the absolute value of the slope of the inverse demand function β is when $H \geq \frac{3}{4}(\mu - s)x$. ||

Proof: The proposition follows directly from (3.10') and its equivalent (3.10), where the sum of the terms in μ is minimized at $\mu = s + 3\beta x$, the sum of the terms in x is minimized at $x = \frac{1}{3\beta}(\mu - s)$, the sum of the terms in s is minimized at $s = \mu - 3\beta x$, and the sum of the terms in β is minimized at $\beta = \frac{1}{3x}(\mu - s) + \frac{1}{9\beta^2}(2H)$. QED

3.2 The Best Response to Flexibility

Suppose now that a firm has chosen a flexible technology. Then flexibility is a best response to flexibility iff $E\Pi^f(f, f) \geq E\Pi^i(f, i)$, that is to say, from (3.5) and (3.9),

$$f = BR(f) \iff \frac{1}{9\beta}[V + \mu(\mu - 2s - \frac{9}{2}\beta x) + \frac{1}{2}(3\beta x + 2s)(3\beta x + s)] - H \geq 0. \quad (3.11)$$

or equivalently from (3.5') and (3.9),

$$f = BR(f) \iff \frac{1}{9\beta}V + \frac{1}{2}\beta\delta^2 - \frac{1}{6}\delta(\mu - s) - H \geq 0. \quad (3.11')$$

Again the difference in profits permitted by adopting a flexible technology rather than an inflexible one can be split into two terms. The first term, $\frac{1}{9\beta}V$, comes from a better adaptability to changing market conditions given a fixed expected size of the market μ . The second one, $\frac{1}{2}\beta\delta^2 - \frac{1}{6}\delta(\mu - s)$, is shown below to come from the gap (either positive or negative) between the capacity production level x and the production level of the leader in a Stackelberg production game where both firms are flexible and the market volatility is zero. Let us denote by $Z(\delta)$ this second term; we get: $\frac{\partial Z}{\partial \delta} = 0$ if $\delta = \frac{1}{6\beta}(\mu - s)$ and $\frac{\partial^2 Z}{\partial \delta^2} = \beta > 0$. Hence $Z(\delta)$ is minimized at $\delta = \frac{1}{6\beta}(\mu - s)$ [which by (3.7) is the upper bound of the admissible values] where its value is negative. But $\delta = \frac{1}{6\beta}(\mu - s)$ is equivalent to $x = \frac{1}{2\beta}(\mu - s)$, that is the leader's production level is the second stage when both firms are flexible and the market volatility is zero. So suppose that $x = \frac{1}{2\beta}(\mu - s)$, then it is clearly better to be inflexible than flexible since adopting a flexible technology would drive the firms to the Cournot equilibrium in the production subgame, which is evidently less profitable than the Stackelberg equilibrium for the leader. Hence, the pure capacity effect is working against flexibility as long as $x \in (\frac{1}{3\beta}(\mu - s), \frac{1}{2\beta}(\mu - s))$. When x is equal to $\frac{1}{3\beta}(\mu - s)$, that is when $\delta = 0$, and volatility is zero, both the flexible technology and the inflexible technology generate the same profits over variable costs. When $x < \frac{1}{3\beta}(\mu - s)$ the picture is reversed: the commitment value of production level x is too low and it would be better to be flexible rather than inflexible.

Since by assumption $x < \frac{1}{2\beta}(\mu - s)$ we can conclude as follows:

Proposition 2: *Flexibility is a best response to flexibility, $f = BR(f)$, when the sum of the volatility effect $\frac{1}{9\beta}V$, permitted by a better second stage adjustment with a flexible technology, and the capacity effect $\frac{1}{2}\beta\delta^2 - \frac{1}{6}\delta(\mu - s)$ which is either positive, if $x < \frac{1}{3\beta}(\mu - s)$, or negative, if $\frac{1}{3\beta}(\mu - s) < x < \frac{1}{2\beta}(\mu - s)$, is larger than the differential fixed cost H , a condition which is more likely satisfied:*

