# WORKING PAPER

## Technology Choice and Market Structure: Strategic Aspects of Flexible Manufacturing

George Norman
Department of Economics
Tufts University

Jacques-François Thisse
CORE
Université Catholique de Louvain

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Department of Economics
Tufts University

Department of Economics
Tufts University
Medford, MA 02155
(617) 627-3560

# Technology Choice and Market Structure:

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George Norman
Department of Economics
Tufts University
Medford, MA 02155
USA

Jacques-François Thisse
CORE,
Université Catholique de Louvain,
35, Voie du Roman Pays,
B-1348 Louvain-la-Neuve,
BELGIUM

*Abstract:*

This paper shows that the adoption of flexible manufacturing techniques by firms leads to a tougher price regime. This need not benefit consumers since the tougher regime deters entry and facilitates segmented market structures. The ability of flexible manufacturing to deter entry is moderated by non-prohibitive costs of re-anchoring flexible manufacturing processes and if entrants produce niche products using designated technologies rather adopt flexible manufacturing. Market preemption will be characterized by excessive product variety. Alternatively, flexible manufacturers may prefer to accommodate entry by small-scale, niche firms. We also identify the circumstances in which existing firms will choose to switch to a flexible technology. This will be profitable for the firms only if it leads to substantially increased market concentration.

(JEL: D42, D43, L11, L12, L13)

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It has been suggested that the only way in which the advanced industrial nations can maintain competitiveness in traditional and new manufacturing industries is if they adopt technically advanced production systems capable of providing customized products tailored to their consumers' requirements (Gerwin, 1993). Such *flexible manufacturing systems* (FMS) defined as:

> "a production unit capable of producing a range of discrete products with a minimum of manual intervention" (US Office of Technology Assessment, 1984, p. 60.)

significantly reduce the operating costs of switching product specification and change dramatically the ways in which firms (and economists) should think about markets and market serving. The emphasis on long production runs to exploit economies of scale must be replaced by thinking of how to employ "wide" production runs to exploit economies of scope.

Recent years have seen the increasing diffusion of flexible manufacturing systems in a wide range of industries (Mansfield, 1993). Hitachi and Mitsubishi use such systems in the production of elevators and heavy construction equipment. Flexibility in manufacture is one of the keys to the world leadership gained by the Italian ceramic tile manufacturer Marazzi, which produces 3.2 percent of world production of ceramic tiles:

> "The company must produce an extraordinary large variety of tiles that vary by shape, color, and sizes... The production process .. appears to be fully automated.. Clays are mixed, fed into presses, transported along tracks through ovens, glazed, sorted, piled, boxed, and stored all by computer-driven equipment without a human involved." (Rosenfeld, 1990, p. 10)

The *New York Times* (March 20, 1996) reports on the "mass customization" adopted by Levi Strauss for women's jeans and Custom Foot who "can draw on a potential inventory of more than 10 million pairs, with every style in every possible size." Other examples are to be found in industries as varied as automobiles, aerospace, furniture, fashion garments, heavy machinery and data warehousing.[1]

Much is now known about the operational aspects of flexible manufacturing but its strategic implications for market structure and performance are unclear and provide the motivation for this paper. The essence of FMS is that it allows firms to customize their products to the requirements of heterogeneous consumers at little or no cost penalty. On first sight this would appear to be unambiguously beneficial but matters are not quite so straightforward. The introduction of FMS by a

[1] Early surveys are to be found in the US Department of Commerce (1985) and the Economic Commission for Europe (1986).

single firm can be expected to give it a technological and cost advantage over its more specialized competitors. This may so change the market environment that a first-mover is able to pre-empt existing and new markets and exercise monopoly power while being able to deter entry.

By contrast, the introduction of FMS by more than one firm in an industry might be thought to be beneficial for consumers by creating a more competitive market environment since FMS makes it much more difficult for an oligopolist to exploit the local monopoly power that characterizes specialized production. Even here, however, there are more complex considerations. A more competitive environment deters entry and may have the apparently paradoxical effect of increasing industry concentration (Sutton, 1991), benefiting producers at the expense of consumers in the long run.

There is a more recent, but related development that may go some way to moderating the entry-limiting features of FMS. Accompanying the increasing use of FMS has been the growth of highly specialized, small-scale niche manufacturers such as the micro breweries in the United States and Britain. A recent report even suggests:

> "(j)ust as pint-size breweries popped up around the corner selling suds to locals, tiny steel mills may soon set up shop just down the street." (Wall Street Journal, Sept. 25, 1995)

The spatial model of product differentiation is a particularly convenient and powerful tool for analyzing these potentially conflicting effects of FMS given the emphasis this model places on product specification as a strategic variable. In this type of model the firm's strategic problem is to locate its products in a characteristics space over which consumers are distributed according to the "address" of their most preferred characteristics combination. A major concern in this theory is the characterization of the equilibrium configuration of products and of the associated market structure. Does the process of spatial competition generate too much or too little product variety in some social welfare sense? Is it possible for one, or a small group of firms to pre-empt the market, using product differentiation as a strategic entry-deterring device?

We now know that the answer to these questions is dependent upon whether firms can price discriminate between consumers in some reasonable manner. The important issue is to establish the conditions under which price discrimination is *feasible*. In the spatial model this is straightforward. All that is necessary is that the firm knows its consumers' addresses and can exploit that knowledge, for example by controlling the delivery service. When the spatial model is interpreted as a model of product specification more subtle questions arise with respect to the meaning and implementation of price discrimination. MacLeod, Norman and Thisse (1988) provide the analogy:

> "In the context of product differentiation, price discrimination arises when the producer begins with a 'base product' and then redesigns this product to the customers' specifications. This means that the firm now produces a *band* of horizontally differentiated products ... instead of a single product ... Transport cost is no longer interpreted as a utility loss, but as an additional cost incurred by the firm in adapting its product to the customers' requirements ... (S)o long as product design is under the control of the producer -- equivalent to the producer controlling transportation -- he need not charge the full cost of design change." (1988, pp. 442-3)

The ability to redesign base products in this way is precisely what a flexible manufacturing system achieves. As a result, FMS facilitates, indeed forces price discrimination by giving manufacturers control over the "delivery" of their products to consumers. But a discriminatory pricing regime is tougher for a firm than is a non-discriminatory regime since it weakens the ability of the firm to commit to a set of prices that will apply throughout its market (Norman and Thisse, 1996). This leads to a trade-off. With a given number of (base) products the adoption of FMS will benefit consumers at the expense of producers. However, because the price regime is now tougher, FMS acts as an entry-deterrent and so is likely to reduce the number of base products. It is possible that the entry-deterring effect of FMS will more than offset the price-reducing effect.

One of the main points of this paper is to show that the balance between these effects is determined by the ease with which a firm using FMS can re-anchor its base product(s) (what Norman and Thisse term the degree of spatial contestability) and by the ownership structure of the base products. Eaton and Schmitt (1994) suggest that if firms enter a market sequentially, FMS will lead to monopoly pre-emption of the market but, at least for the case of inelastic demand, the monopolist will offer the cost-benefit optimal number of base products. We show that this conclusion is dependent upon the implicit assumption that the costs of re-anchoring a base product are prohibitive, an assumption that might be felt to conflict with the underlying philosophy of FMS. When re-anchoring costs are not prohibitive monopoly pre-emption may still be feasible but will be characterized by excessive product variety. With respect to ownership, our analysis also indicates that FMS can be expected to be characterized by a segmented rather than interlaced market structure (Brander and Eaton, 1984), especially since the former can support an equilibrium with lower industry concentration *and* higher individual firm profits than can the latter.

Our second main point is to revisit the feasibility of market pre-emption by a first-mover suggested by Eaton and Schmitt (1994). This is shown to be critically dependent upon the assumption that potential entrants employ FMS. Once we allow for the possibility that entrants can choose instead to employ a *designated* (or specialized) technology (DT hereafter) offering niche products a very different equilibrium can emerge. Given that the first-mover anticipates the actions of the DT entrants, we identify the circumstances under which the first-mover(s) using FMS will actually prefer to accommodate entry by niche manufacturers using DT rather than attempt to pre-empt the market by crowding the product space.

