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# Timeliness, trade and agglomeration.*

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**Abstract**:
An important element of the cost of distance is time taken in delivering final and intermediate goods. We argue that time costs are qualitatively different from direct monetary costs such as freight charges. The difference arises because of uncertainty. Unsynchronised deliveries can disrupt production, and delivery time can force producers to order components before demand and cost uncertainties are resolved. Using several related models we show that this can cause clustering of component production. If final assembly takes place in two locations and component production has increasing returns to scale, then it is likely that all component production will be clustered around just one of the assembly plants.

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## 1. Introduction

People pay a lot of money to save time. A modern economy is inconceivable without air travel and air shipment, ways of saving time at the expense of money. For workers in urban areas, the main component of commuting costs is time. For international trade in manufactured goods estimates of the costs of the time-in-transit range as high as 0.5% of the value of goods shipped, *per day* (Hummels 2001). Protagonists of 'just-in-time' manufacturing techniques emphasise the importance of organising and locating production to ensure timely delivery of parts and components.

Surprisingly, these observations have had little impact on the economic analysis of location decisions.[1] Economists have worked with an aggregate of 'transport costs' or 'trade costs' to capture the penalty of distance, while simply remarking that these costs are a shorthand for a complex set of penalties (e.g. Fujita, Krugman, and Venables 1999). Penalties include freight and other monetary transactions costs; lack of information about markets and suppliers and about local institutions and regulations; difficulty in monitoring contracts; the impossibility of face-to-face contact and communication; and the fact that distance introduces delay into completion of trades. It is unlikely that summarising these penalties as a single value of 'trade costs' is adequate for understanding their effects. The objective of this paper is to contribute to the process of unpacking the different elements of these trade costs.[2]

We focus on the costs associated with delivery times and argue that timeliness is not only a quantitatively important aspect of proximity, but also matters qualitatively, creating an incentive for clustering of activities. The context is the time taken between initiating a project and completing it and making delivery to the consumer. We suppose that physical distance between stages of the production process (eg component manufacture and final assembly) slows down the process, and argue that slowing down matters for several reasons. One reason is discounting and other analogous factors, such as the physical depreciation or technical obsolescence that component parts may incur during shipment. These costs will not be the focus of our attention, although we note that they may be large – computer chips become obsolescent very rapidly, so it is not sensible to ship them on the slow boat.

Other reasons why delay matters are intimately connected with uncertainty. One set of

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[1]For instance, Fujita and Thisse's (2002) lucid and authoritative new book doesn't have "time" in the index. There is some modeling of the issues in Harrigan and Evans (2002) and Venables (2001).

[2] Previous attempts to unpack 'trade costs' include study of the benefits of face-to-face contact, see Leamer and Storper (2001) and Storper and Venables (2003).

arguments is to do with the synchronization of activities; production cannot be completed until all the parts have arrived, so uncertain arrival times of components can have a cost that is quite disproportionate to the cost of any single component. Other arguments arise since, in general, it is profitable to postpone stages of the production process until as much uncertainty as possible has been resolved. We look at several different aspect of demand uncertainty; uncertainty about the product characteristics that are demanded, and uncertainty about the total level of demand or costs.

Of course, saving time is always going to be beneficial, just as is saving freight charges. To make the point that there may be qualitative (as well as a quantitative) implications of timeliness, we develop all our models in a very particular framework that enables us to assess the profitability of clustering activities together. The framework is one in which there are two locations, each of which has an assembly plant supplying final demand. The assembly process uses a number of component parts, and increasing returns in production of these components are sufficiently great that each is produced in a single plant. Where do the component producers locate? Clustered around one of the assembly plants, or divided between the two locations? We show that the demand for timeliness in delivery creates a force for clustering of plants around a single assembler.

We develop this argument in a series of models. Section 3 outlines a benchmark case in which there are monetary trade costs, but delivery is instantaneous and component producers do not cluster. In section 4 we look at the issues raised by the synchronisation of delivery of components, and show that uncertain delivery times will cause clustering of component producers. Sections 5 and 6 show how uncertainty about demand and about costs can also create clustering. However, before developing these models we briefly connect our to approach to the extensive management literature on just-in-time (JIT) production.

## 2. Just-in-time

In the management literature on just-in-time (JIT) production it has been suggested that the spread of JIT systems might be expected to lead to a geographical reconcentration of supplier firms and customers (eg Dicken 1998).

The JIT approach was pioneered by Toyota Motors in the 1950s. Its main features are that components are delivered in small but frequent batches, that minimal stocks are held, and that ‘quantity control is built in’. The perceived advantages are a reduction in the cost of holding stock, rapid response to customer orders, and the ability to rapidly detect and rectify defective components. Effective implementation of JIT is thought to require close and long term supplier/ customer relationships and, where possible, proximity.

The importance of proximity is illustrated by the example of General Electric's appliances division in their attempt to implement JIT in the 1980s and 90s. They were hampered by the fact that some suppliers were several thousand kilometres away from GE plants, this causing a 1993 decision to increase inventory levels (Jones, George and Hill 2000). The US auto-industry has been extensively studied, although identifying the effects of JIT on supplier location is a tricky empirical question. Assemblers tend to locate where suppliers are already located, and in addition there are non-JIT reasons why suppliers may want to be near assemblers (such as minimizing transport costs irrespective of timeliness considerations). Klier (1999) assembles a comprehensive dataset on assemblers and suppliers and shows that, since the advent of JIT, new supplier plants are more likely to locate near their assembly plant customers than they were before the advent of JIT. Klier also finds that proximity generally means "within a days drive", rather than right next door, which implies that the agglomeration force of JIT operates at the regional rather than the urban level.