- the larger the variance of the market size V is,
- the further (either smaller or larger) the expected size of the market μ is from $\frac{9}{4}\beta x + s$,
- the smaller the capacity production level x of an inflexible technology is,
- the smaller the differential cost H of the flexible technology is,
- the further the average variable cost s is from $\mu - \frac{9}{4}\beta x$,
- the smaller the absolute value of the slope of the inverse demand function β is. ||

Proof: The proposition follows directly from (3.11') and its equivalent (3.11), where the sum of the terms in μ is minimized at $\mu = \frac{9}{4}\beta x + s$, the sum of the terms in x is minimized at $x = \frac{1}{2\beta}(\mu - s)$, the sum of the terms in s is minimized at $s = \mu - \frac{9}{4}\beta x$, and the sum of the terms in β is minimized at $\beta = \frac{1}{2x}(\mu - s) + \frac{1}{x^2}H$. QED

From the best responses, we can characterize the Nash and Stackelberg equilibria in technological flexibility $(\gamma^{1*}, \gamma^{2*})$.

4. Simultaneous and Sequential Move Technological Equilibria

4.1 Simultaneous Move Equilibria

Suppose that the firms move simultaneously in the technology choice stage.

Proposition 3: *The subgame perfect Nash equilibrium of the game where at the technology choice stage both firms move simultaneously, can be characterized as follows:*

- (a) *both firms choose inflexible technologies if inflexibility is the best response to both inflexibility and flexibility [inflexibility is a dominant strategy], that is if neither (3.10) [or equivalently (3.10')] nor (3.11) [or equivalently (3.11')] are satisfied – domain I in Figure 1 (where $\sigma = \sqrt{V}$) and in Figure 1';*
- (b) *both firms choose flexible technologies if flexibility is the best response to both inflexibility and flexibility [flexibility is a dominant strategy], that is if (3.10) [(3.10')] and (3.11) [(3.11')] are satisfied – domain II in Figure 1 and in Figure 1';*
- (c) *one firm chooses the flexible technology and the other the inflexible technology if inflexibility is the best response to flexibility and flexibility is the best response to inflexibility, that is if (3.10) [(3.10')] is satisfied but not (3.11) [(3.11')] – domain III in Figure 1 and in Figure 1';*
- (d) *both firms choose the same technology, either flexible or inflexible, if inflexibility is the best response to inflexibility and flexibility is the best response to flexibility, that is if (3.10) [(3.10')] is not satisfied but (3.11) [(3.11')] is – domain IV in Figure 1 and in Figure 1'. ||*

Proposition 3 shows that flexible and inflexible firms may very well coexist in a Nash equilibrium. This will be the case if the differential investment cost H of flexible technologies is neither too small nor too large, in which case one firm adopts a flexible technology and the other an inflexible one. We will see later that the most profitable technology is not always the same. This clearly means that observing the coexistence of

FMS technologies and traditional ones is not peculiar; there are no compelling reasons why the equilibrium should be symmetric. We gave evidence above that American firms are investing significantly less in FMS than their Japanese counterparts. What we have so far established is that such an asymmetric configuration is not incompatible with choices made by rational or competent firms in a strategic environment. What remains surprising though is that Japanese firms are adopting the FMS technologies more often. We will go one step further in understanding that situation by looking at the Stackelberg equilibria in long run technological flexibility choices.

4.2 Sequential Move Equilibria

Suppose that the firms move sequentially in the technology choice stage.¹⁴ Let us characterize the optimal technological choice of the first-mover firm. To achieve that, we must compare the leader's profit for each choice of $\gamma \in \{i, f\}$ given that the second-mover will react according to its best response characterized in Propositions 1 and 2. The only tricky case is the case where no technological choice is a dominant strategy.

When inflexibility is a dominant strategy, that is when neither (3.10) [(3.10')] nor (3.11) [(3.11')] are satisfied, then clearly both the first-mover and the second-mover choose the inflexible technology. When flexibility is a dominant strategy, that is when both (3.10) [(3.10')] and (3.11) [(3.11')] are satisfied, then clearly both the first-mover and the second-mover choose the flexible technology.

When inflexibility is the best response to flexibility, $i = BR(f)$, whereas flexibility is the best response to inflexibility, $f = BR(i)$, the first-mover must compare $E\Pi^i(i, f)$, which he gets when choosing an inflexible technology, to $E\Pi^f(f, i)$, which he gets when choosing a flexible technology.