Our discussion thus far relates primarily to the choice *between* designated and flexible technologies when firms enter a green-field market. Our third contribution is to consider the forces that will lead existing firms to *switch* technologies. A full treatment of this question raises complex issues that we feel are best left to subsequent analysis: for example, we can no longer assume any kind of symmetry in market structure; the switch of technology by some firms can be expected to lead others to exit the market. In order to gain some preliminary insight into the incentives that firms have to switch from DT to FMS we consider a simple case of a market initially containing a given number of DT firms and investigate the impact on market structure that will be caused by the availability of an FMS technology. We find that there will be conditions in which the fully designated structure can survive or in which some of the firms will choose not to switch technologies. We also find that the availability of the FMS technology will force firms to switch technologies even though this might lead to consumers being offered lower prices and firms earning lower profits. For firms rather than consumers to benefit from the switch in technologies, the switch must induce "significant" exit of existing firms.

Our basic model is outlined in section 1 after which our analysis is presented in three sections with increasing degrees of complexity. We begin in section 2 with the assumption of a green-field market in which firms play a two-stage location/price game given that entrants choose the *same* technology, whether flexible or specialized. The important issue here is the relationship between technology and entry with the important modification that the re-anchoring costs of FMS need not be prohibitive. In Section 3 we maintain the assumption of a green-field market but change the timing of the game and introduce a degree of technology choice. The first-mover(s) using FMS must consider the threat of subsequent entry by firms who employ a designated technology. In both these sections we concentrate on symmetric equilibria since it is impossible to derive general results for asymmetric location configurations.

In Section 4 we drop the assumption of a green-field market. We begin with a market populated by firms using a designated technology and investigate the incentives these firms have to switch to a flexible technology once this becomes available. The symmetry assumption of the previous sections can no longer be maintained, with the result that this case rapidly becomes analytically intractable. We therefore concentrate on an example which, while simplified, illustrates how market structure can be expected to be affected by the introduction of this new technology.

Our main conclusions are summarized in section 5.

## 1. The Model

The model is a variant on the familiar spatial model of product differentiation. Assume that consumers are uniformly distributed over a one-dimensional attribute space with support [0,1]. To avoid technical problems associated with end-points it is convenient to think of this space as the circumference of a circle. $x^*$ in [0,1] denotes the consumer's most preferred good (or address). A consumer buys exactly one unit of the good that gives her the greatest utility, where utility from buying good $x$ at price $p(x)$ is:

(1) $$U(x, p(x)) = V - p(x) - t|x - x^*|$$

and $V$ is the consumer's reservation price.

Denote the location of base product $k$ produced by firm $i$ in the attribute space by $X_{ik}$ and let $K^f$ be the set-up cost of an FMS anchored on base product $X_{ik}$. Variable production costs are normalized to zero and the cost of customizing $X_{ik}$ to attribute $x$ is assumed to be:

(2) $$MC_{ik}(x) = r|x - X_{ik}|.$$

The essential features of FMS are, first, that $0 \leq r << t$ and secondly, that the consumer derives the same utility from base product $X_{ik}$ customized to attribute $x$ as she does from a base product with initial attribute $x$ if they are offered at the same price.

This can be contrasted with a designated technology (DT) which produces a single product that the firm does not customize (see Röller and Tombak 1990, 1993). The utility derived by a consumer with most preferred product $x^*$ from consumption of designated product $x$ is given by equation (1). Denote the location of designated product $k$ produced by firm $i$ in the attribute space by $x_{ik}$ and let $K^d$ be the set-up cost of producing $x_{ik}$ using DT. Clearly, $K^d << K^f$ since the designated technology is "simpler" than the flexible technology. We follow Röller and Tombak (1990) by assuming that the variable production costs for DT are the same as for FMS and so can be normalized to zero. In doing so, it should be emphasized that we distinguish between the variable costs of producing a base (or designated) product - raw materials, intermediate inputs, labor, etc. - which can reasonably be assumed to be the same for the two technologies, and the marginal costs of customizing that base product to particular consumer requirements, which cannot. As we have indicated, with FMS customization costs are $r << t$ per unit distance. A firm operating DT could also offer to customize the product but we assume that this is possible only at a marginal cost $r^d >> t$ per unit distance, which is why a DT firm never offers customization.[2]

It is worth emphasizing that this difference in the key parameters of the cost functions for the two technologies does not appear in models comparing non-discriminatory and discriminatory prices (such as, for example, Norman and Thisse, 1996).

Firms are assumed to compete in a two-stage location-price game and we look for a subgame perfect equilibrium for this game. Since FMS facilitates price discrimination, competition in the price stage with FMS is Bertrand-at-every-point. Denote the set of active firms from the first-stage location game by $\vartheta_e$ and the set of base products owned by firm $i$ by $\Omega_i$. Let $X = (X_{ik}); k \in \Omega_i$, $i \in \vartheta_e$ be the location configuration established firms in the first stage. The Nash equilibrium FMS price schedule for base product $X_{ik}$ to a consumer with most preferred good $x^*$ is:[3]

(3) $$p_{ik}^*(x^* | X) = \min[V, \max[r|X_{ik} - x^*|, \min_{\substack{j \neq i \\ l \in \Omega_j}} r|X_{jl} - x^*|]].$$

By contrast, the Nash equilibrium price for designated product $x_{ik}$ is a single price, which will be a function of the market area of this product. We know from Salop (1979) that, if there are $n_d$

[2] It should also be noted that assuming higher variable costs for DT would not affect our qualitative results for a whole domain of values since we deal in our comparisons with strict inequalities.

[3] See, for example, MacLeod *et al.* (1988), Hoover (1937), Eaton and Lipsey (1979), Lederer and Hurter (1986).

symmetrically located DT products with no two neighboring products offered by the same firm, the competitive price equilibrium for each DT product is:

(4) $m^* = t/n_d$.

In technology configurations characterized by a mix of technologies, with some firms employing DT and others FMS, Thisse and Vives (1988) show that there exists no Nash equilibrium when all firms simultaneously choose prices. However, in such a context it seems reasonable to assume that the FMS firms retain the flexibility of choosing their price schedules in reaction to a single price quoted by a DT firm. This is equivalent to assuming that the DT firms act as Stackelberg leaders in the price subgame, the followers of which are the FMS firms: the DT firms set their mill prices correctly anticipating the (discriminatory) prices that the FMS firms will set.

In the next two sections we concentrate on location configurations which are symmetric in the products of a particular technology. This considerably eases computation without affecting the qualitative nature of the analysis. Since we make the assumption that the whole market is covered in equilibrium and since consumers have unit demands, total cost is a sufficient statistic for social welfare – a common feature of this type of model.

## 2. Flexibility and Entry

In this section we first compare the equilibrium outcomes arising under DT and FMS when firms are committed to the locations of their (base) products. This comparison will be shown to be critically affected by the key parameters of the two technologies: relative set-up costs and the degree of flexibility offered by FMS. We then introduce the possibility that firms employing FMS can re-anchor their base products at a finite cost. This significantly affects the set of possible equilibrium outcomes. In particular, we identify conditions under which the socially optimal number of base products no longer deters entry and so does not belong to the equilibrium set.

### 2.1 Prohibitive Re-Anchoring Costs

If re-anchoring costs are prohibitive, standard analysis (see, for example, Norman and Thisse, 1996) tells us that the number of symmetrically located products that can be a subgame perfect equilibrium for the DT technology choice lies somewhere in the interval

$\left[n_{\min}^{d}, n_{\max}^{d}\right] = \left[\left(\frac{3r}{2\left(2+\sqrt{3}\right)K^{d}}\right)^{\frac{1}{2}}, \left(\frac{r}{2K^{d}}\right)^{\frac{1}{2}}\right]$. Judd's (1985) analysis implies that the ownership structure of the DT products will be interlaced (borrowing the language of Brander and Eaton, 1984).

