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ABSTRACT

Are Product Innovation and Flexible Technology Complements?

by Astrid Jung *

This paper revises the interdependence between flexible technology and product innovation in the context of a monopolistic firm. Previous literature argued that flexible machinery reduces the cost of incremental innovation. To take interactions beyond the fixed cost into account, we introduce a 2-period optimization model where technology, innovation and price are chosen first, then stochastic demand realizes and, finally, production is carried out. We find that flexibility increases the expected second period gain from incremental innovation in some but not all cases. Thus, the overall profit function need not be supermodular although fixed cost complementarity might be substantial. Empirical evidence from the German mechanical engineering industry suggests that fixed costs complementarity indeed does not outweigh potential adverse effects in expected operational profits.

Keywords: Supermodularity, flexible technology, product innovation, multi-product firms, demand uncertainty, capacity constraints

JEL Classification: C25, D21, D92, L23

ZUSAMMENFASSUNG

Sind Produktinnovation und flexible Technologien komplementär?

Der vorliegende Beitrag überprüft den Zusammenhang zwischen flexibler Technologie und Produktinnovation im Kontext des Monopols. Die bisherige Forschungsliteratur betonte die Eigenschaft flexibler Produktionstechnologie die Kosten für zusätzliche Innovation zu senken. Um Interaktionen über die Fixkosten hinaus zu berücksichtigen, analysieren wir ein Optimierungsmodell über zwei Perioden, in welchem zuerst die Technologie, Innovation und Preis gewählt werden, danach die stochastische Nachfrage eintritt und schließlich die Produktion stattfindet. Es zeigt sich, dass Flexibilität den erwarteten Gewinn der zweiten Periode aus zusätzlicher Innovation nicht immer steigert. Daher muss die Profitfunktion nicht notwendigerweise supermodular sein, selbst wenn die Komplementarität in den Fixkosten erheblich ist. Empirische Belege aus dem deutschen Maschinenbausektor weisen darauf hin, dass die Fixkostenkomplementarität tatsächlich nicht ausreicht um potentiell gegenläufige Effekte aus den erwarteten operativen Gewinnen zu kompensieren.

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1 Introduction

During the last three decades huge advances in (and decreasing prices of) information technology (IT) have severely affected manufacturing and revolutionized the firm at the shop-floor level. This new technology does not only increase the speed and quality of production, but is also capable to handle a greater variety of product designs at lower costs. Simultaneously costumers have shown interest in commodities that fit their individual tastes and that offer a better quality. The observation that higher levels of IT reduce the cost of incremental product improvement suggests that the two decision variables are complements. Complementarity in conjunction with parameters in the firm's environment shifting in a way that promotes either the adoption of high performance technology or innovative activities, would lead to affiliation between the technology mode and innovation in real business.

Beyond the descriptive aspect, complementarity opens an interesting path for innovation policy: if the goal were to stimulate product innovation this could be done indirectly by giving incentives to adopt complementary technologies. Practically this might be a promising approach because product innovation is difficult to measure and therefore difficult to target. Moreover, the efficiency of policies aimed at promoting innovation might be substantially enhanced by decreasing the obstacles to complementary practices.

Complementarity between flexibility and innovation as it has been widely recognized however, focuses entirely on how product innovation and flexibility interact in the fixed costs. In this paper we take a further well-known property of flexible machinery into account which has not yet been related to product innovation: flexibility provides a hedge against uncertain future conditions. That is, investing in flexibility today a firm can increase discretion in later periods when it is better informed about its environment. To relate this idea to product innovation and (product) flexibility[1], consider a company

[1]The paper excludes a discussion of process flexibility and process innovation because neither randomness of demand nor randomness of marginal costs would qualitatively change results derived from fixed costs only.

with a fixed number of products whose prices are announced in a catalogue. Often such a catalogue is printed without information on what quantities costumers will eventually order and hence production has to be adjusted according to incoming requests.

Because capacity is costly and fixed in the short run firms are usually not prepared to produce all possible quantity realizations. However, by adopting flexible multi-tasking technology that can produce a wide range of products, instead of machines that are specialized in a few designs, a firm is more likely able to meet their costumers' demand with a given capacity. Abstracting from variable cost which might differ across technologies, expected profits in the production period will thus be higher for flexible technology. Moreover, due to imposing varying capacity constraints on production, the level of flexibility might affect the probability that additional orders can be complied with. The latter is especially important in the context of this paper as demand enhancing activities like product improvement will actually pay only if the production capabilities of the firm accommodate induced quantity increments.

To formalize this intuition we build a two-period optimization model. First the multi-product firm decides on whether technology should be dedicated or flexible, what capacity the machines shall accommodate, the level of product innovation and a price. At this stage, only the distribution of demand conditional on price and innovation is known and we assume that flexible technology reduces the cost of incremental product improvement. In the second period demand realizes and actual production is conducted subject to demand and capacity constraints. In order to separate the insurance effect of flexibility as clearly as possible we restrict the analysis to product markets with identical characteristics and marginal costs that are constant, equal across products and independent of technology. The only characteristic that distinguishes our multi-variate setting from the notion of a single-product firm is the fact that stochastic demand shocks are not perfectly correlated across products.

Our results are as follows. Production will on average be higher if technology is flexible, because then the capacity constraint applies to the sum of production of variants, whereas dedicated technology imposes one capacity constraint for every single variant. However, the positive effect of incremental product innovation on expected operational profits (sales minus variable costs) is increasing in flexibility only for a limited range of capacity. This is because the probability that additional demand can be complied with is not necessarily greater for flexible technology. This ambiguity is driven by the fact that the probability that additional demand can be complied with is not necessarily greater for flexible technology. Thus, flexible technology may interact positively or negatively with product innovation in the expected operational profits function.

Without further and possibly unrealistic assumptions on the size of the effects we cannot rule out that a potential negative interaction in expected operational profits might be greater than bilateral costs savings in the fixed costs. Only in the limiting case of our model, where the demand distribution is degenerate (i.e. there is no uncertainty), complementarities in the fixed costs and in the demand function lead to complementarities in overall profits and allow unambiguous comparative statics predictions.

To check the empirical relevance of our model we analyze adoption decision of 532 plants of the German mechanical engineering industry in 1992 and 1994. If indeed complementarities stemming from bilateral fixed cost savings were dominant, we should expect the levels of product innovation and flexibility to be affiliated in practice. The data reveals that indeed highly flexible firms significantly tend to adopt more product improvements. However, after controlling for observed heterogeneity affiliation vanishes.

Our arguments shed some new light on the discussion of what Milgrom and Roberts (1990[2] and 1995a) labelled "modern manufacturing". These authors argue that a paradigm shift in the organization and strategy of the firm replaced traditional mass production of the type that had been characterizing manufacturing during the first half of the twentieth century. Their idea is that many features of production, like high skills,

[2] See also the comments on this article by Bushnell/Shepard (1995), Topkis (1995), and the reply by Milgrom/Roberts (1995b) .

worker involvement, frequent product improvement and flexible machines complement each other. Consequently, monotone shifts in complementary exogenous variables like falling costs of flexibility and communication due to the IT revolution and changes in consumer demand not only favored investments in high capability technology and the orientation towards differentiated product lines with frequent changes but also induced adjustments in complementary variables. This work, however, focuses on fixed costs effects and on properties of the deterministic demand function and does not explicitly model randomness of demand.

This applies also to an article by Athey and Schmutzler (1995) who show that complementarity between product and process innovation in the short run can induce complementarity between long-run product and process flexibility if each type of flexibility decreases the cost of the respective kind of innovation. They explicitly allow for a random gain from flexibility which affects the profitability of the short run variables but its realization does not impose any kind of restriction on the feasible choices. In our model the gain from flexibility stems from deviations of the realized demand of different products to opposite directions of their expectation because this determines the extend to which flexible capacity can be shifted among the products. From this comparison it becomes evident that in our approach the realization of uncertain gains from flexibility imposes constraints on the set of feasible decisions (production) to be taken thereafter, whereas it does not in the article of Athey and Schmutzler.

The way we understand gains from flexibility — the firm invests in technology under uncertainty, stochastic demand realizes and production levels are chosen — has been modeled in a single-firm context by Fine and Freund (1990) who give necessary and sufficient conditions to adopt flexible machines. VanMieghem (1998) extended this work by showing that flexibility might pay also in situations where products are perfectly correlated because it allows the order of production to be according to profit margins when capacity is a binding constraint. Epstein (1980) and also He and Pindyck (1992) discuss technology decisions in a framework where uncertainty is not entirely resolved piecewise. Jones and Ostroy (1984) formalize the intuition that the value of a flexible option increases with uncertainty.[3] DeGroote (1994) generalizes this result to the notions of potentially multidimensional flexibility and diversity. All these articles abstract from competition on the product market.[4]

In our paper flexibility will be exclusively defined as the capability of a production technology to support a variety of products and designs. We ignore any dimension of flexibility that results from differences in variable costs (see Stigler (1939), Vives (1989)). For a survey of different notions of flexibility used in the economics and management science literature respectively see Carlsson (1989) and Gerwin (1993) .

The notion of complementary variables can be formalized by using the concept of supermodular objective functions on lattices. It may be thought of as a generalization of differentiable functions exhibiting positive cross partial derivatives.[5] Monotone increases in a parameter vector whose elements are all complementary to every decision variable lead to monotone shifts of the set of maximizers of a supermodular function as established by Topkis 1978 and generalized by Milgrom and Shannon (1994) . This monotonicity property suggests that given such nicely behaved parameter vector, one should observe association between complementary decision variables in the data. The limits of this approach are discussed by Holmstrom and Milgrom (1994) and also Athey and Stern (1998).