Our goal in this paper is to develop some simple models that capture some of the features referred to in this literature, and to draw out their implications for the concentration of activity.

## 3. A timeless model

We develop our ideas in a family of models, each based on two locations, *A* and *B*, where final assembly occurs and demand is met. Assemblers in *A* and *B* require components, and component suppliers can be located in either *A* or *B*. We refer to the final producers as assemblers but the idea is more general: "assemblers" could be service firms who require a variety of manufactured or service inputs, or retailers who sell a variety of products.[3]

Assemblers produce with constant returns to scale, and the final assembled product is non-tradeable, so assembly must take place in both locations. Components are tradeable, although trade typically takes time. The number of types of components, *N*, is fixed, and production of each incurs a plant level fixed cost and then has constant marginal cost. The fixed cost is large enough to ensure that each component is only produced in one location, either *A* or *B*, and our primary question is to ask where this component production takes place.

In most of the models we develop all components are necessary to production of the final product, raising the question of how surplus is split between assemblers and component producers. The theory of (non-cooperative) bargaining offers no answer to this when there is more than one supplier (see Sutton 1986, Binmore and Dasgupta 1987). However, it does lead us to expect that the outcome will be efficient, maximising the combined returns to all parties. In

[3] Or we could even interpret components as individuals required to turn up to a meeting.

our analysis we therefore look merely at the total returns to different locational patterns, and not at how these might be divided between players.

Before we move to our models of timeliness, it is instructive to look briefly at a timeless case based on ingredients from a standard economic geography model. In this benchmark model, assemblers in *A* and *B* each combine *N* symmetric inputs in a CES production function to create a unit of final output. The value of producing one unit of final output in location *A* is revenue minus the costs of producing and shipping components,

$$V_A = p - \left[ N_A r_A^{1-\sigma} + N_B \left( \tau r_B \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \qquad (1)$$

The exogenously given price of final output, net of any assembly costs, is *p*. The remaining term is the cost of the parts required to produce a unit of output. The cost function has elasticity of substitution $\sigma$; $N_A$ is the number of components sourced locally with unit production costs $r_A$, while the remaining $N_B$ ($N_A + N_B = N$) come from the other location with unit production cost $r_B$ and shipping cost factor $\tau > 1$. Notice that, since we are looking for efficient outcomes, we use the unit production costs of components, $r_i$, which may not be the same as the prices at which they are traded. Furthermore, we will henceforth refer to $V_A$ as the profits of assembly in A, noting that it is both the profits of the assembler and profits (before fixed costs) earned by component producers on supply of parts to *A*. A similar equation gives profits in *B*.

What values of $N_A$ and $N_B$ maximise total profit, $V_A + V_B$? The total number of component suppliers is fixed at *N*, so that $N_A = N - N_B$, and we let input costs be the same in each location. Making these substitutions in (1) and taking the derivative of $V_A$ with respect to $N_B$ gives

$$\frac{\partial V_A}{\partial N_B} = \frac{r(\tau^{1-\sigma} - 1)}{\sigma - 1} \left[ N + N_B(\tau^{1-\sigma} - 1) \right]^{\frac{\sigma}{1-\sigma}} < 0 \qquad (2)$$

$$\frac{\partial^2 V_A}{\partial N_B^2} = \frac{-r\sigma(\tau^{1-\sigma} - 1)^2}{(1-\sigma)^2} \left[ N + N_B(\tau^{1-\sigma} - 1) \right]^{\frac{1}{\sigma-1}} < 0 \qquad (3)$$

These derivatives establish that $V_A$ is decreasing and concave in $N_B$: shifting assembler locations from *A* to *B* has an increasingly negative effect on the returns to assembling in *A*. The opposite is true for the returns from assembly in *B*. The point here is that the *increasing* marginal cost of remoteness implies that the sum $V_A + V_B$ is maximized when half of the suppliers locate in each region. The point is made explicitly in Figure 1, in which there are 10 components, and the

number of component suppliers located in *B* is on the horizontal axis[4]. Curves give profits in each place, and their sum, $V_A + V_B$, is maximised when $N_A = N_B$. A lower elasticity of substitution, σ, gives less curvature and a flatter $V_A + V_B$ schedule, but only in the limit, when the elasticity of substitution is zero, do the curves become linear, and their sum horizontal.

This result does not turn on a CES cost function. Quite generally, if the assembler did not adjust its input quantities as $N_A$ and $N_B$ changed, then $V_A$ would be the straight line joining values of $V_A$ at $N_A = 0$ and $N_B = 0$. The possibility of adjustment means that $V_A$ lies on or above this straight line, as illustrated. More formally, consider any symmetric unit cost function $c(..r..;..r+dr..)$ in which inputs are partitioned into a group (*A*) available at price *r*, the remainder available at price $r + dr$ (group *B*). Quantities demanded in each group are $x_A$, $x_B$, $x_A > x_B$. The increase in costs when a product moves from group *A* to group *B* is $(\partial c/\partial r)dr = x_A dr$ (by Shepherd's lemma). As more products enter group *B* so $x_A$ must increase (in order that input levels are sufficient to produce the unit of output[5]), meaning that the cost of moving inputs from group *A* to group *B* is increasing. This increasing marginal costs gives the convexity of the cost function with respect to $N_B$, and the consequent concavity of profits.

The conclusion is therefore that, in this benchmark case, there is no clustering of activity. The ex ante symmetric locations, *A* and *B*, are also symmetric ex post, as component producers are split in equal numbers between the locations. With this benchmark in mind we now turn to models where remote supply incurs a time cost.