Assume now that all firms choose FMS. If re-anchoring costs are prohibitive, the number of symmetrically located base products that can be a subgame perfect equilibrium for the FMS technology choice lies somewhere in the interval $\left[n_{\min}^{f}, n_{\max}^{f}\right] = \left[\left(\frac{r}{6K^{f}}\right)^{\frac{1}{2}}, \left(\frac{r}{2K^{f}}\right)^{\frac{1}{2}}\right]$.

There is nothing in principle that will determine where within these ranges the DT or FMS industries will settle. It is well known that DT *always* leads to excessive product variety. However, since the socially optimal number of base products is $n^{0} = \left(r/4K^{f}\right)^{1/2}$ (see MacLeod *et al.* 1988), it is impossible to state whether free entry will lead to a market characterized by too much or too little product variety.

We introduce the parameter $a \in [2,6]$, which is inversely related to the actual number of base products, where $n_{\alpha}^{f} = \left(r/\alpha K^{f}\right)^{\frac{1}{2}}$. The range chosen for $\alpha$ corresponds to the range of possible equilibrium outcomes with FMS. As $\alpha$ rises, the number of base products falls. In other words, $\alpha$ can be interpreted as a direct measure of the extent to which firms are able to exploit the economies of scope offered by FMS. The value of $n^0$ implies that the socially optimal number of base products has $a = 4$.

Consider first market structure with these two technologies.

*Proposition 1: FMS has a smaller number of active firms and greater industry concentration than DT:*

- *(i)* *the greater are the set-up costs of FMS relative to those of DT;*
- (ii) *the greater the degree of flexibility of FMS;*
- (iii) *the more effectively firms exploit the economies of scope offered by FMS (the greater is a); and*
- (iv) *the more dispersed is ownership of the DT products.*

(Proof of this and subsequent propositions is given in the Appendix.)

This is consistent with the evidence produced by Mansfield (1993) that the probability of adoption of FMS is positively related to firm size and to the expected rate of return from FMS, and by Röller and Tombak (1993) that adoption of FMS is negatively related to the number of firms in the industry.

Now consider profits and consumer surplus with the two technologies. FMS makes the price regime tougher and so acts as an entry deterrent, leading firms to offer a smaller number of (base) products. The impact of FMS on profits and consumer surplus reflect this tension between price competition and entry deterrence.

*Proposition 2: Assume that the FMS market structure is interlaced. Then the use of FMS can be expected to increase individual base product profits and aggregate profit but to decrease consumer surplus as compared with DT:*

*(i)* *the greater are the set-up costs of FMS relative to DT;*

(ii) *the greater the extent to which FMS firms can exploit the economies of scope offered by FMS; and*

*(iii)* *the lower the degree of flexibility of FMS.*

The impact of $a$ and $K^f$ on profits reflects the balance between their positive effect on individual base product profit and their negative effect on the total number of base products. The effect of flexibility, as defined by the ratio *r/t*, on profits reflects a similar balance. Increased flexibility leads to lower prices but less entry. These forces exactly offset each other for the individual base product. However, the entry reducing effect of flexibility then leads to a reduction in aggregate profit.

Both FMS and DT satisfy the conditions specified by Brander and Eaton (1984) for market segmentation to be more profitable for incumbents than an interlaced ownership structure. But an important distinction between FMS and DT is that with FMS entry deterrence is independent of ownership (Eaton and Schmitt, 1994, Proposition 1). Hence, market segmentation leads to higher profits with FMS but does not induce further entry. We can, therefore, apply Brander and Eaton (1984, Propositions 3 and 4 to suggest that *FMS will be characterized by market segmentation*. Firms in adopting FMS will seek to locate their base products in contiguous parts of the consumer distribution. This strengthens Proposition 2 since market segmentation with FMS further increases prices and profits but reduces consumer surplus.

## 2.2 FINITE RE-ANCHORING COSTS

There are good reasons for relaxing the assumption, characteristic of many models of product differentiation, that firms have no ability to change the specifications of their (base) products, particularly view of the implications this assumption has for equilibrium product variety (Norman and Thisse, 1996). This is even more the case when the model is interpreted as a model of flexible manufacturing since we have noted that FMS confers on its users the ability to customize a base product to particular consumer requirements at a relatively low unit cost penalty.

It seems reasonable to suggest that FMS may well allow the specifications of the base products to be changed relatively cheaply. With a designated technology, relocation in product space requires that the firm “move” its production process to a good that it is not currently making and so may well be costly. By contrast, FMS allows the firm to make a wide range of products, potentially covering the entire consumer spectrum. Re-anchoring merely leads the firm to anchor its production process on a product that is either within its current range of product offerings, or that it has the ability to offer. (In the cases we consider below, re-anchoring does not take the FMS firm outside the range of products that it is currently offering.) In other words, what we are suggesting here is that firms are able to re-anchor their base products by incurring a one-off switching cost that need not be as great as the original set-up cost. If so, firms adopting FMS may not be able fully to exploit its entry deterring power. The claim that any symmetric distribution of base products in the interval $\left[n^f_{\min}, n^f_{\max}\right]$ is a subgame perfect equilibrium for the FMS location-price game need no longer hold.

Consider first the extreme case in which re-anchoring costs are zero.

*Proposition 3: When re-anchoring is costless, the only FMS location configuration that will deter entry by firms operating FMS is* $n^f = n^f_{\max}$.

Now assume that re-anchoring costs $R$ are non-zero but not prohibitive.[4] Further assume that a single firm using FMS enters between some pair of incumbents $i$ and $i$+1. We know that the entrant will locate mid-way between these incumbents. The benefits to incumbents of re-anchoring their base

[4] This implies that re-anchoring costs are one-off switching costs independent of distance. The analysis would be more complex, but qualitatively unaltered, if we were to assume $R$ to be distance-dependent.

products in response to entry are rapidly dissipated the greater is $R$. We can, in other words, envisage situations in which re-anchoring, if it occurs at all, will be confined to the base products $i$ and $i$+1.[5]

We know (from the proof of Proposition 1) that if base products $i$ and $i$+1 are re-anchored they will be established mid-way between the entrant and base products $i$–1 and $i$+2. The impact on incumbent firm $i$'s profit when only base products $i$ and $i$ + 1 are re-anchored in response to entry of an FMS firm between base products $i$ and ($i$+1) is, therefore:[6]

$$(5)\qquad \Delta\pi_i^f\left(n^f \middle| X^e\right) = \left(\frac{3r}{32\left(n^f\right)^2} - R\right) = \left(\frac{3\alpha K^f}{32} - R\right) \quad \alpha\in[2,6].$$

The market area of the entrant when only base products $i$ and $i$+1 are re-anchored is then $3/4n^f$ and her profit is:

$$(6)\qquad \pi^e\left(X^e \middle| n^f\right) = \frac{9r}{32\left(n^f\right)^2} - K^f = K^f\left(\frac{9\alpha}{32} - 1\right)$$

which is non-negative for $a > 32/9$. It follows immediately that:

*Proposition 4: A symmetric location configuration with* $\left(\frac{r}{\alpha K^f}\right)^{\frac{1}{2}}$ *FMS base products will not deter entry by FMS firms if* $a > 32/9$ *and* $R < 3aK^f/32$.

Our analysis is independent of the ownership of the base products. In particular, the analysis applies if the market is monopolized, perhaps through pre-emption by one firm or merger to monopoly.[7] With "prohibitive" re-anchoring costs, Eaton and Schmitt (1994) have shown that a monopolist will establish the socially optimal number of base products $n^0$, so that monopoly pre-emption or merger to monopoly is cost-benefit optimal. Proposition 4 allows us to identify just how high re-anchoring costs must be for this result to hold. Recall that the socially optimal number of base products is equivalent to $\alpha = 4$. Then we have:

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5 This is reminiscent of the Eaton and Wooders (1985) analysis of the way in which incumbents can be expected to change their mill prices in response to entry. The assumption does not affect our analysis below since this is intended to identify the lower bounds on $R$ which are consistent with particular location configurations being sustainable.