Although many empirical investigations have been carried out to test implications and find support for the idea of various aspects of modern manufacturing[6] none has

[3]In an oligopoly context this intuition can be misleading as argued by Vives (1989). He shows that more uncertainty that results from more variable beliefs may decrease the value of flexibility due to interaction in the market. Novshek and Thoman (1999) find that even in monopolized markets optimal flexibility might be decreasing in uncertainty. However, in contrast to most of the literature (including the present paper) where demand uncertainty is understood as variability in demand for products at given prices, they define uncertainty as variability in consumers' types (tastes).

[4]Papers that investigate the impact of an endogenous degree of flexibility on equilibria in oligopoly games include Vives (1986), Vives (1989), Röller and Tombak (1990), Eaton and Schmitt (1994), Norman and Thisse (1999).

[5]For a comprehensive overview see the book by Topkis (1998) and the citations therein.

[6]Examples for studies that assess human recource practices attributed to modern manufacturing are Pil/MacDuffie (1996), Ichniowski/Shaw/Prennushi (1997) and Patibandla/Chandra (1998) . Bresnahan/Brynjolfsson/Hitt (2001) and Parthasarthy/Sethi (1993) devote special attention to the adoption decisions of high performance – and thus flexible – technology. Evidence on what are complementary competences to innovation and whether product and process innovation are complementary

explored whether the adoption of flexible technology favors innovation.

The paper proceeds as follows. In section 2 we first introduce a theoretical model where price announcements are followed by deterministic reactions of the market that make subsequent quantity adjustments unnecessary. This model repeats the reasoning stated in previous literature that fixed costs savings from the joint adoption of practices in conjunction with a supermodular demand function lead to a profit function that is supermodular in all decision variables. We then extend this model to situations where demand is uncertain and quantity adjustments follow earlier price announcements. Because the structure of the fixed costs are unaffected by this change, we will focus on insights at the operational profits level (sales minus marginal costs). Section 3 provides some empirical evidence from adoption decisions in manufacturing. Section 4 concludes.

2 A Model of the Firm

2.1 Model with Deterministic Demand

For later comparisons we will present a non-stochastic version of our model, that involves the decision on flexibility of machinery f, product innovation i, capacity k and price p. Throughout the paper f is assumed to be binary, a value equal to 1 indicating adoption of flexible technology. Some of the definitions and results that are heavily used in what follows are listed in appendix A.

Assume a 2-product firm acting as a monopolist. For simplicity we consider marginal costs c of production that are constant and equal across products and let the product markets be identical in their demand characteristics.[7] Due to this simplifications optimal prices as well as optimal capacities must be the same for both products and we therefore can fully describe the firm's price and capacity choices with scalars p and k.

can be found in Leiponen (2000) and Miravete/Pernias (2000) respectively.

[7]For the discussion of the deterministic demand model we could (without loss) treat the two products as one. A distinction between two products is made only for the sake of consistency with the stochastic version of the model.

Let innovation be an effort that keeps the number of products constant and equally improves the quality of both products. Consumers' demand for each product $j = 1, 2$ can then be denoted by $D_j = D_j(i, p)$ which we assume to be differentiable in i and p with $\partial D_j/\partial p \leq 0$ and $\partial D_j/\partial i \geq 0$ and further, supermodular in (i, p).[8]

Supermodularity of the demand function implies that a price increase will diminish the demanded quantity weakly less if product innovation efforts are high. Supermodularity of the demand function in conjunction with the assumed directions of the first derivatives implies that the price elasticity of demand $(-\frac{\partial D_j}{\partial p}\frac{p}{D_j})$ is decreasing in innovation.[9] Hence, the more a firm improves its products the less sensitive consumers will be to price changes. Total demand for the firm's products will be denoted $D := D(i, p) = 2D_j(i, p)$. This leads to the operational profit function

$$\widetilde{\Pi}(i, p) = (p - c)D(i, p). \tag{1}$$

Total profits Π equal the operational profits minus fixed cost. As is argued by Milgrom and Roberts (1995a), the fixed costs may be characterized by cost savings from the joint adoption of practices in the sense that implementing a higher level of one decision variable gets cheaper at high values of another decision variable. In what follows we repeat the rationale stated by Milgrom and Roberts for savings in the costs of increased product innovation due to a high degree of flexibility.

The fixed costs consist of three components: the cost of capacity γk with γ fixed and independent of technology, the cost of flexibility F and the cost of product innovation I. We say a firm operates under the flexible technology scheme if it can operate all products on a single machine whereas with dedicated technology it needs to possess one machine per product. If the firm invests in flexible technology it will incur a cost

[8] Although we do neither need differentiability nor the cardinal concept of complementarity to assess comparative statics we use the first for its intuitive appeal and the latter because it is easier to verify in the context of the stochastic version of our model. But even under these more restrictive assumptions the stochastic version of the model will be shown to fail the monotonicity property.

[9] A price elasticity that is decreasing in i is equivalent to the log of the demand function being supermodular, or in different words, the demand function is then log-supermodular. This property is sufficient for monotone comparative statics of $(p-c)D_j(i, p)$ and less demanding than D_j supermodular and increasing in i but more difficult to handle once demand is stochastic.

$F = F(f, \omega)$ which depends on a vector of exogenous variables ω and is zero for $f = 0$. Note that in the current setting a firm can never be better off by investing in both types of machines instead of installing only one kind.[10]

The assumptions on the cost of technology are motivated by the fact that IT, which makes machines flexible, has become relatively cheap. Thus, most of the cost difference between flexible and dedicated equipment can be attributed to relatively more expensive adoption (e.g. coordination costs, specific training, need for high skilled operators).

We take the cost of product innovations I to depend on the decision variables i and f and on a parameter vector ω. Product improvements are less costly if they do not require extensive reconfiguration of the production process or extra machinery, i.e. if technology is flexible enough to accommodate changes easily. This suggests complementarity between i and f with respect to $(-I)$. Hence, we assume that $(-I)$ is supermodular in (i, f).

Summarizing the preceding paragraphs, the firm's profit can be written as

$$\Pi := \Pi(i, f, k, p, \omega) = (p - c)D(i, p) - \gamma k - F(f, \omega) - I(i, f, \omega). \tag{2}$$

We are now ready to state the first proposition that derives interactions of the decision variables in the overall profit function from their interactions on either the demand or the fixed cost.

Proposition 1 *Consider the profit function in (2) with* $(i, f, k, p)^T \in R^+ \times \{0, 1\} \times R^+ \times R^+_{p \geq c}$*.Let* ω *be an element of the partially ordered set* Ω*. Suppose that* $D_j(i, p)$ *for* $j = 1, 2$ *is differentiable and supermodular in* (i, p) *and increasing in* i*;* $-I(i, f, \omega)$ *is supermodular in* (i, f) *and has increasing differences in* $((i, f), \omega)$ *and* $-F(f, \omega)$ *has increasing differences in* (f, ω)*. Then*

(i) Π *is supermodular in* (i, f, k, p)*.*

[10] VanMieghem (1998) allows marginal capacity costs to vary with technology and discusses conditions under which firms find it optimal to invest in both, dedicated and flexible technology.

(ii) $\arg\max_{i,f,k,p} \Pi$ *is increasing in* ω.

Proof. See appendix B. ■

As a consequence of proposition 1 we should observe a clustering in the choice of i, f, k and p if the components of ω are associated (i.e. shifts in ω are monotone) and we have controlled for the fixed parameters γ, c and for further individual heterogeneity. Under these circumstances, firms that invest a lot in product improvements will tend to have adopted flexible technology and high prices and vice versa. The monotonicity predicts that firms adjust to changes in parameters which complement all endogenous variables in a coherent fashion, that is, by weakly increasing the level of all decision variables. A complementary parameter to our decision problem could be the skills of potential employees, because high skill levels can be assumed to reduce the cost of adopting flexible technology and make product innovation easier. Another example might be (the negative of) the cost of IT: low IT costs make it more attractive to switch production to the flexible, IT controlled mode (computer aided manufacturing – CAM) and decrease the cost of experimenting with design changes (computer aided design – CAD).

It should be pointed out that, so far, there is no reason to assume a differentiable demand function. Limiting the variability of i and p to discrete changes would affect the proof but none of the implications of proposition 1.[11]

Note further, that we have established supermodularity in k, too. However, as capacity does not interact at all with any other decision variable of our model, supermodularity in k is only weak and neither a strictly positive nor a strictly negative association between k and any other decision variable is predicted. The reason why we have included capacity choice in our model so far is that doing so will be natural in the context of the stochastic model below.

[11] For the proof without differentiability see Topkis (1998), theorem 3.3.3.

2.2 Two-period Model of the Firm with Stochastic Demand

The key feature of the elaborate version of our model[12] is that given price and innovation we allow for two realizations of demand for each product $j = 1, 2$:

$$D_j := D_j(i,p) = \begin{cases} \underline{D} := \underline{D}(i,p) \\ \overline{D} := \overline{D}(i,p) \end{cases} \qquad j = 1, 2.$$

where $\underline{D} \leq \overline{D}$ for each given i and p. We denote the probability that the demand conditional on i and p equals the lower value $\underline{D}$ with δ_0. The joint density function of the identically distributed random variables D_1 and D_2 is fully determined by four free parameters: δ_0, the expectation and standard deviation of the marginal distributions $\mu := E[D_j]$ and $\sigma := var[D_j]$ and the correlation coefficient ρ. We will assume that expected demand is a function of price and innovation, $\mu = \mu(i,p)$ whereas the uncertainty parameter σ is not affected by these variables. Changes in price or the level of product innovation will thus shift the probability function along the horizontal axis maintaining its shape.