## 4. Synchronization

Our first model of timeliness turns on uncertainty about delivery time, and the consequent risk that production may be delayed by the late arrival of components from a distant supplier. We model this by supposing that each assembly firm seeks to produce a unit of output for delivery at a particular date. Assembly uses labour to combine *N* different component parts into final output using a Leontief production function with unit coefficients. Of course, production cannot be completed until all the parts needed have arrived. For the moment, we assume that holding stocks of components is infeasible or prohibitively costly. This might be because of very high storage or depreciation costs, or simply because the exact specification of the product is unknown prior to the decision to produce, an idea we pursue in the next section.

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[4] This and other figures are generated by simulation of the models. Parameter values are given in the appendix.

[5] The cross-partial derivatives of a symmetric unit cost function are positive, so raising the price of some inputs increases demand for other.

Transport of components between locations is costless, but timely delivery of parts can only be guaranteed if the assembler and parts supplier are located in the same region. The probability of timely delivery is $q < 1$ if supplier and assembler are located in different regions. Assuming that delivery of each part is iid across suppliers and assemblers, for assemblers located in *A*,

Pr(*all parts arrive on time*) = $q^{N_B}$

Pr(*at least one part arrives late*) = 1 - $q^{N_B}$

where as before $N_B$ is the number of parts suppliers located in *B*, $N_A + N_B = N$. Clearly, Pr(*all parts arrive on time*) is decreasing in $N_B$ and (importantly, as it turns out) convex in $N_B$:

$$\frac{\partial q^{N_B}}{\partial N_B} = q^{N_B} \ln q < 0 \qquad \frac{\partial^2 q^{N_B}}{\partial N_B^2} = q^{N_B} \left[\ln q\right]^2 > 0 \tag{4}$$

This means that each part which changes from being supplied locally to remotely decreases the probability that all parts arrive on time, but does so at a diminishing rate. The intuition for this is straightforward: if one part is delayed, it doesn't matter if a second part is also delayed.[6]

There are several reasons why delays in completing assembly might be bad for profits. One is demand decay. Many goods and services have demand which peaks at a certain time and the price that the assembler can get for the final product falls unless it is delivered on time. Another is that some assembly costs have to be met whether production occurs or not. For example, if labor must be hired to assemble parts, then wages must be paid regardless of whether all parts have arrived. Think of labour as a cost which must be incurred before the outcome of the delivery process is known, so that if there are delays, labour must be hired again once all parts arrive.

To capture these arguments, let final demand be characterized by a reservation price which is $p$ on the day that demand is realized and $p(1 - \delta)$ one day later, $\delta \in (0,1)$. Profits if all parts are delivered on time are therefore

$$v_A^0 = p - \beta w_A - N_A r_A - N_B r_B \tag{5}$$

where $\beta$ is the daily unit labour requirement for parts assembly and $w_A$ is the wage. If parts are delivered one day late, the reservation price falls and labour must again be hired, so profits are

$$v_A^1 = p(1-\delta) - 2\beta w_A - N_A r_A - N_B r_B \tag{6}$$

[6] This production function is formally identical to Kremer's (1993) o-ring technology.

The difference between profits on day 0 and on day 1, $\delta p + \beta w_A$, is the penalty paid by firms who suffer late delivery of parts. Expected profits are just profits if there is no delay minus the expected cost of delay,

$$V_A = v_A^0 - \left(1 - q^{N_B}\right)\left(\delta p + \beta w_A\right) \tag{7}$$

If we assume that there are no cost differences between the two locations, then (5) and (7) imply that expected profits in *A* are decreasing and convex in $N_B$: the hit to expected profits of sourcing an additional part from far away gets smaller as the number of them increases.

Symmetric results apply to expected profits in *B*, which has the important implication that total expected profits are maximized at $N_B = 0$ and at $N_B = N$. This is illustrated in Figure 2. In contrast to the baseline model of the previous section, total expected profits are *minimized* at $N_B = N/2 = N_A$: with such a division of production, neither suppliers in *A* nor in *B* get the benefit of reliable deliveries. This illustrates the increasing marginal value of timeliness: if almost all parts have guaranteed on-time delivery, an increase in share of timely parts has a bigger effect on expected profits than if most parts are subject to erratic delays. As a result, there is an economic force leading to the agglomeration of all suppliers in either *A* or *B*.

The point of this simple case is then, that although the locations are ex ante symmetric, the efficient location of component producers is asymmetric. It is best to have one assembler operating in a cluster of all the component suppliers and producing without delay, while the other bears the full cost of the uncertainties associated with delivery delay.

Notice also that the difference between locations shows up as a productivity difference. One of the key facts about agglomeration is that localized industries have higher measured productivity (see Rosenthal and Strange, 2003, for a review of the evidence). The model offers an explanation for this: localized activities benefit from timeliness, which reduces or eliminates periods when production is interrupted by delayed delivery. If all suppliers locate in *A*, then assemblers in *A* never have to pay labour twice, while assemblers in *B* have to pay labour a second time with probability $1 - q^N$. Since output is the same in each location, relative productivity in *A* is given by the ratio of expected unit costs:

$$TFP_{AB} = \frac{(2 - q^N)\beta w + rN}{\beta w + rN} > 1 \tag{8}$$

This TFP advantage for assemblers in *A* is increasing in the probability that at least one part is delayed and in the importance of assembly labour in total costs. It is also increasing in the total

number of parts, which might be thought of as complexity.[7] This is intuitive, since the greater the number of parts the greater the chance of a delay in having all parts arrive. This result suggests that parts used in more complex activities have a greater incentive to cluster than do parts used in simpler activities.