6 The profit impact on incumbent $i$ is, of course, unaffected by whether or not $i$+1 is re-anchored.

*Corollary: If re-anchoring costs are $R < 3K^f/8$, the socially optimal number of FMS base products will not be sufficient to deter FMS entry and monopoly pre-emption will not be cost-benefit optimal*.

Low re-anchoring costs dissipate the profits earned by incumbents to at least some extent. Nevertheless, provided that an entrant uses FMS it remains the case that the profitability of entry is unaffected by the ownership structure of the incumbent base products. Hence, given that FMS incumbents adopt a segmented market structure they will earn positive pure profits even if re-anchoring costs are zero because neighboring products compete less harshly when owned by the same firm. Furthermore, there is nothing in the analysis above that would prevent a first-mover from monopolizing the market *provided that both incumbents and potential entrants employ FMS*. The question to which we now turn is whether such monopoly pre-emption is possible when the entrant can choose the technology with which she enters the market.

**3. Technology Choice and Entry Deterrence**

Assume that firms enter sequentially *and* that they can choose the degree of flexibility of their technologies (Chang, 1993; Röller and Tombak 1990, 1993) choosing between FMS and DT with costs as defined in section 1. Let $\kappa = K^d / K^f$ and $\rho = r/t$ . $k$ is an inverse measure of the set-up cost penalty of FMS over DT and $\rho$ is an inverse measure of the degree of flexibility of FMS. Note that $\kappa, \rho < 1$. Assume further that a first-mover using FMS establishes $n^f$ equidistantly located base products.

If the first-mover anticipates that her rivals will also use FMS and if $R > 3K^f/8$, then by our Corollary, she will establish the socially optimal location configuration $n^0$ and no other flexible manufacturer will be able to enter the market. But now consider the first-mover's strategy if she anticipates subsequent entry by firms using DT. The DT entrant has a rather wider choice of potential locations than an FMS entrant. To keep matters simple, we confine attention to the case in which a single DT firm enters with a single product. This analysis can be extended to situations in which there are several DT entrants and/or a DT firm enters with several neighboring products. (We present the results for the two-firm case in the Appendix.)

7 Merger of any pair of neighboring firms is always profitable, even with no change in the degree of product variety offered by the merging firms: see Reitzes and Levy (1995).

*Proposition 5: Assume that the FMS first-mover has established $n^f$ equidistantly located base products.*

*A single-product DT firm entering between two of the first-mover's base products:*

*i. will set price* $m_e^* = r/4n^f$ *;*

*ii. will choose a location distance d from the mid-point between the two base products where d lies in the interval* $d \in [-\rho/4n^f, \rho/4n^f]$;

*iii. will earn profit* $\dfrac{t\rho^2}{8n^{f\,2}(1+\rho)} - K^d$ .

The bold line in Figure 1 illustrates the resulting price equilibrium.

(Figure 1 near here)

*Proposition 6: An FMS first-mover will not deter entry by a DT firm by choosing the profit maximizing (socially optimal) location configuration $n^0$ if*:

$$\kappa < \rho/2(1+\rho) . \qquad (\alpha_1)$$

These propositions show that an entrant is able to carve out a niche in the market precisely because she is able to pre-commit to a single price and a single product.

We might have considered a rather different first stage in which a number of FMS firms enter simultaneously. These firms will establish $n_\alpha^f = \left(r/\alpha K^f\right)^{\frac{1}{2}}$ base products where $\alpha \in [2,6]$ and the upper limit on $\alpha$ is determined (from section 2) by relocation costs. We then have:

*Proposition 7: FMS first-movers who establish* $n_\alpha^f = \left(r/\alpha K^f\right)^{\frac{1}{2}}$ *base products will not deter entry by DT firms if:*

$$\kappa < \alpha\rho/8(1+\rho) . \qquad (\alpha_2)$$

Note that $(\alpha_2)$ is a weaker or stronger condition than $(\alpha_1)$ depending upon the value of $\alpha$.

We should also consider the possible strategic reaction of an FMS first-mover to the threat of entry by DT firms. Should the first mover attempt to deter entry or is it in the interests of the incumbent to accommodate entry? There is a connection between this analysis and the work of Gelman and Salop (1983) who note (p. 319) that for an incumbent to be willing to accommodate entry it is at least necessary that "the entrant can make credible capacity-limitation commitments." (p. 319). The problem confronting a potential entrant is how to make such a credible commitment. In the model being presented here this problem is resolved. There is no *ex ante* commitment by an entrant to limit capacity but there is a credible commitment to its choice of technology, which turns out *ex post* to limit the equilibrium output of the entrant. Our analysis will show that the smaller the market share the entrant needs to cover its set-up costs, the more likely it is that the incumbent will prefer to accommodate rather than deter entry.

The formal analysis is confined to the case in which the DT firms establish a single product mid-way between each pair of FMS base products but our qualitative conclusions extend to cases in which there is more than one DT entrant between each pair of base products.[8] We focus on a central location by the DT firm since this is the location choice that maximizes the FMS firm's post-entry profit and so is most likely to induce the FMS firm to accommodate rather than deter entry.

The FMS first-mover cannot deter entry by replicating the actions of the potential entrants and adopting a mix of technologies, interlacing FMS basic products with DT products.[9] Judd's (1985) analysis now applies. It will not pay the first-mover to defend its DT products against direct attack. The only viable entry-deterring strategy by the FMS firm is to crowd the product space sufficiently that condition $(\alpha_1)$ does not hold. The entry-deterring number of base products is:[10]

$$(7) \qquad n_d^{fm} = t\rho \Big/ 2\sqrt{2K^d(1+\rho)} \, .$$

By contrast, if the first-mover FMS firm chooses to accommodate entry of the DT firm(s) with one DT product between every pair of FMS base products, the optimal number of base products is:

$$(8) \qquad n_a^{fm} = \frac{(\rho+2)}{4}\sqrt{\frac{\rho}{(\rho+1)\left(tK^f + V^2\right)}} \, .$$

8 We feel that the relevant comparison is accommodation/deterrence of entry by multiple DT firms rather than by a single entrant. After all, if entry of a DT firm between one pair of base products is accommodated, why should the FMS firm(s) not anticipate further entry between other pairs of base products?

9 We do not consider the case in which the DT products are established as independent, profit maximizing divisions of the FMS firm(s) since the resulting market structure and prices are identical to those obtained when the entrants are independent single-product firms (Schwartz and Thompson, 1986).

10 See Mathematical Appendix. Further details of these and subsequent calculations can be obtained from the authors on request.

Comparison of $n^0$ and $n_a^{fm}$ over the relevant range of $K^f$ indicates, as we would expect, that $n^0 > n_a^{fm}$. Accommodation of DT entry leads the first-mover to establish less than the socially optimal number of base products. More importantly, equations (7) and (8) indicate that, for given values of $K^f$ and ρ, the profit to the first-mover of deterring entry is an increasing function of $K^d$ whereas the profit from accommodating entry is independent of $K^d$. Entry deterrence will, of course, be preferred if $K^d$ is such that $(\alpha_1)$ "nearly" holds, but there will be a value of $K^d$ below which accommodation will be the preferred strategy. Tedious calculations show that for the FMS first-mover to prefer accommodation to deterrence the following inequality must hold:

$$\text{(9)} \qquad \Delta = \left[\left(1+\frac{\rho}{2}\right)\left(V-\sqrt{\frac{\rho\left(V^2+tK^f\right)}{1+\rho}}\right)\right]-\left[V-\frac{t\left(\rho K^f+2K^d(1+\rho)\right)}{2\sqrt{2tK^d(1+\rho)}}\right]>0$$

where the first term in (9) is profit from accommodation and the second is profit from deterrence. Further tedious calculations show that $\frac{\partial \Delta}{\partial K^d}<0$ and $\frac{\partial \Delta}{\partial V}<0$. Accommodation will always be preferred if the set-up costs of the designated technology are "low enough" or if the consumer reservation price is low.