Imposing random realizations instead of deterministic demand allows us to analyze a key property of flexible technology, namely its capability to shift capacity among products[13]. Clearly, if there is no uncertainty this can hardly be an advantage compared to dedicated technology. Total capacity would then be chosen to equal the demand for all products. With uncertainty a firm can only make use of capacity shifting, if they can adjust production after demand has realized. This suggests to split the firm's decision into two periods as has been done by VanMieghem (1998): in the first period demand will be uncertain and the firm decides on the level of i, f, k and p. Then demand realizes and actual production $y = (y_1\, y_1)^T$ is chosen. Note that no direction of the correlation between the demand shocks is primarily assumed, thus we incorporate situations where the interdependence of the product demands is mostly influenced by macro shocks (like one that increases income of the whole economy) as well as settings

[12] To safe notation, functions in the current model are named in the same way as in section 2.

[13] Throughout we will ignore the quantitative dimension of flexibility and rather treat the capacity as a generally binding constraint to production. This is, we assume marginal cost of production being infinite above the capacity level.

where these macro shocks are outweighed by omitted demand drivers that hit the two markets differently.

Firms are risk neutral and hence they maximize expected profits

$$\begin{aligned} E\Pi \ : \ &= E\Pi(i,f,k,p,y,\delta_0,\sigma,\rho,\omega) = E\widetilde{\Pi}(D(i,p,\delta_0,\sigma,\rho),f,k,y,c) \\ &-I(i,f,\omega) - \gamma k - F(f,\omega), \end{aligned} \tag{3}$$

with c and γ fixed as above and variable parameters δ_0, σ, ρ and the vector of omitted exogenous variables ω.

After demand has realized, the firm faces the optimization problem

$$\begin{aligned} \max_y \quad & (p-c)\sum y_j \\ \text{s.t.} \quad y_j \ &\leq \ \frac{1}{2}k \qquad \text{if } f=0, \\ \sum y_j \ &\leq \ k \qquad \text{if } f=1, \\ y_j \ &\leq \ D_j. \end{aligned} \tag{4}$$

It is quite intuitive, that for a given k the capacity constraint is less likely to be binding in the flexibility case because then every capacity unit is multifunctional. Optimal values of production are in either case straightforward: if technology is dedicated ($f = 0$), the optimization is done for each product independently. The firm will for each $j = 1, 2$ produce the minimum of the demand D_j and the capacity $\frac{1}{2}k$. In the case of $f = 1$, optimization is done simultaneously for both products. Total production will then equal the minimum of total demand ΣD_j and total capacity k. This rule unambiguously determines the levels of y_j. Expected operational profits including second period maximization are thus

$$E\widetilde{\Pi}_y^* := E\max_y \widetilde{\Pi} = \begin{cases} (p-c)\sum E\min(D_j,\frac{1}{2}k) & \text{for } f=0 \\ (p-c)E\min(\Sigma D_j,k) & \text{for } f=1 \end{cases}. \tag{5}$$

Given capacity and realized demand, the optimal quantity vector is not influenced by any parameters. As a consequence, if we want to assess comparative statics of our model it comes without loss of information and is thus sufficient to consider the profit function where quantity is already maximized for.

Equation (5) can be rewritten as

$$E\widetilde{\Pi}_y^* = \begin{cases} (p-c)\left\{2E\left[D_j|\Xi_0\right]\Pr\left(\Xi_0\right) + k\left[1-\Pr\left(\Xi_0\right)\right]\right\} & \text{for} \quad f=0 \\ (p-c)\left\{2E\left[D_j|\Xi_1\right]\Pr\left(\Xi_1\right) + k\left[1-\Pr\left(\Xi_1\right)\right]\right\} & \phantom{\text{for}} \quad f=1 \end{cases}, \qquad (6)$$

where Ξ_0 and Ξ_1 denote the events of having demand as the only binding constraint, that is, $D_j < \frac{1}{2}k$ and $\Sigma D_j < k$ respectively.

Equation (6) does not involve any distributional assumption so far. However, inspection of the second line reveals what difficulties would be involved by assuming some general distribution for demand: given we know the marginal distribution of D_j there are no general results concerning the distribution of the sum of such random variables even if they are identically distributed[14]. Even worse, we do not know whether the marginal distribution of D_j conditional on Ξ_1 behaves nicely, namely, whether it has an expectation. And although we can give an explicit formula[15] for the probability of Ξ_1 this will not be differentiable in the demand shifters i and p even if distributions are continuous. It is for these reasons that we apply a two-dimensional two-point distribution and thus stick to the simplest possible model of random demand. By doing so we can easily compute the joint and conditional marginal distributions and identify regions in which differentiability is ensured.

Using the definitions of mean, variance, correlation and marginal probabilities it is straightforward to derive the joint probabilities $\delta_{00} = \rho\left(\delta_0 - \delta_0^2\right) + \delta_0^2$, $\delta_{11} = \delta_{00} + 1 - 2\delta_0$ and $\delta_{10} = \delta_{01} = \delta_0 - \delta_{00}$ with the j-th index equal to zero if $D_j = \underline{D}$ and equal to one for $D_j = \overline{D}$ $(j = 1, 2)$. Note, that by definition $\delta_{00} \in [0, \delta_0]$. Table 1 displays the probability that demand is binding and, given it is, the expected demand in the respective settings for dedicated and flexible technology.

[14]Remember that although the random variables are identically distributed we want to allow for correlation between them.

[15]For two continuous random variables x and y with joint density h on support $[a,b]^2$ we have

$$\Pr[x + y \le k] = \int_a^c \int_a^d h(x,y)dxdy$$

with $c = \min(k-a, b)$ and $d = \max(a, \min(k-y, b))$.

case	condition	$\Pr(\Xi_0)$	$E[D_j \vert \Xi_0]$	$\Pr(\Xi_1)$	$E[D_j \vert \Xi_1]$
I	$k \leq 2\underline{D}$	0	/	0	/
IIa IIb	$2\underline{D} < k \leq \underline{D} + \overline{D}$ $\underline{D} + \overline{D} < k \leq 2\overline{D}$	δ_0	$\underline{D}$	δ_{00} $1 - \delta_{11}$	$\underline{D}$ $\underline{D}\frac{\delta_{00}}{1-\delta_{11}} + \frac{1}{2}\left(\underline{D} + \overline{D}\right)\frac{2\delta_{10}}{1-\delta_{11}}$
III	$2\overline{D} < k$	1	μ	1	μ

Table 1: Probability that demand is a binding constraint to production and expected demand given demand is binding.

Plugging the results from table 1 into equation (6) leads to

$$E\widetilde{\Pi}_y^*(f=0) = \begin{cases} (p-c)\,k & \\ (p-c)\left[2\delta_0\underline{D} + (1-\delta_0)\,k\right] & \text{for} \\ (p-c)\,2\mu & \end{cases} \begin{matrix} \text{I} \\ \text{IIa,b} \\ \text{III} \end{matrix} ,$$

$$E\widetilde{\Pi}_y^*(f=1) = \begin{cases} (p-c)\,k & \\ (p-c)\left[2\delta_{00}\underline{D} + (1-\delta_{00})\,k\right] & \\ (p-c)\left[2\left(\delta_0\underline{D} + (\delta_0 - \delta_{00})\,\overline{D}\right) + (1 - 2\delta_0 + \delta_{00})\,k\right] & \text{for} \\ (p-c)\,2\mu & \end{cases} \begin{matrix} \text{I} \\ \text{IIa} \\ \text{IIb} \\ \text{III} \end{matrix} . \tag{7}$$

Although the function $E\widetilde{\Pi}_y^*$ is not differentiable over its entire range it is continuous as can be checked by plugging in the case boundary conditions.

Note, that given positive costs of increasing capacity and product improvement efforts, no profit maximum would ever involve capacity and product innovation and price such that k lies outside $\left[2\underline{D}, 2\overline{D}\right]$, the support of ΣD_j and $2D_j$. If there were an optimal decision leading to $k < 2\underline{D}$, the firm could decrease its product improvement efforts or increase the price of the products without affecting production, because capacity is a binding constraint to production with probability one. Similarly, $2\overline{D} < k$ cannot be optimal, because the firm could save capacity costs without decreasing revenues. Keeping this in mind we will focus on cases IIa and IIb for further discussion although all statements to appear below apply equally — at least in a qualitative way — to cases outside this range[16].

[16]The case $k = 2\underline{D}$ should, of course, not be excluded. For the sake of calculating $E\widetilde{\Pi}_y^*$ it can be incorporated into the case $2\underline{D} < k \leq \underline{D} + \overline{D}$ because $E\widetilde{\Pi}_y^*$ is continuous.

2.3 Analysis of the Extended Model

We proceed by analyzing the impact of the endogenous variables on the expected profit function (7) and derive thereafter whether they are complements. The key question is how the presence of technology dependent constraints to production alters the incentives to invest into additional capacity and product innovation.

Our strategy to derive whether the decision variables i, f, k and p are complements is to check their interactions in each part of the profit function and then use the summation property of supermodular functions. Complementarities in the fixed costs are assumed to exist as in the preceding section. Because the set of feasible actions is a finite product of chains in our model it suffices to establish pairwise complementarity. Hence, the profit function is supermodular if and only if it is supermodular in any subset of decision variables.