**5. Inventories and product specification uncertainty.**

The obvious question on the preceding section is: what about stocks? We now follow up the brief discussion of inventories in that section with a model in which assemblers choose inventories optimally, and we show that the convexity of profits with respect to location may -- depending on the cost of holding stocks -- continue to hold. We also vary the model by removing uncertainty about the timing of arrival of components, and instead having uncertainty about the exact specifications of products that consumers demand. This uncertainty creates an incentive to produce quickly (after information about demand has been revealed), as well as potentially making stocks very expensive to hold.

In each location, *A*, *B*, there is a unit mass of consumers, each of whom consumes one unit of final product. Each assembler, as above, uses $N$ components with fixed unit coefficients to produce one unit of a final product. However, each component now comes in a continuum of characteristics (of measure one), and consumer preferences are defined over the characteristics of each component – i.e. consumers want a car with a particular engine specification, body-work, interior trim, etc. These preferences are represented by supposing that, for each component, consumers have 'high' preference for a subset of characteristics of measure $\mu$, and 'low' preference for the remaining $1 - \mu$. Thus, each characteristic in the set $\mu$ faces $1/\mu$ units of high preference demand; characteristics not in this set will be consumed only if high preference characteristics are not available, and only at lower price.

This is illustrated in figure 3, in which the horizontal axis is the characteristic space for one component. The unit mass of consumers has high preferences for characteristics in a set of measure $\mu$. These characteristics need not form a connected set although, for simplicity, this case is illustrated. The rectangle ABCD represents total high preference demand so has area

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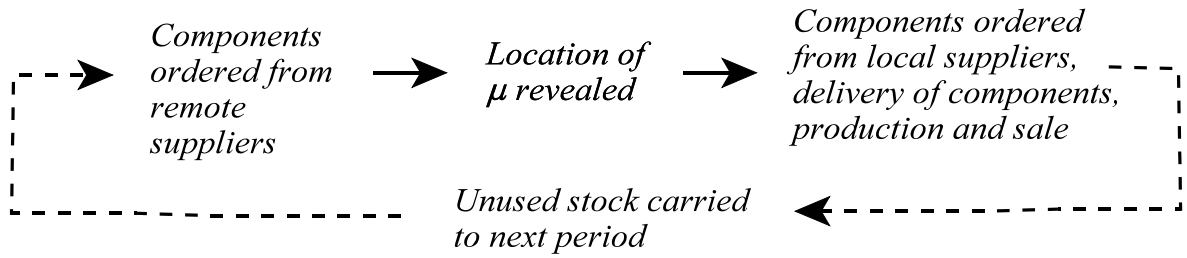
[7] To show this, we calculate the derivative of TFP with respect to $N$, holding labor's share in cost fixed (this requires an offsetting drop in $r$ as $N$ increases so that $rN$ is constant, that is, $Ndr + rdN = 0$). The result is

$$\frac{\partial TFP_{AB}}{\partial N} = \frac{-\beta w}{\beta w + rN} q^N \log q > 0$$

unity, implying that high preference demand for each of these characteristics is 1/μ. This pattern is repeated for each component, and we assume that there is no correlation between demand for the characteristics of different components; preferences over engine size are uncorrelated with preferences over exterior colour. The value of μ is known and the same for all components, however its location (in characteristic space) is initially unknown. In other words car assemblers know that μ exterior colours will be demanded, but they do not know which ones. Clearly, preferences are less uncertain the larger is μ, and when μ = 1 then there is no uncertainty as all characteristics are demanded in equal quantity.

Delivery of components from remote suppliers takes time, so these components have to be ordered before the assembler knows the exact specification of demand. This is then revealed, and components are ordered from local suppliers, delivery and production takes place. The production cycle is then repeated indefinitely. This gives the following time line:




Given this timing, what quantities of what characteristics of each component should the assembler in *A* order be holding when production commences? For each locally supplied component the assembler knows the μ characteristics that have high preference, and orders quantity 1/μ of each of these. For each remotely supplied component, *s* denotes the quantity of each characteristic held when production commences. If $s = 1$ then only μ consumers can be served with their preferred variety of the component, the remainder $(1 - \mu)$ having to make do with a low preference variety; all $s = 1$ units of each component get used up in production. If $s > 1$, then $s\mu$ consumers get their high preference variety and the remaining $(1 - s\mu)$ make do with a low preference characteristic (the shaded area of figure 3). Since one unit of each component gets used in production each period, stock of $s - 1$ is carried into the next production cycle, with new purchases replacing stock used.[8] Notice that it is never optimal to have $s < 1$, as one unit is

[8] For each of the 1- μ low preference characteristics the volume of stock carried forward is $s - (1 - s\mu)/(1 - \mu) = (s - 1)/(1 - \mu)$.

required to produce the one unit of output, nor $s \geq 1/\mu$, as this is sufficient to perfectly match consumer preferences.

The final ingredient we need is to specify the price of final output according to the extent to which it matches consumer preferences. Products that are 'perfect' – all their components having the high preference characteristics – have price $\bar{p}$. Those that have $k$ low preference components ($k$ 'mismatches') have price $\bar{p}\phi(k)$, $\phi(0) = 1$. We assume that $\phi(k)$ is decreasing and convex in $k$, implying that the price falls at diminishing rate with multiple mismatches; as a consequence, a firm will produce as many perfect products as it can, concentrating all its mismatched components in as few a products as possible (rather than spreading its mismatched components over many units).