This relates to our description of the recent growth in small-scale niche manufacturers in a number of sectors. One side effect of the development of flexible manufacturing technologies has been a significant reduction in the manufacturing costs of specialized, low-volume capital equipment. We have the interesting implication that *flexible manufacturing of intermediate capital equipment undermines the ability of flexible manufacturers at later stages in the production chain to deter entry of specialist firms.*

## 4. Technology Switching

Our analysis thus far has considered the choice *between* designated and flexible technologies by firms entering a *new* market. We now turn to a different, but equally important issue: the decision by firms within an *existing* market to *switch* to a flexible technology once it becomes available. An immediate problem arises with this analysis. A switch from DT to FMS may induce some firms to exit the market and/or may not be made by all surviving firms. This breaks down the symmetry upon which the analysis of previous sections relies, making the analysis intractable with *n* firms. As a result, we develop analytical results for a particular example which, while simplified, nevertheless has the merit of highlighting the issues that arise in a more general treatment of firms' decisions to switch technologies.

Assume that the market, which purely for convenience we take to have support [0,3], initially contains three symmetrically located firms operating the designated technology and that this configuration is just entry-proof against entry by a DT firm between each of the existing firms. Given the price equilibria of equation (4) this implies that $K^d/t = 1/4$. Now assume that a flexible technology becomes available to these firms and consider the technology configurations that are likely to arise. In doing so we reinterpret the costs $K^d$ and $K^f$ as fixed rather than set-up costs.

We seek a subgame-perfect equilibrium to a three-stage technology-location-price game between these firms. This requires that we specify the timing of the game. We assume that technology choice is sequential and without loss of generality assume that firm 1 chooses its technology first, firm 2 second and firm 3 last. By contrast, the location and price subgames are each assumed to be simultaneous. This seems not unreasonable given that locations (with FMS) and prices are relatively easy to change but technology is not.

More formally, in the first stage the firms decide sequentially whether to continue with their existing designated technology, switch to the flexible technology or exit the market. We denote the result of this first-stage game by the triple $\mathbf{T} = \{T_1,T_2,T_3\}$, where $T_i$ = D, F or 0 if firm *i* chooses DT, FMS or exit respectively. In the second stage the surviving firms simultaneously choose their locations given the technology configuration established at the end of the first stage. We assume that any firm that does not switch technologies cannot change its location but that a firm which switches to FMS can costlessly re-anchor its base product. The result of this stage is the triple $\mathbf{L}(\mathbf{T}) = \{L_1(\mathbf{T}),L_2(\mathbf{T}),L_3(\mathbf{T})\}$. In the third stage the surviving firms simultaneously choose their prices given the technology and location configurations established in the first two stages.

The price equilibria with technology configuration {D,D,D} are, from (4), $m_i^* = t$ and for {D,D,0} are $m_1^* = m_2^* = 3t/2$. Now consider the mixed technology configurations.[11] With the technology configuration {F,D,0} the FMS firm centers its base product directly opposite the DT product and the Nash equilibrium price for the DT product is $m_d^* = 3r/4$. With mixed technology configurations more complex considerations arise, determined by the nature of the interactions between the firms. For example, with {F,F,D} the FMS firms locate nearer to the DT firm the more flexible is the flexible technology: a high degree of flexibility makes competition between the FMS firms fiercer but gives them a greater cost advantage relative to the DT firm. With the technology configuration {F,D,D} the equilibrium to the price subgame depends upon whether or not the market areas of the two DT firms touch. We also have to consider the possibility (as in Salop, 1979) that there is a corner solution to the price subgame for the DT firms such that the market areas of the two DT firms just touch for a range of values of ρ.

### 4.2 THE TECHNOLOGY CHOICE GAME

The full characterization of the solution to the sequential technology-choice game is given in the Mathematical Appendix. It is illustrated in Figure 2 in which we take ρ and κ as axes: recall that ρ is an inverse measure of the degree of flexibility of FMS and κ is an indirect measure of the fixed-cost penalty of FMS relative to DT.

(Figure 2 near here)

The shaded region in Figure 2 identifies the parameter values for which {D,D,D} is the Nash equilibrium technology choice. The upper boundary of this region is defined by the condition that the first-mover is indifferent between FMS and DT given that its rivals continue to operate DT. This boundary is upward sloping, as expected, for $\rho < 0.5$ and $\rho > 0.694$, implying that a switch from DT is more likely the more flexible is the FMS technology (the lower is ρ). By contrast, the boundary is downward sloping for $0.5 \leq \rho \leq 0.694$, indicating that *decreased* flexibility is likely to induce the switch to FMS in this region.

[11] Details of the solutions to the location and price subgames are omitted but can be found in the Discussion Paper version of this paper (Norman and Thisse, 1997).

This arises because, as we noted above, for these values of ρ the DT firms are at a corner solution in their choice of price, giving rise to perverse comparative statics similar to those found by Salop (1979).

When ρ is "high" (> 0.694) the critical value of κ above which {D,D,D} cannot be an equilibrium is much lower than when ρ is "low" (< 0.5). This is the result of a tension between two forces. When ρ > 0.694 a single firm switching to FMS gains a much smaller market share than when ρ < 0.5. On the other hand, the equilibrium prices for the DT firms with technology configuration {F,D,D} are higher when ρ > 0.694 than when ρ < 0.5, allowing the FMS firm to charge higher prices. The price effect dominates the market share effect.

It is interesting to note that if κ is greater than approximately 0.4 a switch in technology may result if the degree of flexibility is "low" or "high" or if the fixed cost penalty of the flexible technology is "low" or "high". That a high degree of flexibility (low ρ) will favor FMS should be obvious enough. A flexible firm then has such a strong cost advantage with respect to designated rivals that the {D,D,D} configuration is not sustainable, in which case firm 1 exploits its first-mover advantage to eliminate its rivals. That a "high" degree of flexibility has the same effect comes from the perverse comparative statics that apply for 0.5 < ρ < 0.694. The boundary condition determining whether {D,D,D} is sustainable is downward sloping in this interval implying that lower flexibility *raises* the relative profitability of FMS as a result of the equilibrium price response of the designated firms.

The relationship between technology choice and fixed costs has a more straightforward explanation. When the fixed cost penalty of the flexible technology is high, the first mover knows that a switch of technology will lead to sufficient exit of its rivals for the switch to be profitable. By contrast, when the fixed cost penalty of FMS is low (κ high) the fully designated equilibrium may not be sustainable in which case, if the first two firms do not switch technology, then the third firm will. In other words, the first movers are *forced* to switch technologies even though, as we shall see below, this will reduce their profits. Not switching results in an even greater reduction in profit for these firms!

Figure 2 indicates, as we might expect, that the introduction of FMS is more likely to induce exit the more flexible is FMS and the greater is its fixed cost penalty. The configuration {F,F,F}, with all three firms switching to FMS, is an equilibrium for κ > 1/2ρ. In any other situation, a switch to FMS may be partial, with one firm continuing to operate DT, and induces at least one firm to exit the market. "High" flexibility and "high" fixed costs induce more exit in response to a switch in technology by the first-mover.

It is also interesting to note that there is a part of the parameter space for which {F,D,0} is the Nash equilibrium technology choice. This is the type of equilibrium we discussed in section 3. In this region, a switch to FMS by firm 1 would not be profitable if firms 2 and 3 continued to operate. However, firm 1 knows that such a switch will induce the exit of firm 3 while the fixed costs of FMS are sufficiently great that firm 2 will prefer to continue with its designated technology rather than switch.