First order effects are discussed in the beginning because they reveal important properties of the model which are helpful for the understanding of the interaction results.

The expected gain in operational profits from using flexible versus dedicated machines is the difference

$$E\widetilde{\Pi}_y^*(f=1) - E\widetilde{\Pi}_y^*(f=0) = \begin{cases} 0 & \\ (p-c)\,(\delta_0-\delta_{00})\,(k-2\underline{D}) & \\ -(p-c)\,(\delta_0-\delta_{00})\left(k-2\overline{D}\right) & \\ 0 & \end{cases} \quad \text{for} \quad \begin{matrix} \text{I} \\ \text{IIa} \\ \text{IIb} \\ \text{III} \end{matrix}\;. \tag{8}$$

Retrieving that the joint probability δ_{00} cannot be greater than the marginal probability δ_0 and using further $2\underline{D} < k \leq \underline{D} + \overline{D}$ in the second and $\underline{D} + \overline{D} < k \leq 2\overline{D}$ in the third line of equation (8), it can easily be seen that $E\widetilde{\Pi}_y^*(f=1) - E\widetilde{\Pi}_y^*(f=0) \geq 0$. This leads to our first lemma:

Lemma 1 *Using flexible instead of dedicated technology cannot lead to lower profits in the production period.*

The superiority of flexibility in the production period reveals clearly that our model captures the idea of using flexibility as a hedge against risky demand as stressed in the introduction. We would also expect that the higher uncertainty about demand — i.e. the greater the standard deviation σ in our model — the higher the expected gain from operating under the flexibility scheme. To check this, we want to vary $\underline{D}$ and $\overline{D}$ in a way that keeps the mean but not the variance constant. Solving the definitions of μ and σ for the upper and lower realization and using that $\underline{D} \leq \overline{D}$ of demand yields

$$\underline{D} = \mu - \sigma\sqrt{\frac{1-\delta_0}{\delta_0}} \qquad \text{and} \qquad \overline{D} = \mu + \sigma\sqrt{\frac{\delta_0}{1-\delta_0}}. \tag{9}$$

Inserting (9) into (8) above reveals that $E\widetilde{\Pi}_y^*(f=1) - E\widetilde{\Pi}_y^*(f=0)$ is indeed increasing in σ.

The notion of flexibility in this paper suggests further, that the more positively correlated demands of the two products are (and thus, the greater δ_{00} and δ_{11} for a given marginal probability δ_0), the scarcer the situations in which flexible firms can shift capacity between the products. This can be seen to hold in our model as $E\widetilde{\Pi}_y^*(f=1) - E\widetilde{\Pi}_y^*(f=0)$ is decreasing in δ_{00}. Because neither σ nor ρ affects the fixed costs their influence on the profitability of flexible technology at the production stage directly translates to overall profits as stated in lemma 2.

Lemma 2 *The gain from flexibility is nondecreasing in demand risk and nonincreasing in demand correlation.*

Before we discuss how decision variables other than f affect profits a few remarks on the demand shifters i and p are in order. Throughout the paper we assumed that demand is supermodular in price and innovation. In the current context we thus have $\partial^2\underline{D}/\partial i\partial p \geq 0$ and $\partial^2\overline{D}/\partial i\partial p \geq 0$ but neither the direct effect of i and p nor the cross partials need to be of the same magnitude for the upper and lower demand realization to ensure that also expected demand is supermodular in i and p. However, in order to separate changes in profits due to variation in μ from those due to variance shifts it is useful to assume that marginal effects on $\underline{D}$ and $\overline{D}$ are of the same size and thus equal to $d\mu$, such that σ remains at its initial value.

Intuitively, the impact of intensified innovation or enlarged capacity on expected operational profits consists of two effects. First, there is an upward shift in expected production due to either higher expected demand or enhanced capability. Second, the probability that demand is a binding constraint to production will change at the case boundaries. From (7) it is easily seen that $E\widetilde{\Pi}_y^*$ is upward sloping with respect to i and k.

Figure 1 shows for the case with flexible technology how the magnitude of the change of $E\widetilde{\Pi}_y^*$ in μ and k depends on the size of k compared to μ. The effect of changes in demand is positive and greater in magnitude for high values of $(k - 2\mu)$. This is consistent with intuition because more slack capacity will better accommodate additional demand. Accordingly, intuition suggest, that the operational gain from additional capacity should be decreasing in slack capacity $(k - 2\mu)$, because capacity is then less often needed to comply with demand. This can be seen from figure 1 to hold in our model.

A price increase affects expected operational profits in two ways. It reduces expected demand but on the other side it boosts operational profits from every item that is finally produced. The latter results in an upward shift of the graphs in figure 1. Without further assumptions on the magnitude of this demand effect, on σ and on ρ the price effect is not determined in sign. Lemma 3 summarizes the results on the first-order effects of i, k and p.

Lemma 3 *Expected operational profits ($E\widetilde{\Pi}_y^*$) are nondecreasing in product innovation and capacity and increasing or decreasing or non-monotone in price. Gains from product innovation are nondecreasing in slack capacity ($k - 2\mu$), whereas expected revenues from additional capacity are nonincreasing in $k - 2\mu$.*

To check whether $E\widetilde{\Pi}_y^*$ exhibits complementarity in f, i, k and p we will now discuss how each of these variables changes the first order effect of the remaining decision variables. By inserting (9) into the operational profits in (7) and using $\partial^2\mu/\partial i\partial p \geq 0$ and $\partial\mu/\partial i \geq 0$ it is straightforward to see that $\partial^2 E\widetilde{\Pi}_y^*/\partial i\partial p \geq 0$ where it exists. The upper graph in figure 1 illustrates that indeed the complementarity relationship between i and p in the expectation of demand is translated into complementarity in the function $E\widetilde{\Pi}_y^*$, over the whole range of its support. Note, that a price increase leads to a rightward shift on the abscissa (μ is decreasing in p) and shifts the graph upwards. Intuitively, because μ is supermodular in i and p, an increase in price always boosts the demand gain from improving products and also (at the boundaries indicated in the graph) the probability that the additional demand can be produced and, eventually, the net profit from producing an item.

From the lower graph in figure 1 we see that a higher price (i.e. lower μ) decreases the probability that additional capacity is used in production once the case boundaries are passed. However, there is also a potential for p interacting positively with k, because, whenever additional capacity is used, it pays more when price is high. Thus, a higher price would lead to an upward shift of the graph. Without further assumptions the net effect of price on marginal changes of capacity is undetermined.

Lemma 4 summarizes the interactions of k and i with price.

Lemma 4 *The gain in expected operational profits due to a higher level of product innovation is nondecreasing in price* ($\frac{\partial^2 E\widetilde{\Pi}_y^*}{\partial i \partial p} \geq 0$)*. The effect of a price increase on the expected operational gain from additional capacity is undetermined* ($\frac{\partial^2 E\widetilde{\Pi}_y^*}{\partial k \partial p} \gtreqless 0$)*.*

We argued above that, as long as product demands are not perfectly positively correlated, there is a potential gain from being able to shift capacity among the products, i.e., $E\widetilde{\Pi}_y^*(f = 1) - E\widetilde{\Pi}_y^*(f = 0)$ cannot be negative. But how is this gain influenced by other decisions of the firm? Figure 2 displays the gain in operational profits from flexible machinery as a function of expected demand and capacity. Using that higher innovative activity would shift μ to the right, the flexibility gain is increasing in μ and thus in i at low values of μ (case IIb, holding capacity constant) and decreasing for high values (case IIa). Thus, neither (f, i) nor $(f, -i)$ are complements in the function $E\widetilde{\Pi}_y^*$. This is not a surprise: remember that the marginal effect of μ is simply $(p - c)\Pr(\Xi_0)$ for dedicated and $(p - c)\Pr(\Xi_1)$ for flexible technology because within the case boundaries demand changes leave the probability that demand is a binding constraint constant. From the discussion of table 1 we know that $\Pr(\Xi_0) \geq \Pr(\Xi_1)$ in case IIa and $\Pr(\Xi_0) \leq \Pr(\Xi_1)$ in case IIb.

The fact that the probability that demand is binding is not strictly greater for one of the two technologies is not a result of the distributional assumption we made here. To see this, recall $\Pr(\Xi_0) = \Pr\left(D_j < \frac{1}{2}k\right) = \Pr(2D_j < k)$ and $\Pr(\Xi_1) = \Pr(\Sigma D_j < k)$. Irrespective of the distribution of D_j the random variables $2D_j$ and ΣD_j are defined on support $[2\underline{D}, 2\overline{D}]$, have the same mean, but $var(2D_j) \geq var(\Sigma D_j)$. Let the distributions of $2D_j$ and ΣD_j be G and H respectively. For some small value ε we have

$$\begin{aligned} G(2\underline{D}+\varepsilon) &\geq H(2\underline{D}+\varepsilon) \qquad \text{and} \\ G(2\overline{D}-\varepsilon) &\leq H(2\overline{D}-\varepsilon), \end{aligned}$$

because for the sum to realize some value in the interval $[2\underline{D}; 2\underline{D}+\varepsilon]$ it takes both random variables D_j, $j = 1, 2$ to realize very close to the lower bound, which cannot happen with greater probability than the event that the realization of a single D_j is near $\underline{D}$. Equivalently, ΣD_j will less frequently be close to the upper bound of the support than $2D_j$.