¹⁴ A Stackelberg equilibrium is a reasonable equilibrium concept for long run decisions. Moreover, although the endogenous emergence of a leader-follower market structure is not modeled here, it should be understood that such a structure may very well have emerged from a previous stage even if firms were in a completely symmetric and similar position at the beginning of that previous stage. See Daughety and Reinganum (1990) for one such model. See also Boyer and Moreaux (1987) for a model in which firms do not compete for leadership or followership but indeed agree on a distribution of roles.

Hence, from (3.4) and (3.5), he will choose a flexible technology iff:¹⁵

$$\frac{1}{4\beta}[V + (\mu - s - \beta x)^2] - \frac{1}{2}x(\mu - s - \beta x) - H \geq 0 \quad (4.1)$$

that is, from (3.4') and (3.5'), iff:

$$\frac{1}{4\beta}V - \frac{1}{2}\delta(\mu - s) + \frac{3}{4}\beta\delta^2 - H \geq 0, \quad (4.1')$$

When inflexibility is the best response to inflexibility, $i = BR(i)$, whereas flexibility is the best response to flexibility, $f = BR(f)$, the first-mover must compare $E\Pi^i(i, i)$, which he gets when choosing an inflexible technology, to $E\Pi^f(f, f)$, which he gets when choosing a flexible technology. Hence, from (3.8) and (3.9), he will choose a flexible technology iff:¹⁶

$$\frac{1}{9\beta}[V + (\mu - s)^2] - x(\mu - s - 2\beta x) - H \geq 0 \quad (4.2)$$

that is, using (3.8'), iff:

$$\frac{1}{9\beta}V + \frac{1}{3}\delta(\mu - s) + 2\beta\delta^2 - H \geq 0. \quad (4.2')$$

¹⁵ The conditions (4.1) and (4.1') are more likely to be satisfied:

- the larger the variance of the market size V is,
- the larger the expected size of the market μ is [the function $W(V, \mu, x, s, \beta, H)$ defined by (4.1) is increasing in μ in the region of interest],
- the larger δ is when it is larger than the Cournot quantity $\frac{1}{3\beta}(\mu - s)$ [the function $\Delta(V, \delta, H)$ defined by (4.1') is increasing in δ if $\delta > \frac{1}{3\beta}(\mu - s)$]
- the smaller the capacity production level x of an inflexible technology is [the function $W(V, \mu, x, s, \beta, H)$ defined by (4.1) is decreasing in x in the region of interest],
- the smaller the differential cost H of the flexible technology is,
- the smaller the absolute value of the slope of the inverse demand function β is [the function $W(V, \mu, x, s, \beta, H)$ defined by (4.1) is decreasing in β in the region of interest].

¹⁶ The conditions (4.2) and (4.2') are more likely to be satisfied:

- the larger the variance of the market size V is,
- the larger [smaller] the expected size of the market μ is when μ is larger [smaller] than $\frac{9}{2}\beta x + s$,
- the smaller the capacity production level x of an inflexible technology is when $x > \frac{1}{4\beta}(\mu - s)$,
- the smaller the differential cost H of the flexible technology is,
- the larger the absolute value of the slope of the inverse demand function β is when $\beta > \frac{1}{4x^2}(H + x(\mu + s))$.

Lemma 1: If $i = BR(i)$ and $f = BR(f)$, then $E\Pi^i(i, i) > E\Pi^f(f, f)$. ||

Proof: We must show that if (3.11) is met but not (3.10) [domain IV in the figures], then (4.2) is not met and the leader always choose an inflexible technology. We have $i = BR(i)$ and $f = BR(f)$ if

$$4\beta H - (\mu - s - 3\beta x)^2 > 9\beta H - \mu(m - 2s - \frac{9}{2}\beta x) - \frac{1}{2}(3\beta x + 2s)(3\beta x + s)$$

which holds iff

$$-5\beta H + \frac{3}{2}\beta x(\mu - s - 3\beta x) \geq 0 \quad (\ell.1)$$

which holds only if $(\mu - s - 3\beta x) \geq 0$. Now, (4.2) fails to be satisfied when $i = BR(i)$ and $f = BR(f)$ if

$$4\beta H - (\mu - s - 3\beta x)^2 < 9\beta H + 9\beta x(m - s - 2\beta x) - (\mu - s)^2$$

which holds iff

$$5\beta H + 3\beta x(\mu - s - 3\beta x) \geq 0. \quad (\ell.2)$$

Clearly, $\ell.1$ implies $\ell.2$. QED.