An important question that Figure 2 leaves unanswered is whether the switch in technology choice is desirable for firms or consumers. Despite the sequential nature of technology choice, it is *not* the case that the switch of technology will necessarily benefit firms. With the technology configuration {F,F,F} the *highest* price that consumers pay is $t.\rho$ while with {D,D,D} the *lowest* price they pay is $t$. In this region of the parameter space the switch of technology unambiguously harms firms and benefits consumers. A similar outcome characterizes the configuration {F,F,0}. The highest price consumers pay is $3t\rho/2$ and the average price is $3t\rho/4$, with the result that consumers on average always benefit from this switch and all consumers benefit if $\rho < 2/3$. The switch to {F,F,0} will increase the surviving firms' profits if and only if $\kappa > 2/(9\rho - 6)$ which cannot hold in the parameter region for which {F,F,0} is a Nash equilibrium. Nevertheless, as we have already noted, the switch in technology in the parameter regions for which {F,F,0} and {F,F,F} are equilibria cannot be avoided. The first movers correctly anticipate that not switching technologies will lead to an even greater loss of profits than switching.

It is only with the technology configurations {F,D,0} and {F,0,0} that we find consumers, in general, losing from the switch in technology. In the configuration {F,D,0} the profits of firm 1 are higher while those of firm 2 (and, of course, firm 3) are lower than with {D,D,D}. It is, however, easy to show that the technology switch lowers aggregate profits. So far as consumers are concerned, the mill price for consumers who purchase from the designated firm is reduced from $t$ to $m_i^*(\rho) = t(3\rho - 1)/2$. As a result, all consumers who buy from the designated firm benefit from the technology switch, as do some who buy from the flexible manufacturer. Since we know that $0.595 < \rho < 0.6$ for this configuration to be a Nash equilibrium, it is only those consumers within a distance of approximately 0.6 of the designated firm who will pay lower prices after the switch in technology. Price is increased for all other consumers. As a result, *both* firms and consumers are worse off in the aggregate with {F,D,0} as compared with {D,D,D}.[12]

The impact of the technology switch is even clearer when the resulting equilibrium is {F,0,0}. Now the surviving firm charges the reservation price $V$ to every consumer and earns profits of $3V - 9t\rho/4 - K^f$. All consumers are worse off while the surviving firm's profits are greater than with the designated technology provided only that $V$ is "high enough".

### 4.3 Possible Extensions

Our discussion can be interpreted as indicating that the availability of a potentially superior flexible technology will not necessarily lead to its being adopted nor need it lead to the elimination of designated manufacturers with FMS becoming the dominant technology. There are at least two further reasons why we should expect to find that industries will be characterized by a mix of firms operating different technologies.

First, if we extend the analysis to more than three firms, the range of parameter values for which a mix of technologies is a Nash equilibrium is likely to increase. As an illustration, assume that the market contains $n_d$ designated firms and that $n_f$ of them switch to FMS. If the flexible firms are evenly spaced a designated firm will continue to operate between any two flexible firms and will prefer to operate DT rather than FMS provided that $\frac{2(1+\rho)}{\rho^2} \leq \left(\frac{n_d}{n_f}\right)^2 \leq \frac{2(1+\rho)}{\rho} \cdot \frac{(1-\kappa)}{\kappa}$. This interval is non-empty provided that $\kappa < \rho/(1+\rho)$ which is a weaker condition than either ($\alpha_1$) or ($\alpha_2$) in section 3.

Secondly, our example imposes a lower limit on fixed costs (specifically, on the ratio $K_d/t$) to ensure that the three-firm configuration is an equilibrium with DT. One of the reasons we don't find a greater incidence of "mixed" equilibria is because of our further assumption that this limit is unaffected by the introduction of FMS. However, as we noted in section 3, an important by-product of FMS has been a reduction in the fixed costs of designated technologies. An immediate implication is that, in a more generalized setting where flexible manufacturing in one sector reduces the fixed costs of specialized manufacturing in others, FMS may initially drive out designated manufacturers but will

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[12] That both consumers and producers lose in the switch from {D,D,D} to {F,D,0} is not contradictory. The total surplus to be distributed is $3V$ minus the fixed costs of the appropriate technology configuration.

subsequently be countered by the entry of new niche firms. It is significant that this is a pattern consistent with the stylized facts presented in the introduction.

## 5. Conclusions

It has been suggested that firms in post-industrial, developed nations must switch to flexible manufacturing techniques if they are to compete with low-cost manufacturers in the fast-growing newly industrializing economies of South-East Asia and China. This requires a radical change in the ways that firms should think about market serving, moving from a concentration on methods that exploit economies of scale to those that exploit economies of scope.

Flexible manufacturing has equally dramatic implications for market structure. If a firm can produce a wide range of differentiated products customized to the desires of heterogeneous consumers it is also able to price these products individually. This implies that a firm can cut prices for one set of its product variants without having to change the prices of the remaining product variants. The ability of the firm to commit to a set of prices is, therefore, weakened and the price regime is much tougher. But this will not necessarily lead to lower prices. A tougher price regime deters entry precisely because incumbents can react to the threat of entry by localized price-cutting without any of the pecuniary externalities that arise with more traditional manufacturing technologies. Whether consumers or firms (or both) will benefit from flexible manufacturing is determined by the interplay between these pro- and anti-competitive effects. The change in the price regime induced by flexible manufacturing provides at least two reasons for thinking that the balance will favor producers rather than consumers. First, it facilitates market segmentation, increasing the profitability of incumbent firms without the fear that this will induce additional entry. Secondly, there is the possibility of market pre-emption by one, or a few firms.

We have to be careful, of course, not to read too much into the redistributive effects of flexible manufacturing. In pure welfare terms, what should concern us are the efficiency properties of the technology: for example, whether equilibrium exhibits too much, too little or the socially optimal degree of product variety. We have seen that there are reasons to believe that flexible manufacturing will be characterized by excessive product variety. First, it seems reasonable to suggest that flexible manufacturing will allow the specification of a base product to be changed, or re-anchored, at relatively low cost.  Low re-anchoring costs increase the number of base products that are necessary if entry is to be deterred, leading to a loss of efficiency. Secondly, we should consider the possibility that entrants can choose to operate a specialized technology, manufacturing niche products.  We have shown that a distribution of base products that will deter flexible manufacturing entry may not deter niche entry. Once again, entry deterrence will require excessive product variety.

The ability to choose between technologies leads to the alternative possibility that flexible manufacturers will prefer to accommodate the entry of niche firms and offer fewer than the socially efficient number of base products.  But then we note that the market will also contain a potentially large number of niche firms.

Somewhat different considerations arise when pre-existing specialized firms are given the opportunity to switch to a flexible technology. Our results shed some light on the so-called ‘productivity paradox’ associated with the information technology (IT) revolution.  According to an aphorism attributed to Robert Solow, ‘you can see computers everywhere but in the productivity statistics’, an observation confirmed by many empirical studies: see also, *The Economist*, September 28, 1996. A recent study (OECD, 1996) suggests that a growing share of IT investment is in product-differentiating rather than cost-reducing technologies. As suggested in the introduction, FMS is a typical example of an IT investment of the former type.  Our model would thus explain why firms may all switch to such a technology while ending up with lower profits.  Such a switch may be forced by competition between the firms but will not necessarily benefit those firms that change technologies: the productivity paradox would then be (at least partially) a consequence of strategic interaction.  Extrapolating from our simplified example, a switch in technology can be expected to increase profits and lead to consumers paying higher prices only if it is partial (with some firms not switching) or if it leads to "significant" exit.

While the range of parameter values for which a mix of technologies is an equilibrium is relatively limited in our example, we have argued that this type of outcome is increasingly likely given that one side-effect of flexible manufacturing has been a reduction in the costs of low-volume, specialized machinery.  We should be looking forward, in other words, to a situation in which manufacturing will not be fully flexible precisely because flexibility in some manufacturing sectors facilitates specialization in others. This is a much more complex scenario in which to formulate competition policy but a much more challenging one for producers, consumers and economists.