The profit from assembly at $A$ as now given by

$$V_A = s\mu\bar{p} + (1 - s\mu)\bar{p}\phi(N_B) - (s - 1)\gamma N_B - N_A r_A - N_B r_B. \qquad (9)$$

The first term says that, with stock level $s$, $s\mu$ consumers can receive products that perfectly match their preference. Other products contain mismatch in all $N_B$ of their remotely supplied inputs, so are valued at $\bar{p}\phi(N_B)$. Remaining terms in the expression give the costs of producing the components and the inventory cost, where $\gamma$ is the unit cost of holding stock to the next production cycle, so $(s - 1)\gamma N_B$ is the total cost of inventories.

Efficiency is achieved by choosing $s$ to maximise (9). The problem is linear in $s$, so the solution is to go to one corner or the other. Thus, the assembler either chooses $s = 1/\mu$, to perfectly match demand, or chooses $s = 1$, the minimum required to produce one unit of output regardless of specification. Evaluating $V_A$ at these points, we find:

$$\begin{aligned} s &= s_{\max} = 1/\mu \qquad \textit{if } \bar{p}\mu\left[1 - \phi(N_B)\right] > \gamma N_B \\ s &= s_{\min} = 1 \qquad \textit{otherwise.} \end{aligned} \qquad (10)$$

Outcomes are illustrated on figure 4, for the case with $r_A = r_B$. The horizontal axis is $N_B$ ($N_A = N - N_B$), the intersecting dashed curves give profit when maximal and minimal levels of stock are held, and the maximised value is the upper envelope, with switch point as indicated in equation (10). To the left of the switch point maximal stock levels are held and $V_A$ is linear in $N_B$. If it were the case that for all $N_B \in (0, N)$, $\bar{p}\mu\left[1 - \phi(N_B)\right] > \gamma N_B$, and analogously for $V_B$ and $N_A$, then both $V_A$ and $V_B$ would be linear over the entire range. If $r_A = r_B$ then their sum is a constant, independent of the location of suppliers. This confirms the idea that holding

inventories removes the incentive for agglomeration and, in this simple example, makes the location of suppliers indeterminate.

If however $\bar{p}\mu\left[1 - \phi(N_B)\right] = \gamma N_B$ for some $N_B \in (0, N)$, then the outcome is as illustrated. When no stock is held, $s = 1$, $V_A$ is convex, and the upper envelope of the profit curves is also convex. Adding profits in each location gives a convex sum $V_A + V_B$, so that efficiency is achieved by putting all suppliers in one place. At this equilibrium then, one assembler has all components produced locally, and produces 'customised' products that perfectly match demand; it does this without holding stocks, because it relies on the proximity of suppliers. The assembler in the other location chooses not to hold stocks, instead preferring to produce a product range which is less well tailored to consumer demand.

What factors are conducive to there being an interior switch point and consequent clustering? The first is a high direct cost of holding a unit of stock, $\gamma$. The second is greater uncertainty about the exact product specifications that will be demanded (higher $\mu$). These factors raise respectively the cost and the quantity of stock that needs to be held to completely match high preference demand. The third factor is the curvature of the function $\phi(k)$, giving the cost of mismatches. For the argument of this section to work, this function has to be convex so that – as in the preceding section – the first mismatch is more expensive than the second, and so on.

The model of this section therefore gives two main messages. One is that, even if the direct costs of holding a unit of stock ($\gamma$) are not that high, the fact that stocks need to be held over a wide range of component specifications (if $\mu$ is low) can make the stock-holding strategy expensive. The other is that uncertainty about demand specification coupled with time in transit can generate clustering. Putting these together, we see that in industries where products are complex (a high $N$) or demand is volatile (high $\mu$), the presence of time in transit will induce an equilibrium with clustering. One location will contain all the suppliers and produce customised products; the other has to import components, and produces 'generic' products. Although physical productivity is the same in both locations, the output price and hence the value of output per worker is higher in the location with the cluster.

**6. Demand (or cost) uncertainty.**

In the preceding models incurring failures (late delivery or mismatched components) becomes progressively less costly, and it is this that gives the convexity of the profit functions. We now turn to an alternative model in which the mechanism is somewhat different. There is no uncertainty about the arrival time of components, or about the composition of demand. Instead, there is simply uncertainty about the level of demand, and the location of plants affects the extent

to which it is possible to react to information about the position of the demand curve. In this way, we build on the work of Evans and Harrigan (2002), who examined a model of "lean retailing" and its implications for international specialization.[9] We develop the model for the case of demand uncertainty, although show at the end of the section that assembly cost uncertainty has identical effects.

Demand for the output of each assembler can be high or low, represented by a linear inverse demand curve in which the intercept depends on the state of nature, so

$$p_i = \alpha^s - \beta y_i \qquad i = A, B, \quad s = H, L, \quad \alpha^H > \alpha^L. \tag{11}$$

where $p_i$ is price and $y_i$ is quantity of final product in region $i$, and superscript denotes the state of nature. High demand occurs with probability $\rho$. Whether high or low, demand is fleeting, and falls to zero if not met immediately.

As before, the production function has fixed unit input coefficients for each component, and we ignore labour costs in assembly. The assembler in region $A$ faces the following sequence of decisions. First, she has to choose the quantity $x_B$ of components to order from each of the $N_B$ remote suppliers. These have to be ordered before the state of nature is revealed if they are to arrive in time for production. The state of nature is then revealed, and firms choose quantities of components $x_A^s$ from each of the local suppliers. Finally, delivery of all components takes place and production occurs. This is summarised by the following time line:

Choose $x_B$: → $\alpha^s$ revealed: → Choose $x_A^s$: → Produce $y_A^s = \min[..x_B.., ..x_A^s..]$.