We may conclude as follows, denoting by $E\Pi^L(\gamma, \gamma')$ and $E\Pi^F(\gamma, \gamma')$ the expected profits of the first-mover (leader) and of the second-mover (follower) when the leader chooses a technology γ and the follower a technology γ' :

Proposition 4: The subgame perfect Stackelberg equilibrium $(\gamma^{L*}, \gamma^{F*})$ can be characterized as follows:

- (a) both firms choose inflexibility and their expected profits are similar either if inflexibility is a best response to both flexibility and inflexibility, that is if neither (3.10) [(3.10')] nor (3.11) [(3.11')] hold – domain I in Figure 1 and in Figure 1' – or if inflexibility is the best response to inflexibility, flexibility is the best response to flexibility and $E\Pi^L(i, i) > E\Pi^L(f, f)$, that is if (3.11) [(3.11')] holds but neither (3.10) [(3.10')] nor (4.2) [(4.2')] – domain IV Figure 1 and in Figure 1';

- (b) both firms choose flexibility and their expected profits the similar if flexibility is a best response to both flexibility and inflexibility, that is if both (3.10) [(3.10')] and (3.11) [(3.11')] hold – domain II in Figure 1 and in Figure 1';
- (c) the first-mover will be flexible and the second-mover inflexible if inflexibility is the best response to flexibility, flexibility is the best response to inflexibility and $E\Pi^L(f, i) > E\Pi^L(i, f)$, that is if (3.10) [(3.10')] and (4.1) [(4.1')] hold but not (3.11) [(3.11')] – domain III.A in Figure 1 and in Figure 1'; first-movership is the preferred position;
- (d) the first-mover will be inflexible and the second-mover flexible if inflexibility is the best response to flexibility, flexibility is the best response to inflexibility and $E\Pi^L(f, i) < E\Pi^L(i, f)$, that is if (3.10) [(3.10')] holds but neither (3.11) [(3.11')] nor (4.1) [(4.1')] – domain III.B in Figure 1 and in Figure 1'; first-movership is the preferred position. ||¹⁷

We immediately have the following corollaries.

Corollary 1: *The expected profits of the first-mover are never lower than the expected profits of the second-mover, whatever the equilibrium configuration of technologies. Hence, technological flexibility choices are strategic substitutes rather than complements. ||*

Consider Figure 1 and Figure 1'. The Nash equilibria and the Stackelberg equilibria are the same in domains I and II; in III and IV, there are two Nash equilibria, $\{(i, f), (f, i)\}$ in III, $\{(i, i), (f, f)\}$ in IV, but only one Stackelberg equilibrium, the one most favorable to the first-mover, that is (i, f) in III.B, (f, i) in III.A, and (i, i) in IV. Hence:

¹⁷ It may be informative to restate Proposition 4 in a different way as follows:

- (a) if $f = BR(f)$ and $f = BR(i)$, then $(\gamma^{L*}, \gamma^{F*}) = (f, f)$
- (b) if $i = BR(f)$ and $i = BR(i)$, then $(\gamma^{L*}, \gamma^{F*}) = (i, i)$
- (c) if $i = BR(f)$ and $f = BR(i)$, then $(\gamma^{L*}, \gamma^{F*}) = \begin{cases} (f, i) & \text{if (4.1) is satisfied} \\ (i, f) & \text{otherwise} \end{cases}$
- (d) if $f = BR(f)$ and $i = BR(i)$, then $(\gamma^{L*}, \gamma^{F*}) = (i, i)$.

Corollary 2: A flexibility trap is present in industries represented in domain IV. Although (f, f) is a legitimate Nash equilibrium, both firms would make more profits if they were to choose inflexible technologies (i, i) . ||

It is interesting and revealing to see how the predicted Stackelberg equilibrium evolves as the volatility and the (expected) size of the market change. The following two corollaries give two particular “paths of technological flexibility adoptions”.