Given this very general property which equally applies to settings with more than two products, we must have some region of the support where $\Pr(\Xi_0) \geq \Pr(\Xi_1)$ and also some region where $\Pr(\Xi_0) \leq \Pr(\Xi_1)$. As a consequence, within the regions where $\Pr(\Xi_0)$ and $\Pr(\Xi_1)$ do not react to changes of demand, the interaction between innovation and flexibility in operational profits equals $(p-c)2\frac{\partial \mu}{\partial i}[\Pr(\Xi_1) - \Pr(\Xi_0)]$ and that between capacity and flexibility equals $(p-c)[\Pr(\Xi_0) - \Pr(\Xi_1)]$. Each of these terms will be positive for some cases and negative for others, irrespective of the distribution of D_j.[17]

The result that neither (f, i) fail to be complements in the function $E\widetilde{\Pi}_y^*$ can be understood intuitively by comparing the gains from innovation across the two technological regimes: For "small" changes (i.e. within the boundaries of the cases above) the

[17]At this point it should be repeated, that the analysis could not be done for general continuous distributions due to the difficulties involved with differentiating the marginal expectation given a constraint on the sum of dependent random variables. Of course, the statements about whether $\Pr(\Xi_0)$ exceeds $\Pr(\Xi_1)$ remain true in the continuous case.

shift in expected production given that demand is the binding constraint is invariant to flexibility such that it is sufficient to compare the probability that demand is actually constraining production (i.e. the probability that innovation actually results in a sales boost). The fact that the probability of the sum has less probability weight on the tails than the expanded marginal distribution translates into a relatively smaller probability that demand is binding for flexible technology if k is sufficiently small. If k is sufficiently large, it is less likely for total demand than the expanded single demand to be even greater than k and thus the expected gain from innovation will be greater for flexible technology.

Note that, whenever flexibility increases the returns (in terms of $E\widetilde{\Pi}_y^*$) from higher innovation it must decrease the gains from extra capacity, as the capacity and demand constraints are binding with complementary probabilities. This can easily be verified in figure 2. Lemma 5 states our results on how the choice of the technology type affects gains from additional capacity and innovative efforts at the production stage.

Lemma 5 *Operational gains from product innovation are nonincreasing (nondecreasing) in the degree of technological flexibility for low (high) values of* $k-2\mu$. *The marginal effect of capacity, is nondecreasing (nonincreasing) in the degree of technological flexibility for low (high) values of* $k-2\mu$. *Furthermore, whenever flexibility with respect to operational profits* $E\widetilde{\Pi}_y^*$ *is a complement to product innovation it is a substitute to capacity and vice versa. For any number of products whose demand conditional on price and innovation is a random draw from the same discrete marginal distribution we have that flexibility complements capacity (product innovation) but substitutes product innovation (capacity) at sufficiently low (high) values of* $k-2\mu$.

Again, the price effect on $E\widetilde{\Pi}_y^*(f=1) - E\widetilde{\Pi}_y^*(f=0)$ is more difficult to determine. As a higher price decreases demand its effect on the flexibility gain should be opposite to that of a higher level of innovation. But, unlike in the case of changing i, price has also an effect on the slope of the graph: if the probability of the constraints Ξ_0 and Ξ_1 remains unchanged (i.e. within the cases IIa and IIb) a higher price increases the per

Â	i	p	k	f
i	Â	$+$	$+$	$-$ $+$
p		Â	?	$+$?
k			Â	$+$ $-$

Table 2: Bilateral interactions in $E\widetilde{\Pi}^*_{\mathsf{y}}$.

unit value of flexible technology. In sum, as stated in lemma 6, the effect of price on $E\widetilde{\Pi}^*_y(f=1) - E\widetilde{\Pi}^*_y(f=0)$ is nonnegative at $\underline{D} + \overline{D} > k$ (case IIa) and undetermined elsewhere.

Lemma 6 *With respect to expected operational profits ($E\widetilde{\Pi}^*_y$) flexible technology and price are complementary for small values of $(k - 2\mu)$. Outside this range their interaction is undetermined.*

The discussion of figure 2 reveals the advantage of assuming differentiability of expected operational profits in i, p and k: allowing for discrete changes in these variables would lead to the possibility of switching between cases IIa and IIb and hence, further complicate the discussion. In a qualitative sense, however, our results would remain unchanged.

We summarize our results visually in table 2. The signs "+" and "-" denote respectively a nonnegative and a nonpositive interaction of two decision variables with respect to $E\widetilde{\Pi}^*_y$, the question mark stands for interactions that we cannot derive in their sign. In cases where one sign does not apply to the whole range of the support the upper value is valid for $\underline{D} + \overline{D} \geq k$ and the lower for $\underline{D} + \overline{D} \leq k$.

As becomes evident from table 2, $E\widetilde{\Pi}^*_y$ is not supermodular in (i, f, k, p), because irrespective of assumptions that can be made to determine missing bilateral interactions and of the optimal values of k, $\underline{D}$ and $\overline{D}$ there is no unique direction of the interactions.

Note, that given linear capacity costs as we have assumed so far, there is no interaction of f and k in the fixed costs that could outweigh their potential negative interaction in the expected operational profits $E\widetilde{\Pi}_y^*$. Taking the fixed costs into account will also not help to overcome the ambiguities of table 2 where price is involved. A potential negative interaction between innovation and flexibility, however, might be overcompensated by fixed cost savings of their joint adoption.

Proposition 2 summarizes the results from the discussion of the stochastic model.

Proposition 2 *Consider the function of expected profits* $E\Pi$ *in (3) and the second period optimization problem (4) with* $(i, f, k, p)^T \in R^+ \times \{0, 1\} \times R^+ \times R^+_{p \geq c}$. *Suppose that* $D_j(i, p)$ *for* $j = 1, 2$ *is differentiable and supermodular in* (i, p) *and increasing in* i; $-I(i, f, \omega)$ *is supermodular in* (i, f). *Then the following holds with respect to the function* $E\Pi$

(i) i *and* p *are complements.*

(ii) i *and* k *are complements.*

(iii) f *and* k *are neither complements nor substitutes.*

(iv) i *and* f, f *and* p *as well as* k *and* p *might be complements or substitutes or neither.*

(v) i *and* f *are complements if their complementarity with respect to* $-I(i, f, \omega)$ *is sufficiently strong.*

Proof. *Follows directly from lemmas (3)-(6) and the summation property.* ■

The analysis in this paragraph illustrates that the slight change in the model structure due to the introduction of uncertainty of demand has a substantial impact on complementarity even though uncertainty was set up in a way that conditions for optimality in the extended model converge for sufficiently small uncertainty to those of the basic model in section 2.1.[18] Thus, the limiting case of the stochastic model indeed

[18] To derive this recall that any optimally chosen capacity, price and innovation effort must ensure $k \in \left[2\underline{D}, 2\overline{D}\right]$. If the risk approaches zero ($\overline{D} - \underline{D} \to 0$) we must have $k \to S$ for optimality. Or, in words, maximizing behavior under certainty allows for neither capacity nor demand slack.

leads to an overall profit function that is supermodular as proposed by existing literature. However, the slightest demand uncertainty destroys the system of complementary decision variables.

Although the decision variables of our model fail to be complements, they could still meet the conditions of the monotonicity theorem in appendix A. To have a set of maximizers that is increasing in complementary parameters the payoff function only needs to satisfy the weaker concept of quasisupermodularity. Quasisupermodularity is more demanding to check (see Milgrom and Shannon (1994) for details). However, with differentiability we can investigate whether, as a direct consequence of the monotonicity property, all first order conditions are nondecreasing in all other decision variables. This is done by plugging in as many FOCs as necessary for sign determination into a given cross partial of the profit function. In our model this procedure does not lead to any new information. Hence, without further assumptions on the strength of interactions in fixed costs and operational profits we cannot conclude that increases in parameter values that lead to the adoption of flexible technology would eventually stimulate product innovation.

This means for example, that even though price and innovation have a positive direct interaction, they may shift to opposite directions after monotonic parameter shifts. To see this, consider an example where for the optimal decision of firm 1 we have $\underline{D} + \overline{D} > k$ (case IIa) and $f = 1$. Another firm faces lower product improvement costs and might therefore opt to engage more in innovation than firm 1. This will in turn make higher prices more profitable than for firm 1, but additionally shrinks the expected gain from flexible technology. If, as a result, $f = 0$, a lower price compared to firm 1 might be optimal.

What we can actually gain from comparative statics reasoning is some economic interpretation of the relationship between innovation and flexibility: Imagine extra capacity is sufficiently cheap but not without cost (i.e. γ is small but greater than zero), such that in optimum a firm will have a high capacity compared to expected demand. Hence, it will rarely face situations were demand cannot be met due to capacity restrictions. Then a change in exogenous variables that promotes the adoption of flexible technology will also unambiguously shift the optimal level of product innovation upwards, because at a sufficiently large k relative to μ the probability that additionally generated demand can be complied with is larger for flexible than for dedicated technology. On the other hand, high values of γ might induce the capacity constraint to be frequently binding and therefore lead to the case were a negative interaction between product innovation and flexible technology at the production stage outweighs their fixed costs complementarity. Note however: if γ converges to zero, the incentive to invest into the more expensive flexible technology vanishes, as the firm can then afford to buy a lot of dedicated machines — although it will almost never fully employ it — and therefore cannot gain from the capacity shifting a flexible technology would allow for.