## Appendix

*Proof of Proposition 1:*

We provide a proof for the case where the number of designated products is the least packing number. The proof is identical for any other number within the relevant range. Let $\kappa = K^d / K^f$ and $\rho = r/t$. With DT we assume that there are $m^d$ identical firms, each of which owns a number $\mu = n^d/m^d$ of the DT products. The number of FMS base products is less that the number of DT firms if:

(A.1) $$\kappa \cdot \rho < \frac{3\alpha}{2\left(2+\sqrt{3}\right)\mu^2} = 0.401\alpha/\mu^2 \text{, where } \alpha \in [2,6].$$

*Proof of Proposition 2:*

Again, we provide a proof for the case where there is the lowest equilibrium number of designated products. The profit to each (base) product with an interlaced market structure is:

(A.2) $$\pi_\bullet^d = \frac{\left(1+2\sqrt{3}\right)}{3}K^d \text{ ; } \pi_\bullet^f = \left(\frac{\alpha}{2}-1\right)K^f .$$

Aggregate profit over all products is:

(A.3) $$\Pi^d\left(n_{\min}^d\right) = \frac{\left(1+2\sqrt{3}\right)}{\sqrt{6\left(2+\sqrt{3}\right)}}\sqrt{tK^d} \text{ ; } \Pi^f\left(n_\alpha^f\right) = \frac{(\alpha/2-1)}{\sqrt{\alpha}}\sqrt{rK^f} .$$

Total revenue from all products is:

(A.4) $$TR^d\left(n_{\min}^d\right) = \frac{5\sqrt{2+\sqrt{3}}}{2\sqrt{6}}\sqrt{tK^d} \text{ ; } TR^f\left(n_\alpha^f\right) = \frac{3\sqrt{\alpha}}{4}\sqrt{rK^f}$$

and consumer surplus is $V$ - $TR$( ).

It follows that:

i. $\pi_\bullet^f > \pi_\bullet^d \Rightarrow \kappa < \frac{3(\alpha/2-1)}{\left(1+2\sqrt{3}\right)}$;

ii. $\Pi^f\left(n_\alpha^f\right) > \Pi^d\left(n_{\min}^f\right) \Rightarrow \kappa < \frac{6\rho\left(2+\sqrt{3}\right)}{\left(1+2\sqrt{3}\right)^2}\frac{(\alpha/2-1)^2}{\alpha}$;

iii. $CS^f\left(n_\alpha^f\right) < CS^d\left(n_{\min}^d\right) \Rightarrow \kappa < \frac{27\rho\alpha}{50\left(2+\sqrt{3}\right)}$.

*Proof of Proposition 3:*

If entry takes place the entrant will locate mid-way between two base products. There are then three parts to the proof.

*1. Assume that the incumbents have established $n^f$ base products, that re-anchoring costs are zero and that entry occurs mid-way between base products i and i+1. Base product i* ($i$+1) *will be re-anchored mid-way between the entrant and base product i-1* ($i$+2).

We provide the proof for the case $V > 3r/2n^f$: the proof for $V < 3r/2n^f$ has exactly the same structure. The only part of the profit of base product $X_i$ that is affected by its location, given the locations of the entrant $X^e$ and the base product $X_{i-1}$ is the shaded area in Figure A.1. If base product $i$ is located distance $d$ from base product ($i$-1) this area is:

$$A(d) = r.d.\left(3/2n^f - d\right)$$

which is maximized at $d = 3/4n^f$.

(Figure A.1 near here)

2. *If a firm wishes to locate a base product j between any two of its base products $X_i$ and $X_k$ it will locate j mid-way between $X_i$ and $X_k$.*

The proof is identical to 1: merely relabel $X^e$ as $X_k$ and $X_{i-1}$ as $X_i$.

3. *Assume that the incumbents have established $n^f$ base products, and that re-anchoring costs are zero. The equilibrium location configuration in response to entry between base products i and* ($i$+1) *will have the* ($n^f$ + 1) *products equidistantly located.*

Proof follows from 1 and 2.

It then follows immediately that entry will continue until a potential entrant does not perceive the possibility of at least breaking even, given that in the post-entry location configuration the products of the entrant and the incumbents will be equidistantly located. ■

*Proof of Proposition 5:*

Profit of a DT entrant located distance $d$ from the mid-point between any two FMS products is:

(A.5) $$\pi^d\left(x^d \middle| n\right) = \frac{m^d}{t+r}\left(\frac{r}{n} - 2m^d\right) - K^d$$

which is independent of $d$. The profit-maximizing price is $r/4n$. This assumes that $d$ satisfies the constraint:

(A.6) $d \le \rho/4n$ .

Suppose that it does not. Then the profit-maximizing price is ($r/4n$ - $dr/2$) and profit is $\frac{tr^2(2dn-1)^2}{8n\left(t^2 - r^2\right)} - K^d$ which is clearly decreasing in $d$. ■

*Proof of Proposition 6:*

The post-entry market radius of the DT firm is:

(A.7) $$\tilde{x}^d = \frac{r/2n^0 - p\left(X^d\right)}{r+t}$$

and her profit is:

(A.8) $$\pi^d\left(X^d \middle| n^0\right) = 2p\left(X^d\right)\tilde{x}^d - K^d .$$

It follows from (A.7), (A.8) and the definition of $n^0$ that the profit-maximizing price for the DT entrant is:

(A.9) $$m^*\left(x^d \middle| n^0\right) = \frac{r}{4n^0} = \left(\frac{rK^f}{4}\right)^{\frac{1}{2}}$$

and her profit is:

(A.10) $$\pi^{*d}\left(x^d \middle| n^0\right) = \frac{rK^f}{2(r+t)} - K^d .$$

$\pi^{*d}\left(x^d \middle| n^0\right) > 0$ if condition $(\alpha_1)$ is satisfied.

Now consider the possibility that two DT entrants will wish to enter simultaneously between a pair of base products $i$ and ($i$ +1). We can show[13] that they will locate symmetrically about the mid-point between $i$ and ($i$ +1) such that their market areas just touch with delivered price $r/2n^o$. The profit-maximizing price for each DT firm is:

(A.11) $$m^*\left(x_i^d \middle| n^0\right) = \frac{2rt}{n^0(r+7t)}$$

and the entry-deterring condition is:

[13] Details of these and the other calculations can be obtained from the authors on request.

(A.12) $\kappa < \dfrac{8\rho(3+\rho)}{(1+\rho)(7+\rho)^2}$ .

This is tighter than the condition $(\alpha_1)$.

*Deterrence vs. accommodation of DT entrant*:

The profit of a DT entrant if there are *n* FMS base products is:

(A.13) $\pi^d\left(x^d|n\right) = \dfrac{r^2}{8n^2(r+t)} - K^d$ .

Setting this to zero and solving for *n* gives equation (7). Profit if an FMS firm with *n* base products allows DT entry is:

(A.14) $\pi_a^{fm}(n) = V\dfrac{(r+2t)}{2t} - \dfrac{r(r+2t)^2}{16nt(r+t)} - \dfrac{n}{t}\left(tK^f + V^2\right)$.

Maximizing with respect to *n* and solving for *n* gives equation (8).

*Section 4.*

The full characterization of the subgame perfect equilibrium for the first-stage technology game is as follows:

*The subgame-perfect Nash equilibrium technology configuration is:*

*i.* $0 \le \rho \le 0.5$:

{D,D,D} *for* $2/9\rho < \kappa \le \dfrac{1-\rho^2}{2-3\rho+3\rho^3}$;

{F,F,0} *for* $k \ge 2/9\rho$ *and* $\kappa \ge \dfrac{1-\rho^2}{2-3\rho+3\rho^3}$;

{F,0,0} *for* $2/9\rho \ge \kappa \ge 1/(12V-9t)$.