Corollary 3: Suppose that the expected size of the market is fixed at $\hat{\mu}$ in Figure 1; then, as the volatility of demand σ increases, we obtain the following sequence of predicted equilibria $(\gamma^{L*}, \gamma^{F*})$: $(i, i), (i, f), (f, i), (f, f)$. Hence for intermediate values of demand volatility, an increase in volatility induces the two firms to “trade” their technologies: the inflexible leader switches to a flexible technology inducing the follower to switch from an inflexible technology to a flexible one. ||

Corollary 4: Suppose that the volatility of demand is fixed at $\hat{\sigma}$ in Figure 1; then, as the expected size of the market μ increases, we obtain the following sequence of equilibria $(\gamma^{L*}, \gamma^{F*})$: $(i, f), (i, i), (f, i), (f, f)$. Again the two firms may wish to “trade” their technologies but through a stage in which both firms choose inflexible technologies. ||

To represent different industries directly on Figure 1 as points in (μ, σ) -space, we must normalize the measurement of μ and σ . To do so, we can normalize the production levels q in terms of x and β by rewriting the demand function in a given industry as:

$$\hat{p} = \frac{p}{\beta x} = \frac{\alpha}{\beta x} - \beta \frac{q^L + q^F}{\beta x} = \hat{\alpha} - (\hat{q}^L + \hat{q}^F).$$

In this way, β and x can be said to be normalized to 1. We obtain $E(\hat{\alpha}) = E(\alpha)/\beta x$ and $\sigma(\hat{\alpha}) = \sigma(\alpha)/\beta x$. Hence, changes in β or x in a particular industry move the point representing it, in the (μ, σ) -space, on the ray from the origin through the original point: away from the origin if βx decreases and towards the origin if βx increases. Those changes have no effect on the boundaries of the different domains in Figure 1.

Let us consider three changes typically associated with the emergence of flexible

technologies: a *reduction* in the differential cost of flexibility H , a *reduction* in the minimum efficiency scale x and a *reduction* in β . The last two changes represent increases in competitive pressures: the reduction in β implies an increase in demand elasticity at all production levels¹⁸ while the reduction in x may be interpreted as softer entry conditions and therefore more aggressive competition from the competitive fringe for our duopolists.

Corollary 5: *If the competitive pressures increase in an industry, either through an increase in the price elasticity of demand or through a reduction of the minimum efficiency scale of production, then*

- for industries in I close to the border of $III.A$, one would predict a switch from (i, i) to (i, f) , that is an increase in overall flexibility because of the second-mover's switch to a flexible technology;
- for industries in I close to the border of $III.B$, one would predict a switch form (i, i) to (f, i) , that is an increase in overall flexibility due to the first-mover's switch to a flexible technology;
- for industries in $III.A$ close to the border of $III.B$ one would predict a switch from (i, f) to (f, i) , that is would see the first-mover and the second-mover ‘trade’ their technologies !
- for industries in $III.B$ close to the border of IV , one would predict a switch form (f, i) to (f, f) , that is an increase in overall flexibility due to the second-mover's switch to a flexible technology;
- for industries ‘located’ in I close to the border of II , one would predict a switch from (i, i) to (f, f) , that is an increase in overall flexibility because of a switch by both firms to a flexible technology. ||

The following corollary on the impact of a reduction in the differential investment cost

¹⁸ But of course the demand elasticity at every price level remains the same.

H of flexible technologies is expressed in terms of the distribution of industries in the (μ, σ) -space. A change in H has no effect on the distribution of industries in (μ, σ) -space but displaces the boundaries of the different domains. If H decreases by dH , then all the boundaries in Figure 1 moves down vertically: (4.1) and (3.10) by $4dH$, and (3.11) by $9dH$. Suppose that the normalized minimum value of μ is above the value for which (3.10) intersects with the horizontal axis, say $\mu \geq 2.8$. Then a reduction in the differential investment cost H of flexible technologies increases domain II, reduces domains I and III.A but has no effect on domain III.B. Hence:

Corollary 6: *A reduction in the differential investment cost H of flexible technologies unambiguously reduces the probability of observing configuration (i, i) and increases the probability of observing configuration (f, f) . Although the overall effect is favorable to the adoption of flexible technologies, the specific effect on the probabilities of observing asymmetric equilibria (f, i) and (i, f) depends on the distribution of industries in (μ, σ) -space [assuming that the distribution is uniform over $[(2.8, 0), (\bar{\mu}, \bar{\sigma})]$ for the parameter values of Figure 1, then a reduction in H would not change the probability of observing configuration (i, f) but would reduce the probability of observing configuration (f, i) , hence an increase in the probability of (i, f) relative to (f, i) !]. ||*

5. Technological Flexibility and Entry Deterrence

Technological choices may be aimed at preventing entry. We will characterize in this section the circumstances under which the first mover may switch to a *more (less)* flexible technology in order to prevent entry and those under which technology *cannot* be used to prevent entry. Suppose that there exists a sunk cost of entry K independent of the investment cost of the technology that the entrant will eventually choose. We will continue to assume that $H(i) = 0$ and $H(f) = H > 0$.

We must first characterize the level of profits a firm would obtain if it were able to blockade entry and act as a monopolist.

Proposition 5: *The optimal technology choice of a monopolist can be characterized as follows:*

$$\begin{aligned}\gamma^M &= f \quad \text{if } \frac{1}{4\beta}[V + (\mu - s)^2] - x(\mu - s - \beta x) - H \geq 0 \\ \gamma^M &= i \quad \text{otherwise} \quad \| \end{aligned}$$

Proof: If $\gamma = i$, then the monopolist inelastically put on the market the quantity $q = v = x$ and his profit is

$$E\Pi^M(i) = E[(\alpha - \beta x)x - sx] = x(\mu - s - \beta x). \quad (5.1)$$

If $\gamma = f$, then the monopolist puts on the market the quantity $q(\alpha) = \frac{1}{2\beta}(\alpha - s)$ and realizes an expected profit of

$$E\Pi^M(f) = E[(\alpha - s - \beta q(\alpha))q(\alpha)] - H = \frac{1}{4\beta}[V + (\mu - s)^2] - H. \quad (5.2)$$

The proposition follows from comparing the profit levels. QED.

We can use (5.1), (5.2), the profit functions derived in section 3, and proposition 4 above to obtain the following propositions. In each case, the leader will consider switching from γ , the flexible (inflexible) technology, to γ' , the inflexible (flexible) one, to enjoy monopoly profits when doing so can prevent entry, that is when K and $E\Pi^F(\cdot, \cdot)$ satisfy the following two conditions, with $\gamma \neq \gamma'$:

$$E\Pi^F(\gamma', BR(\gamma')) < E\Pi^F(\gamma, BR(\gamma)) \quad (5.3)$$

$$K \geq E\Pi^F(\gamma', BR(\gamma')), \quad (5.4)$$

that is when the entrant's profit decreases with the switch by the incumbent from γ to γ' and the entry cost K is at a proper level. By assumption, $K < E\Pi^F(\gamma, BR(\gamma))$, that is the original choice of the incumbent would not prevent entry.

Proposition 6: When $f = BR(f)$ and $f = BR(i)$ [domain II in Figure 1], the leader chooses a flexible technology; he will switch to an inflexible one if

$$V \leq 9\beta H - (\mu - s)^2 + 9\beta x(\mu - s - \beta x) \quad (5.5)$$

$$V \leq -(\mu - s)^2 + \frac{18}{5}\beta x(\mu - s) - \frac{9}{5}\beta^2 x^2 \quad (5.6)$$

provided that K is at an appropriate level. ||

Proof: The leader would consider switching to an inflexible technology if $E\Pi^M(i) > E\Pi^L(f, f)$ which is condition (5.5) and if $E\Pi^F(i, f) < E\Pi^F(f, f)$ which is condition (5.6). Hence if those conditions are satisfied, the leader will switch to an inflexible technology provided that K satisfies (5.4). QED.

Conditions (5.5) and (5.6) define the $\|$ -subdomain in domain II in Figure 1; (5.6) does not appear because it is way above (5.5) on the graph. This subdomain represents industries in which a leader (or incumbent) will choose an *entry preventing inflexible technology*, if the entry cost K is at an appropriate level, rather than the flexible technology he would choose otherwise.