3 Empirical Evidence

3.1 Methodology

Before specifying estimation equations some remarks on measuring complementarity among variables are in order. The attempts to test for complementarity conducted by the literature follow two main directions. The first alternative is to estimate the decision maker's objective function[19]. If the decision variables are indeed complements, their interaction terms in the objective function should be positive and significant. This approach can in principle give very useful understanding of how strong the interaction between endogenous variables is. However, one needs to know what exactly decision makers maximize which is not necessarily profits in case of firms. Even if one beliefs to know this, it might turn out to be very difficult or impossible to get data on the objective.

[19]Examples for empirical studies following this approach include Bresnahan/Brynjolfsson/Hitt (2001), Ichniowski/Shaw/Prennushi (1997), Leiponen (2000), Parthasarthy/Sethi (1993) and Patibandla/Chandra (1998). Beresteanu (2000) introduces nonparametric techniques for the estimation of supermodular objective functions.

The second approach taken in the literature[20] builds on implications of Topkis' (1978) monotonicity theorem: given a system of complementary decision variables and a vector of complementary parameters that are exogenous to the optimization problem, monotone shifts in the parameter vector imply monotone reactions of the set of arguments that maximize the objective. Empirically the requirement of monotone shifts means that variables should be correlated, or, more generally, associated[21] (Holmstrom and Milgrom 1994). Thus, complementary practices are expected to be associated (unconditional association). Of course, in real life problems, parameters might not move monotonically and there are often relevant exogenous variables which are not complementary to all endogenous variables. In this case, one must control for these potentially troublesome variables and test for dependence in the residuals (conditional association).

The association approach has the advantage that researchers do not need to know what the objectives of the decision makers are and with what functional form it can be approximated. The cost for the less demanding data requirements is that the estimation will not give indications of the direct effect of the decision variables on the objective. Further, strong positive association between decision variables (or between their residuals if some variables are controlled for) may not be interpreted as particularly strong complementarity as part of it may be due to association in the driving exogenous variables that were not controlled for. We might even find positive association between the decision variables when they are in fact not complementary. However, Athey and Stern (1998) show that the tendency to overestimate complementarity if unobserved exogenous variables are associated is also a problem in the approach where the objective function is estimated[22].

One attempt to deal with unobserved heterogeneity is proposed by Miravete and Pernias (2000) who estimate a system of decision variables with random effects using panel data. They consider the association between the purely random components

[20] Arora/Gambardella (1990) and Miravete/Pernias (2000) are examples for this approach.

[21] Association is preserved by monotone transformations of the random variables whereas correlation is not.

[22] Part of their findings coincide with Arora (1996) .

of the reduced-form residuals (error term minus the idiosyncratic component) as the relevant indicator of complementarity[23]. Athey and Stern (1998) propose a method to overcome the unobserved-heterogeneity problem in the context of cross sectional data. It relies on the estimation of the objective function and can only be used with extremely rich data.

In this paper we follow the association approach on the basis of reduced-form adoption equations for flexible technology and product innovation. We estimate both equations separately and allow for random effects to take unobserved heterogeneity into account. This method provides consistent reduced-form estimates of the coefficients but does not allow to attribute observed association separately to unobserved heterogeneity and pure error terms because neither does the estimation relate the disturbances of the two equations nor can we expect to get reliable estimates for the firm idiosyncratic error term with only two periods.[24]

3.2 Data and Estimation

The data[25] used in this paper is a balanced panel of 532 German plants operating in mechanical engineering for two years, namely 1992 and 1994. It contains information on the formal and informal organization of the plant, e.g. human resource practices, technology choices, employee characteristics, and other strategic variables. The panel is available for the period 1990-1997 but various items of interest are not included in the questionnaires of all waves. Product innovation is measured as a binary variable[26] INNOVATION which equals one whenever the plant had introduced new products

[23]The authors point out a possibly important limitation of their approach: if decisions are state dependent (e.g. a firm that uses a given technology today is likely to continue to do so in the near future) and this cannot be explicitely modeled because the panel is to short, the random firm effect in the adoption equation will contain some of this state dependence. Hence, excluding the part of random variation that is idiosyncratic to the firm gives a tendency to overestimate unobserved heterogeneity and bias the estimated complementarity.

[24]The firm-specific time-independent part the error term can in principle be estimated. See Waclawiw/Liang (1993) for a Bayesian technique.

[25]We would like to thank Ulrich Widmaier, University of Bochum (German National Science Foundation, SFB 187) for the allowance to use this data set.

[26]All variable definitions that appear in this sections are summarized in table 4 of appendix D for convenience.

and zero otherwise. The variable FLEXIBILITY equals zero if the plant adopted conventional, numerically controlled[27] (NC) or computer-numerically controlled (CNC) machines but no more integrated technologies and it is equal to one if machining centers, flexible manufacturing cells (FMC) or flexible machine systems (FMS) are installed. The difference between the two groups is an ordering with respect to the flexibility of a single machine as well as with respect to the flexibility of the entire shop floor.

Table 6 in appendix D contains the mean values for both variables in both years. In 1992 roughly 46% of the firms had adopted the more flexible technologies, whereas in 1994 their number had increased to 51%. The share of firms that reported to engage in product innovation on the other hand decreased from 78% to 66% during the same period. Where the apparent raise in flexibility might reflect a general trend towards high capability systems, the pattern of innovation might be the result of the recession that followed the reunification boom shortly after 1990. We report numbers for East and West Germany separately, however, the numbers differ only slightly.

Association between FLEXIBILITY and INNOVATION is measured by Kendall's tau (τ) as defined in Appendix C. Contrary to the standard Pearson correlation coefficient it captures nonlinear dependence. Unconditional on any exogenous variables we find a slightly positive but significant dependence (τ = .097, p-value .001). As indicated above the assumptions we need to take this as evidence for complementarity between flexible machines and product innovation are very restrictive and we should therefore control for plant characteristics.

As our data is a panel of only two years we capture time effects by the dummy YEAR94 which equals zero in 1992 and one in 1994. The log of the total number of employees of the plant[28] (LOGSIZE) might have an effect on technology choice and

[27] NCs and CNCs are single-task machines with decentralized numerical control, i.e. there is no coordination between the machines. Machining centers are also stand-alone devices but they perform a variety of tasks. Very often they include automatic tool changing. FMC/S denote systems of a few (FMC) or many (FMS) machines that are connected by automatic material handling and controlled by a single, central device. See Gurisatti, Soli, Tattara (1997) for the definitions.

[28] We use the logarithm because the original size variable is extremely skewed: Most firms have less than 100 employees and only very few reach very large numbers such as several thousands.

innovation due to many reasons, like economies of scale, size dependent coordination costs and so forth. We further include variables that indicate whether decisions are actually taken at the plant level: FIRMLEVEL equals one if technological or organizational issues were reported to be on the firm-level agenda.

Because the firm-level influence may not always be directly perceived by plant managers but still be significant we include further the variable MULTIPLANT which equals one if the plant belongs to some multi-plant firm[29]. The share of products that are not standardized, but the customer can add their wishes to a basic design or completely specify the design (CUSTOMIZE) is expected to positively influence flexibility whereas there is no such clear cut intuition for its effect on product innovation. We include the variable HIERARCHY in our analysis to proxy communication costs that might hinder all sorts of changes and especially product innovation. It takes the value one if managers reported the number of hierarchical levels on their plants to be average or more. Information on hierarchy is available for 1992 only, in the estimation we assume it had not changed in 1994. Worker's skills, which typically cannot be freely determined in every period, might play a crucial role in the decision whether new products are introduced to the market and on the complexity of machines a firm wants to install. We try to capture this effect by the share of skilled workers, foremen and engineers in production (EDUCATION).

The theoretical part of this paper argued that the gain from flexibility tends to increase with demand uncertainty the firm faces. The bivariate variable RISK is a very rough proxy for uncertainty as it indicates whether a crucial part of revenues is assured by long term contracts or not. If, according to managers' subjective judgement, there are such long-term contracts, RISK is equal to zero (one otherwise).

To account for unobserved heterogeneity we estimate random effects models of the

[29]The correlation between FIRMLEVEL and MULTIPLANT is surprisingly low (0.24).

form

$$\begin{aligned} y_{it}^* &= \beta x_{it} + \varepsilon_{it} \\ \text{with } \varepsilon_{it} &= u_i + v_{it} \\ \text{and } u_i &\sim N(0, \sigma_u^2),\ v_{it} \sim N(0, \sigma_v^2), \end{aligned}$$

where y_{it}^* and x_{it} denote the latent endogenous and the vector of exogenous variables of individual i at time t respectively and β is the parameter vector. The error term ε_{it} is additively separable into an individual component that is fixed over time (u_i) and a pure random term (v_{it}). We assume that the variance of the disturbances has the simple form $var(\varepsilon_{it}) = \sigma_u^2 + \sigma_v^2$, i.e., u_i and v_{it} are uncorrelated.

Table 8 presents the estimates of the random-effects probit models. Note first that the correlation between the disturbances over the two periods is large and highly significant in both equations. This suggests that indeed unobserved heterogeneity is a serious issue in this study. One potential source for the high magnitude of correlation is, of course, inertia to switch technology and innovation modes that, due to the two-period limitation of our data, we could not estimate separately. If this inertia plays the role that intuition suggests, the extent of individual heterogeneity in our model may be substantially overestimated. Note that the estimated correlation between the disturbances of two periods is stronger in the flexibility equation which may be caused by the fact that sunk costs, and thus inertia, for technology are greater than for innovative activities.