*ii.* $0.5 < \rho \le 0.694$:

{D,D,D} *for* $2/9\rho < \kappa \le \dfrac{(1+\rho)}{(3\rho-1)(3\rho+2)}$ *if* $\rho < 0.595$ *and* $\dfrac{2(1+\rho)}{2+11\rho} < \kappa \le \dfrac{(1+\rho)}{(3\rho-1)(3\rho+2)}$ *if* $\rho > 0.595$

{F,D,0} *for* $0.595 < \rho < 0.6$ *and* $\dfrac{4(1+\rho)}{9(2+\rho)^2} < \kappa < \dfrac{2(1+\rho)}{2+11\rho}$;

{F,F,F} *for* $\kappa \ge 1/2\rho$; {F,F,0} *for* $\dfrac{(1+\rho)}{(3\rho-1)(3\rho+2)} \le \kappa \le 1/2\rho$;

{F,0,0} *for* $1/(12V-9t) \le \kappa < 2/9\rho$ *and* $\rho < 0.595$;

*iii.* $0.694 < \rho < 1$:

{D,D,D} *for* $k \le \dfrac{(1+\rho)(5+\rho)^2}{69+87\rho+31\rho^2-3\rho^3}$;

{F,F,0} *for* $\dfrac{(1+\rho)(5+\rho)^2}{69+87\rho+31\rho^2-3\rho^3} < \kappa < 1/2\rho$;

{F,F,F} *for* $\kappa \ge 1/2\rho$;

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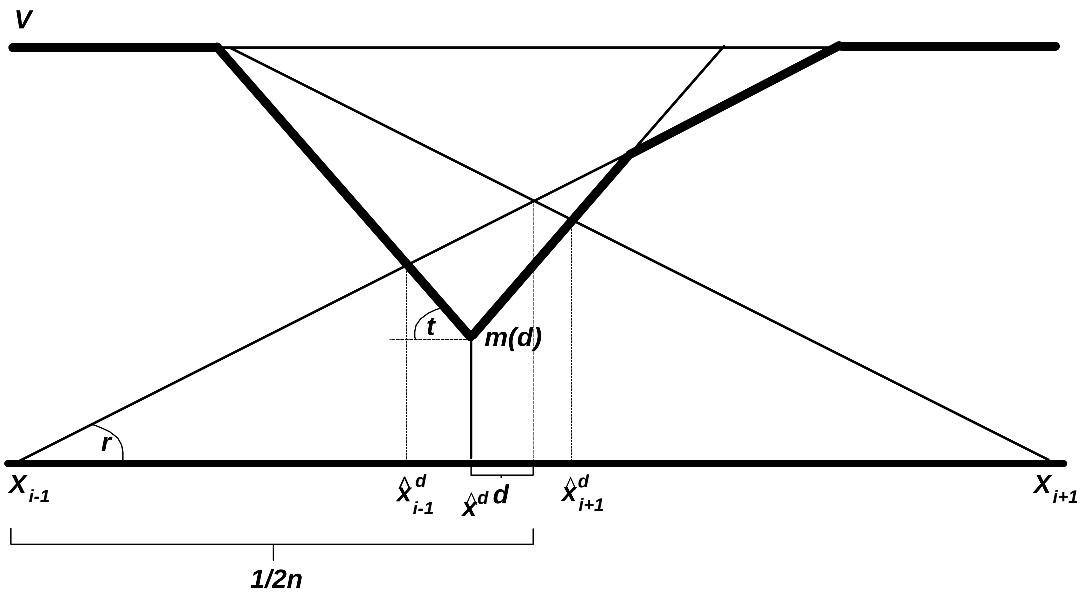


**Figure 1: Entry of a DT firm**

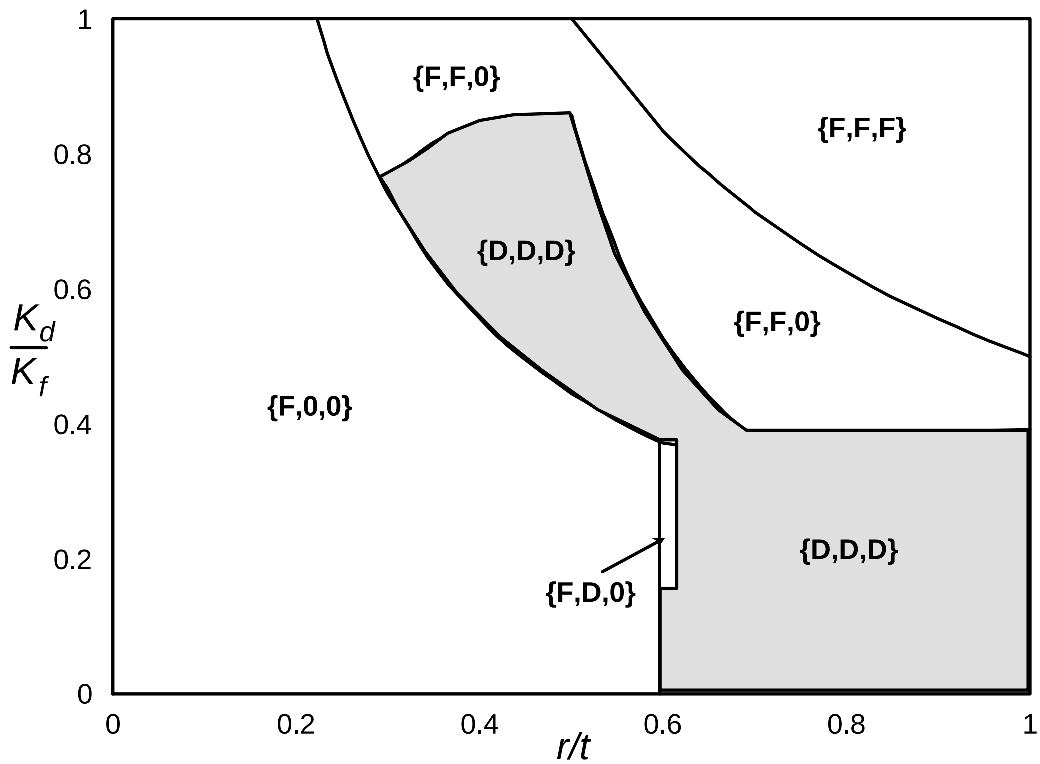


**Figure 2: Equilibrium Technology Configuration -**

**Sequential Technology Choice**

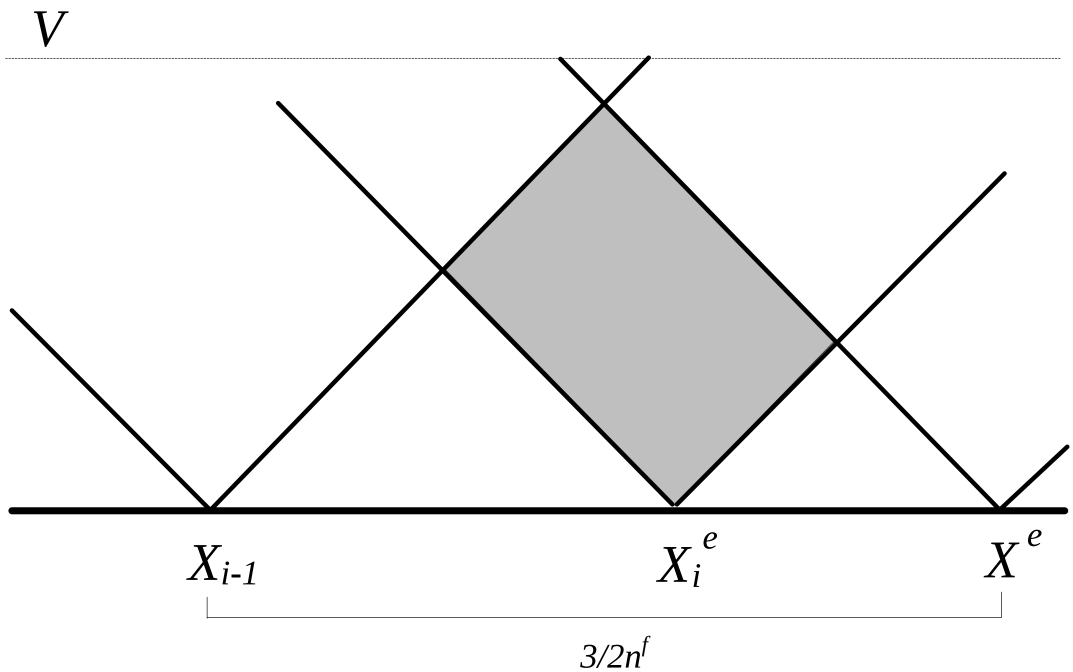


**Figure A.1: Re-anchoring of base product *i***

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