The assembler's second choice problem (once the state of nature, $s = H, L$, is known) is to choose $x_A^s$ to maximise $v_A^s$, defined as

$$v_A^s = x_A^s(\alpha^s - \beta x_A^s) - N_A r_A x_A^s, \quad s.t. \quad x_A^s \le x_B \qquad s = H, L. \tag{12}$$

The maximand is revenue (where we have used the production function and the inverse demand curve) minus the costs of locally supplied inputs. The constraint reflects the fact that the assembler will never choose more local components than the quantity set by the supply of

[9] This section goes beyond their model in focusing on the location of multiple input suppliers.

components coming from region *B*, because of the fixed coefficient technology. We solve this problem by maximising the Lagrangean

$$L_A^s = x_A^s(\alpha^s - \beta x_A^s) - N_A r_A x_A^s + \lambda^s[x_B - x_A^s] \qquad s = H, L. \tag{13}$$

The first order condition with respect to $x_A^s$ implies,

$$\lambda^s = \alpha^s - 2\beta x_A^s - N_A r_A, \qquad s = H, L. \tag{14}$$

The solution to this problem gives two qualitatively different regimes. In one the constraint binds, so $x_A^s = x_B$ and $\lambda^s > 0$ is given by equation (14). In the other the constraint does not bind so $\lambda^s = 0$ and $x_A^s$ is solved from (14); some components ordered from *B* are disposed of.

The assembler's first problem is to choose $x_B$ before the state of nature is known, to maximise expected profits

$$V_A = \rho v_A^H + (1 - \rho) v_A^L - N_B r_B x_B. \tag{15}$$

Varying $x_B$ changes costs directly, and also changes $v_A^H$ and $v_A^L$ via the constraint in (12). The first order condition for this problem is

$$\partial V_A / \partial x_B = \rho \lambda^H + (1 - \rho)\lambda^L - N_B r_B = 0 \tag{16}$$

since the Lagrange multiplier measures the value to the objective of a unit relaxation of the constraint.

As noted above, there are two cases to study. One we call the no-flexibility case, in which production is the same in both periods $x_A^L = x_A^H = x_B$. Since production is constrained by components supplied from the remote producers $\lambda^H > 0,\ \lambda^L > 0$. The other is the flexibility case in which, if demand is high, production is constrained by the supply of pre-ordered components, so $x_A^H = x_B$ and $\lambda^H > 0$. However, if demand is low then not all these components are used, so $x_A^L < x_B$ and $\lambda^L = 0$. There is free disposal of unused components.[10]

[10] Obviously, it is not profitable to discard components in both the high and the low state. The assumption of free disposal could be replaced by costly stock holding into a future period.

Which regime applies depends on parameters, including the values of $N_A$ and $N_B$. We look first at the flexibility case, then turn to the no-flexibility case and the boundary between the regimes.

In the flexibility case, solution of first order conditions (14) and (16) gives,

$$\begin{aligned} x_A^H = x_B = \left[\alpha^H - N_A r_A - N_B r_B/\rho\right]/2\beta, \qquad & \lambda^H = N_B r_B/\rho, \\ x_A^L = \left[\alpha^L - N_A r_A\right]/2\beta < x_B, \qquad & \lambda^L = 0. \end{aligned} \tag{17}$$

Using these equations we can show that the inequality $x^B > x_A^L$ holds providing $N_B r_B < \rho(\alpha^H - \alpha^L)$, this condition defining the boundary of the flexibility regime. Notice that quantities produced depend on the location of input producers. Increasing $N_B$ has the effect of decreasing output in the high demand state and increasing it in the low state. Formally, using $N_A = N - N_B$, setting $r_A = r_B = r$ and differentiating (17),

$$\frac{dy_A^H}{dN_B} = \frac{dx_B}{dN_B} = \frac{r(\rho - 1)}{2\beta\rho} < 0, \qquad \frac{dy_A^L}{dN_B} = \frac{dx_A^L}{dN_B} = \frac{r}{2\beta\rho} > 0. \tag{18}$$

Intuitively, higher $N_B$ increases the number of components left unutilised, and hence the expected cost of production; this reduces the profit maximising level of output in the high demand state. However higher $N_B$ also means that, if the low demand state transpires, a higher proportion of inputs have zero shadow price (the components from region *B* which, at the margin, are discarded). This reduces the marginal cost of production in the low state, so increasing quantity produced.

The effects of varying $N_B$ on profits are given by differentiating (15) and (12) with $r_A = r_B = r$, to give:

$$\begin{aligned} \frac{dV_A}{dN_B} &= \rho\frac{dv_A^H}{dN_B} + (1-\rho)\frac{dv_A^L}{dN_B} - N_B r\frac{dx_B}{dN_B} - rx_B \\ &= r(1-\rho)\left[x_A^L - x_B\right] = \frac{r(1-\rho)}{2\beta}\left[\alpha^L - \alpha^H + \frac{N_B r}{\rho}\right] \end{aligned} \tag{19}$$

The second equation comes from using the first order conditions (14) and (16). It says that -- once quantities of inputs are optimised -- the loss of profits due to a marginal increase in $N_B$ is simply the expected cost of quantities of this component that remain unused. The final equation

uses (17) to express this in terms of variables that are exogenous to the firm. From (19), we see that in the flexibility case (in which $N_B r_B < \rho(\alpha^H - \alpha^L)$)

$$\frac{dV_A}{dN_B} < 0, \qquad \frac{d^2V_A}{dN_B^2} = \frac{r^2(1-\rho)}{2\beta\rho} > 0. \tag{20}$$

Increasing $N_B$ therefore reduces profits, and does so at a decreasing rate, by the convexity of $V_A$. The intuition for the convexity is that the cost of a component changing from being supplied locally to being supplied remotely is that some of the component remains unused; increasing $N_B$ decreases output in the high demand state and increases it in the low state, as we have already seen (equations (18)), so reducing the gap between $x^B - x_A^L$. The implication is that there is a force for clustering of component suppliers around one of the final assemblers.