The year 1994 has a significant impact on the decision to innovate. The sign of the coefficient may be interpreted as a business cycle effect in the case of innovation and as a positive time trend for the adoption of flexible technology as discussed above. Plant size is significantly positively related to both, product innovation and flexibility, whereas decisions that are widely taken at the firm instead of plant level or being part of a company with multiple plants do not significantly alter the tendency to install high capability machines or to rework the product line. A plant that offers to customize a large part of its product line is less likely to introduce new products to the market.

Presumably, the term "new" will be interpreted in different ways by the firms: with perfectly standardized products very small changes in design can be interpreted as a new product. A customizing supplier on the other hand will define product innovation probably abstracting from minor changes in design if these are within the usual variety and even if a given combination of features had never been created before.

Somewhat surprising, neither CUSTOMIZE has a significant effect on flexibility nor is there any significant impact of RISK and EDUCATION. This may indicate that the construction of these variables is not appropriate but rather constrained by the data. Very hierarchical structures, as expected, seem to work as obstacles to product innovation because they are likely to increase communication costs.

To assess how controlling for observed heterogeneity changed the empirical association we now compute Kendall's tau for the generalized residuals (defined as in appendix C) of the two equations. We find that the relation between product innovation and flexible technology has decreased to only .033 and is significant only at the 10% level. Table 3 compares the results. Note again, that the conditional association reported there contains the part of the dependence between the two endogenous variables that can be attributed to unobserved heterogeneity, because without estimating a simultaneous system of equations we cannot disentangle the sources. It is not clear whether dependence based on random effects u_i or on the pure noise v_{it} have the same sign. Hence, we cannot exclude the possibility that the association between the pure noise of would be much larger than .033. Everything else equal the presence of strictly positively affiliated vector of unobserved characteristics tends to overestimate complementarity due to residual dependence. If, on the other hand, unobserved characteristics are strictly negatively affiliated one might observe negative association between the residuals of complementary decision variables. Athey and Stern (1998) give examples for such misbehavior and demonstrate further that even if unobservable factors are independent, omission tend to reduce testing power.

In the light of our theoretical findings we note that the residual correlation may also be affected by noncomplementary endogenous variables that we did not control for. For

	unconditional	**conditional**
Kendall's tau	.097	.033
p-value	.001	.100

Table 3: Association between INNOVATION and FLEXIBILITY. Number of observations: 1074.

example, price increases where assumed to favor innovation due to complementarity in the demand function but we found the impact on the gains from flexible technology was inconclusive.

4 Conclusion

This paper reconsiders the firm's decision on technology and innovative activities. An optimization model with stochastic demand is introduced which takes into account gains from flexibility due to a wider set of future production possibilities. Because product innovation affects demand while the degree of flexibility sets constraints to production the interaction between both variables is shown to be more than just a fixed cost issue. Our results point out that the gain from incremental innovation might be lowered by flexibility even though the fixed cost of introducing a new product to the market are decreased by flexible machines.

As theoretical predictions are ambiguous we use empirical evidence to check whether complementarity in the fixed costs is strong enough to compensate potentially adverse effects in operational profits. For the German mechanical engineering sector there is some slight association between innovative activities and the use of highly flexible, IT related machines. However, this association vanishes once observed heterogeneity is controlled for. Although our empirical approach is in some respects simplistic and any interpretation of the results should involve some caution, the findings raise doubts that complementarity between flexibility and product innovation is strong.

There is some room to generalize the concerns. Many applications of the theory of technological complementarity in the context of monopolistic firms derived their results mainly from fixed cost considerations but ignored uncertainty and optimization over time. These two features — information that is revealed over time coupled with the possibility that firms adapt to it — might give some new insight to the question whether the complementarity and monotonicity predictions based on fixed costs considerations really hold for overall (expected) profits.

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A Complementarity and Supermodular Functions

This appendix provides the definition of a supermodular function and points out some of its properties which are used in the main part of the paper. For details see Topkis (1998).

Definition 1 *Suppose that $f(x)$ is a real-valued function on a lattice X. If $f(x') + f(x'') \leq f(x' \vee x'') + f(x' \wedge x'')$ for all x' and x'' in X, then $f(x)$ is supermodular in x on X. Supermodularity is strict if the inequality holds strictly. For the definition of (strict) submodularity reverse the inequality symbol.*

If, as in this paper, X is a sublattice of some n-dimensional product of chains, supermodularity is equivalent to complementarity. Supermodularity on any finite product of chains is equivalent to supermodularity on the product of each pair of chains and thus can be checked pairwise in these cases.

Supermodularity is preserved by summation, multiplication with a factor and partial maximization. The latter property ensures that qualitative results gained from the inspection of a subsystem of complementary decision variables will still hold once the whole system is considered. As supermodularity is a cardinal property, it is not preserved by arbitrary increasing transformations.

Exogenous variables are parameters of the decision making process and may be included in the vector x of the definition above. However, to address effects of monotone changes in exogenous variables it is sufficient to assume that they are complements to the endogenous variables but not necessarily complements among themselves. This property is formalized by the notion of increasing differences:

Definition 2 *Let X and Ω be partially ordered sets and $f(x, \omega)$ be a real-valued function on a subset S of $X \times \Omega$ For $\omega \in \Omega$, let S_ω denote the section of S at ω. If $f(x, \omega'') - f(x, \omega')$ is (strictly) increasing in x on $S_{\omega''} \bigcap S_{\omega'}$ for all $\omega' \prec \omega''$ in Ω, then $f(x, \omega)$ has (strictly) increasing differences in (x, ω) on S. Analogously, if the difference $f(x, \omega'') - f(x, \omega')$ is (strictly) decreasing, $f(x, \omega)$ has (strictly) decreasing differences.*

Increasing differences in (x, ω) is equivalent to stating that all parameters are complements to all decision variables. Twice differentiable functions exhibit increasing differences, if and only if all cross-partial derivatives of the objective with respect to any combination of decision variables and parameters are nonnegative.

For monotone comparative statics supermodularity and increasing differences in conjunction with a feasible set that is increasing in the parameter are sufficient conditions:

Theorem 1 (Topkis 1978) *If X is a lattice, Ω is a partially ordered set, the section S_ω is a subset of X for each ω in Ω, S_ω is increasing in ω on Ω, the function $f(x, \omega)$ is supermodular in x on X for each ω in Ω, and $f(x, \omega)$ has increasing differences in (x, ω) on $X \times \Omega$, then $\arg\max_{x \in S_\omega} f(x, \omega)$ is increasing in ω on $\{\omega : \omega \in \Omega, \arg\max_{x \in S_\omega} f(x, \omega)$ is nonempty$\}$.*

Milgrom and Shannon (1994) generalized theorem 1 by showing that it also holds for the ordinal concepts of quasisupermodularity and single crossing (ordinal complementarity). Thus, the conditions of the theorem hold whenever all decision variables are ordinal complements and all components of the parameter vector ω are ordinal complements to the vector x. The components of ω need not be ordinal complements.

B Proof of Proposition 1

$-F(f, \omega)$ and $-\gamma k$ are trivially supermodular in f and k respectively. As supermodularity is preserved under summation, we have that $-I(i, f, \omega) - \gamma k - F(f, \omega)$ is supermodular in (i, f, k).

The cross partial derivative of $[(p - c)D_j(i, p)]$ with respect to i and p exists and is positive because differentiability and supermodularity of $D_j(i, p)$ imply $\partial^2 D_j / \partial i \partial p \geq 0$ and we assumed that $\partial D_j / \partial i \geq 0$. Thus $[(p - c)D_j(i, p)]$ and $2[(p - c)D_j(i, p)]$ are supermodular in (i, p). Applying the summation property again gives the first statement of the proposition.

To proof part (ii) of the proposition, note that we have assumed that every summand of the profit function has increasing differences in $((i, f, k, p), \omega)$. As these are preserved by summation, Π exhibits increasing differences in $((i, f, k, p), \omega)$. Together with the first part of the proposition and the fact that the set of feasible actions does not depend on ω the conditions of monotonicity theorem (see appendix A) are met and the result established.

C Definitions

Kendall's tau

To calculate Kendall's tau (τ) of two vectors x and y we use the following definition:

$$\tau = \frac{c - d}{\sqrt{(c + d + t_x)\,(c + d + t_y)}},$$

where c and d are the number of concordant and discordant pairs respectively and t_x (t_y) denotes the number of pairs tied on x (y) but not on y (x). Values of τ lie in the interval $[-1, 1]$, positive (negative) values indicate positive (negative) dependence.

Generalized Residuals

The Pearson residual for a binary response model is defined as

$$r_i = \frac{y_i - \widehat{\pi}_i}{\sqrt{\widehat{\pi}_i(1 - \widehat{\pi}_i)}},$$

where y denotes the endogenous variable that can take values equal to zero or one, i indexes the observation and $\widehat{\pi}_i$ is the estimated probability that $y = 1$. Because in such a model $var(y_i - \widehat{\pi}_i) \neq \widehat{\pi}_i(1 - \widehat{\pi}_i)$ we have that $var(r_i) \neq 1$. Pregibon (1981) developed the standardized Pearson residual for this case

$$r_i^{st} = \frac{r_i}{\sqrt{(1 - h_i)}},$$

where $h_i = \widehat{\pi}_i(1 - \widehat{\pi}_i)x_i\widehat{var}(\widehat{\beta})x_i'$ and x_i denotes the row vector of exogenous variables and $\widehat{\beta}$ is the estimated parameter vector. In our estimation there is practically no difference between r_i and r_i^{st} but only the latter are used for computation of Kendall's tau.