Proposition 7: When $i = BR(f)$ and $f = BR(i)$ [domain III in Figure 2], the leader will never operate a switch in his technology because doing so cannot prevent entry. ||

Proof: If the leader has chosen a flexible technology, then it must be the case that $E\Pi^L(f, i) > E\Pi^L(i, f)$; but recall that $E\Pi^L(f, i) = E\Pi^F(i, f)$ and that $E\Pi^L(i, f) = E\Pi^F(f, i)$; hence it is impossible for the leader to prevent entry since $E\Pi^L(f, i) > E\Pi^L(i, f)$ implies $E\Pi^F(i, f) > E\Pi^F(f, i)$. And similarly for the case where the leader has chosen an inflexible technology. QED.

Hence in those industries characterized by a (μ, σ) in domain III, a change in technological flexibility, either from f to i or from i to f , cannot prevent entry.

Proposition 8: When $i = BR(f)$ and $i = BR(i)$ [domain I in Figure 2], the leader chooses an inflexible technology; he would switch to a flexible technology if

$$V > 4\beta H - (\mu - s)^2 + 2\beta x[\mu - s - 2\beta x] \quad (5.7)$$

$$\mu \geq 3\beta x + s \quad (5.8)$$

provided that K is at an appropriate level. ||

Proof: Condition (5.7) is the condition under which $E\Pi^M(f) > E\Pi^L(i, i)$ and condition (5.8) is the condition under which $E\Pi^F(f, i) < E\Pi^F(i, i)$; therefore if those conditions hold, the leader will switch to flexibility provided that K satisfies (5.4). QED.

Note that condition (5.7) and (5.8) define the \equiv -subdomain in domain I of Figure 2; this subdomain represents industries in which a leader (or incumbent) will choose an *entry preventing flexible technology*, if the entry cost K is at an appropriate level, rather than the inflexible technology he would choose otherwise.

6. Conclusion

Most studies of technological flexibility concentrate on the minimization of costs in a decision-theoretic context. We have shown in this paper that those choices have important strategic implications which depend on market structure. More precisely, we have shown *how* technological flexibility choices and equilibrium (both simultaneous and sequential) configurations in different industries depend on the (six) characteristics of the industry and on the strategic positioning of the firms and *how* changes in those characteristics are likely to affect the technological flexibility configuration observed in a given industry and therefore the distribution of those flexibility configurations in the economy as a whole. Flexible and inflexible technologies can coexist in an industry when the normalized expected or average value μ and the normalized variance or standard error σ of market size fall in a particular region of the parameter space [domain III in Figure 1, 1' and 2] which we characterized. Low market volatility, V or σ , combined

with intermediate market size μ will favor inflexible technologies; large values of *either* μ or σ will favor flexible technologies; low values of both σ and μ and intermediate values of both σ and μ will favor asymmetric choices of technological flexibilities. There is a possibility of flexibility trap in industries characterized by low volatility and intermediate to large market size. Finally, inflexible technologies can be part of an entry preventing strategy in some industries while flexible technologies will be in other industries.

Our results not only shed light on the underlying factors explaining the ‘stylized fact’ described in the introduction, namely that Japan invests significantly more in FMS technologies than the United States, but also suggest explicit empirical hypotheses to be tested with time series data on an industry or with cross sectional data on a set of industries. Those empirical hypotheses characterize the impact of variations in the relative investment costs of flexible and inflexible technologies, in market size, in demand volatility and in competitive market pressures on the equilibrium configuration (or adoption path) of flexible technologies in different industries. Although many of those impacts might confirm one’s prior expectations, a significant subset are rather surprising: firms may wish to “trade” their technologies, the increase in flexibility may come sometimes from the leader firm and sometimes from the follower firm, increases in market size may favor inflexible technologies, firms in an industry may find themselves in an ‘excessive liquidity’ trap, flexible technologies may be used to prevent entry, etc. Hence, some prudence is required in predicting the emergence (and adoption) of technological flexibility positions by firms: decision-theoretic contexts differ significantly from strategic equilibrium contexts.

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