In the no-flexibility case, solution of first order conditions (14) and (16) gives

$$\begin{aligned} x_A^L = x_A^H = x_B &= \left[\rho\alpha^H + (1-\rho)\alpha^L - N_A r_A - N_B r_B\right]/2\beta \\ \lambda^L &= N_B r_B - \rho(\alpha^H - \alpha^L) \\ \lambda^H &= N_B r_B + (1-\rho)(\alpha^H - \alpha^L). \end{aligned} \tag{21}$$

The first equation gives purchases of components and hence also the level of output. This is the same in both states, so demand variability goes entirely into the price. Expected profits, $V_A$, can be computed using (21) in (12) and (15). For present purposes, the important point to notice is that if $r_A = r_B$ then output and sales levels do not depend on location of assemblers (the division of $N$ between $N_A = N_B$, see equation (21)), so neither do profits. In the interior of this regime having more local component suppliers does not bring any flexibility, nor therefore any change in production or profits.

We can now pull threads together by noting that the edge of the no-flexibility regime is where the shadow value of $x_B$ in the low state, $\lambda^L$, is zero, i.e. $N_B r_B < \rho(\alpha^H - \alpha^L)$. This is of course the same condition that gives the edge of the flexibility regime, where output levels in the high and low demand states just become equal, equation (17).

The complete picture is illustrated in figure 5. The horizontal axis gives $N_B$, and the vertical axis gives levels of production and profits of the country *A* assembler. The no-flexibility

regime is where $N_B r_B > \rho(\alpha^H - \alpha^L)$; a sufficiently large number of components come from remote suppliers that it is very costly to leave some of each of them unused if the low state occurs. Alternatively, when $N_B r_B < \rho(\alpha^H - \alpha^L)$ then only a small share of component types face the risk of being left unutilised and discarded. It is therefore worthwhile to order a larger quantity of each type of remote component, $x_B$, output becomes state contingent, and the flexibility case applies.

Notice that there are now two distinct arguments creating convexity of profits, $V_A$, with respect to $N_B$. One is that, within the flexibility regime, profits are convex, as discussed above (equation (20)). The other arises because of the kink in the upper envelope of $V_A$ due to the change in regimes. Intuitively, having more local suppliers is of no value until some threshold is passed – only then is it worth adjusting production to exploit the benefits of rapid delivery times. The implication is, once again, that input suppliers will all cluster in one location. One of the assemblers becomes completely flexible, ordering all its inputs from local suppliers once the level of demand is known. The other is inflexible, as all its inputs have to be imported and are ordered before the state of nature is known.

Several other remarks are worth making on this model. First, price variability is lower in the location with the cluster of activity, as quantities are responding to demand shocks. With linear demands the expected price is the same in both *A* and *B*,
$Ep_i = \rho p_i^H + (1-\rho)p_i^L = (\bar{\alpha} + Nr)/2$, as is the expected quantity sold,
$Ey_i = \rho y_i^H + (1-\rho)y_i^L = (\bar{\alpha} - Nr)/2\beta$. However, since the region with the cluster produces more in the higher price state, the average value of output produced $E(p_i y_i)/Ey_i$ is higher in the region with the cluster.

Finally, notice that this structure is isomorphic to a model in which shocks are on the cost side, rather than the demand side. Suppose that revenue $x_A^s(\alpha^s - \beta x_A^s)$ (equation (12)) were to be replaced by revenue net of labour costs, $\bar{p}x_A^s - (c^s + bx_A^s)x^s$ where $\bar{p}$ is an exogenously given price, and $c^s$ and $b$ are technology coefficients, giving the level and slope of average costs. If $c^s$ is state dependent, then this model is evidently identical to the one above, with parameter $\alpha^s$ replaced by parameter $\bar{p} - c^s$. Uncertainty – in either costs or demand – means that profits are higher if input decisions can be postponed. The argument of this section shows that it also generates convexity of profits with respect to the location of component suppliers, implying that this uncertainty gives rise to clustering.

**7. Policy implications**

Governments are perenially interested in regional economic development, and subsidies have often been used (and even more often proposed) as a means of sustaining regional economies. In

particular, subsidies to manufacturing assembly plants have been justified in the hope that their presence in a region will trigger agglomerations of related activities. The baseline model of section 2 offers some theoretical support for such a subsidy: starting from a world with one assembly plant with all suppliers located nearby, establishment of a second assembly plant elsewhere creates an incentive for some suppliers to move near the new plant. This is because of the decreasing marginal value of proximity in such a model: the first supplier that moves to the location of the new assembler will generate greater value as a result.

In contrast, our models of timeliness deliver the opposite conclusion. Because of the increasing marginal value of timeliness (and hence proximity), there is no incentive for any supplier to move to the location of a new assembly plant. If these models apply, we would expect new assembly plants that locate far from existing plants (for whatever reason) to not be followed by their suppliers. As shown by Klier (1999), this is what has happened in the US auto industry: assembly plants established far from the "auto corridor" as a result of government subsidies (BMW in South Carolina, Mercedes Benz in Alabama) or private incentives (NUMMI in California) have not been followed by a substantial number of suppliers.[11]

**8. Concluding comments.**

This paper offers several exploratory models of the importance of timeliness in shaping the location decisions of firms. We argue that the costs of stockholding can be very high for firms that produce a wide variety of product specifications. Absent inventories, we show how either uncertainty about the arrival time of components or uncertainty about final demand or costs mean that there is a cost to suppliers being remote, and this cost is typically convex in the number of remote suppliers. Consequently, efficient organisation of production requires the concentration of all component plants next to just one of the assembly plants.