D Tables and Figures

Variable	Description
FLEXIBILITY	=1 if the plant adopted machining centers, FMC or FMS, 0 otherwise
INNOVATION	= 1 if new products were introduced, 0 otherwise
YEAR94	=1 for 1994, =0 otherwise
LOGSIZE	log of total number of employees (except administrative)
FIRMLEVEL	=1 if technological or organizational issues were decided at the firm instead of the plant level, 0 otherwise
MULTIPLANT	=1 if plant belongs to some multi-plant firm, 0 otherwise
CUSTOMIZE	share of products that where not standardized, but the custumer could add to a basic design or completely specify the design
RISK	=0 if an essential (for continuation of the business) share of revenues is from long term contracts with costumers, 1 otherwise
EDUCATION	number of skilled workers, foremen and engineers relative to total number of employees in production
HIERARCHY	=0 if organizational structure is reported to be less hierarchical than average, 1 otherwise (only available for 1992)

Table 4: Variable definitions.

Variable	Mean	Std.Dev.	Minimum	Maximum
INNOVATION	0.719924812	0.449246881	0	1
RISK	0.814849624	0.388602165	0	1
FIRMLEVEL	0.202067669	0.401731262	0	1
EDUCATION	0.750329707	0.232603765	0	1
FLEXIBILITY	0.484022556	0.499979664	0	1
HIERARCHY	0.706766917	0.455458458	0	1
CUSTOMIZE	0.817937970	0.276060422	0	1
LOGSIZE	4.05922346	1.06918760	0	8.45
MULTIPLANT	0.290413534	0.454166680	0	1

Table 5: Descriptive Statistics. N=1064.

	FLEXIBILITY			**INNOVATION**		
	1992	**1994**		**1992**	**1994**	
East	.3333 (.4771)	.4524 (.5038)	.3929 (.4913)	.8333 (.3772)	.6667 (.4771)	.7500 (.4356)
West	.4714 (.4997)	.5122 (.5004)	.4918 (.5002)	.7776 (.4163)	.6571 (.4751)	.7173 (.4505)
	.4605 (.4989)	.5075 (.5004)	.4840 (.5000)	.7820 (.4133)	.6579 (.4749)	.7199 (.4492)

Table 6: Mean of INNOVATION and FLEXIBILITY (standard deviation in parenthesis). Number of observations per year: East: 42, West: 490.

	1992	1994	
East	.316*	.237	.239*
	(.043)	(.129)	(.029)
West	.082	.104*	.087**
	(.068)	(.022)	(.006)
	.095*	.114**	.097**
	(.028)	(.008)	(.001)

Table 7: Unconditional correlation (Kendall's tau) between INNOVATION and FLEXIBILITY (p-value in parenthesis). Number of observations per year: East: 42, West: 490. * (**) indicates significance at the .05 (.01) level (2-tailed).

	Innovation		Flexibility	
	Coefficient	P-value	Coefficient	P-value
CONSTANT	.5890675881	.1405	-4.094333881***	.0000
YEAR94	-.5425365516***	.0000	.3790892066***	.0040
LOGSIZE	.3516162630***	.0000	.9512584420***	.0000
FIRMLEVEL	.1314831593	.4541	.5556288603E-01	.7972
MULTIPLANT	.2474844253	.1442	.3010922655	.1974
CUSTOMIZE	-1.575403089***	.0000	.8910673912E-01	.8102
RISK	.2354568168	.1501	-.2262075791	.3236
EDUCATION	.4934053273*	.0865	-.1033049901E-01	.9833
HIERARCHY	-.2785720441*	.0693	-.4909537266E-01	.8600
$\widehat{corr}(\varepsilon_{it}, \varepsilon_{is}),\ s \neq t$	.4978222791***	.0000	.8348466787***	.0000

Table 8: Estimation results of random effects model . ***, **, * represent significance at the 1%, 5%, 10% level respectively. ML estimates using the Broyden-Fletcher-Goldfarb-Shanno algorithm (BFGS).

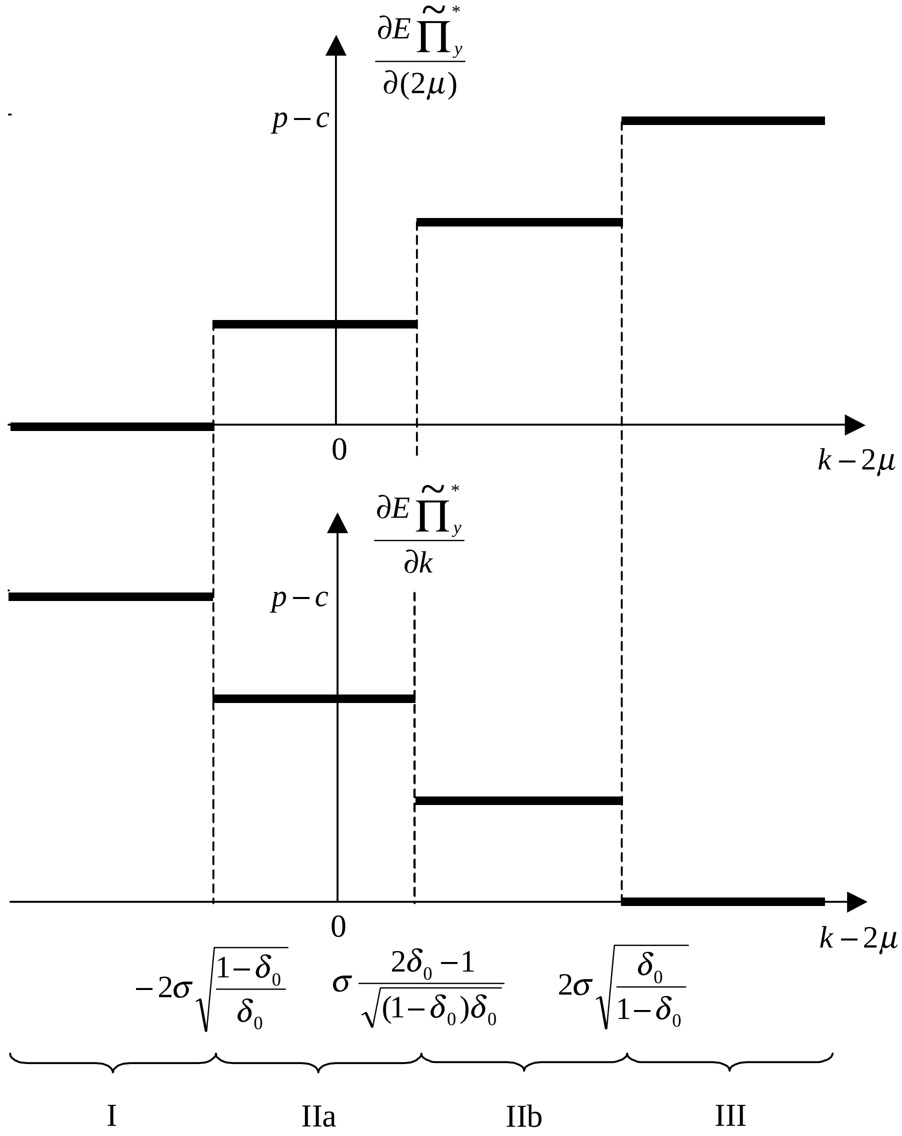

Figure 1: The impact of demand drivers and capacity on expected operational profits as a function of the difference between initial capacity and demand ($f = 1$). The case boundaries are calculated using equation (9). Depending on the size of δ_0 the vertical axis may shift further to the right.

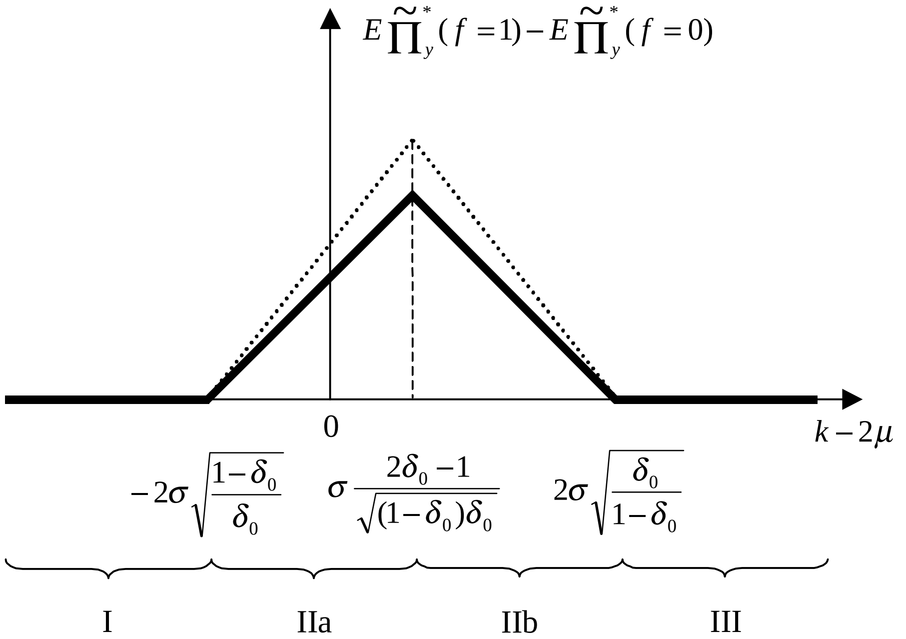

Figure 2: Expected gain from flexibility in the production period as a function of μ and k. A price increase shifts the graphs upwards (dotted lines). The case boundaries are calculated using equation (9). Depending on the size of δ_0 the vertical axis may shift further to the right.

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