[11] The "auto corridor" is the region in the middle of the country where most auto production is concentrated. It includes seven contiguous states: Michigan, Ohio, Indiana, Illinois, Wisconsin, Kentucky, and Tennessee.

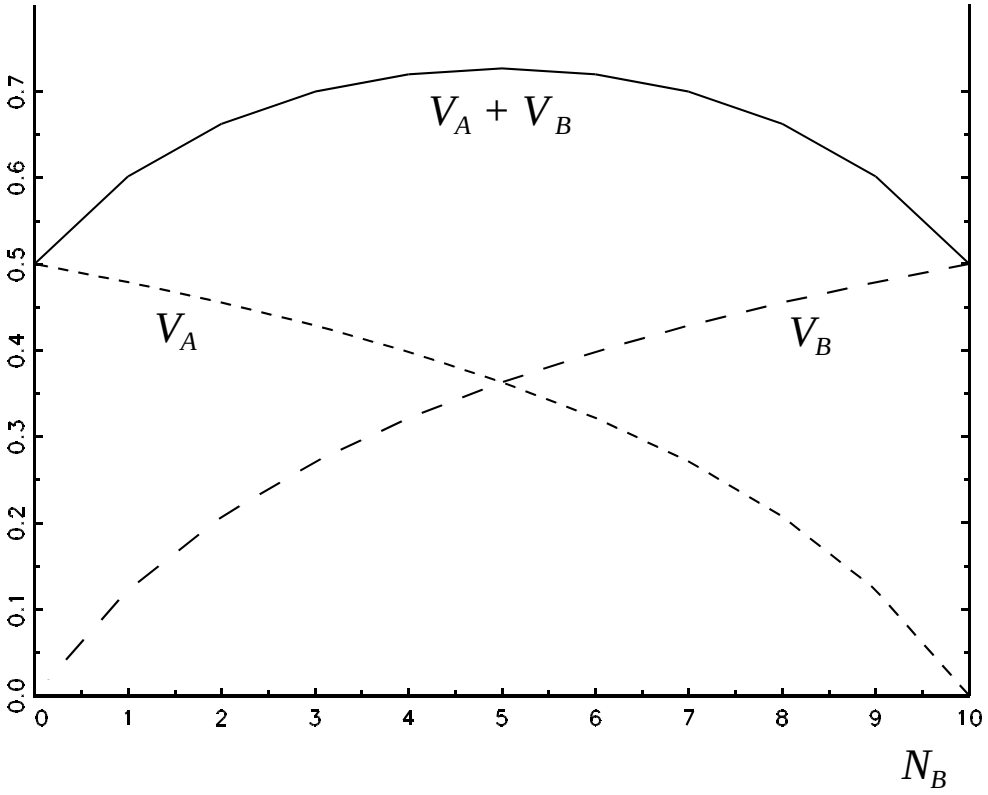



Figure 1: CES assembly (σ = 5)

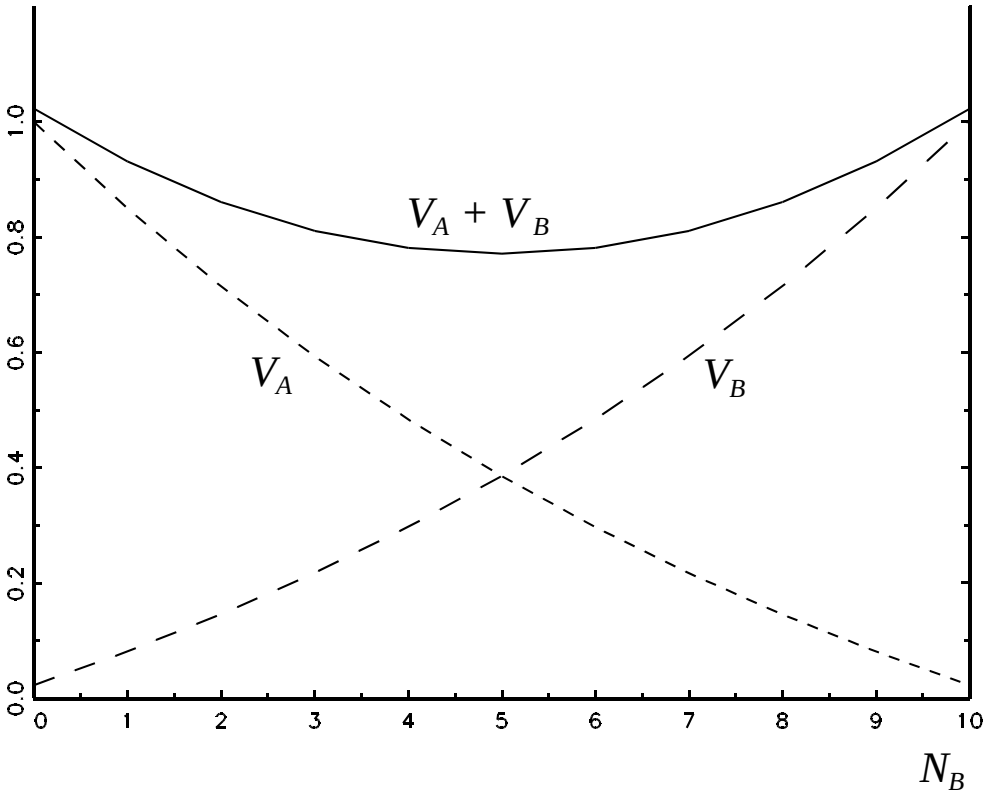



Figure 2: Arrival uncertainty

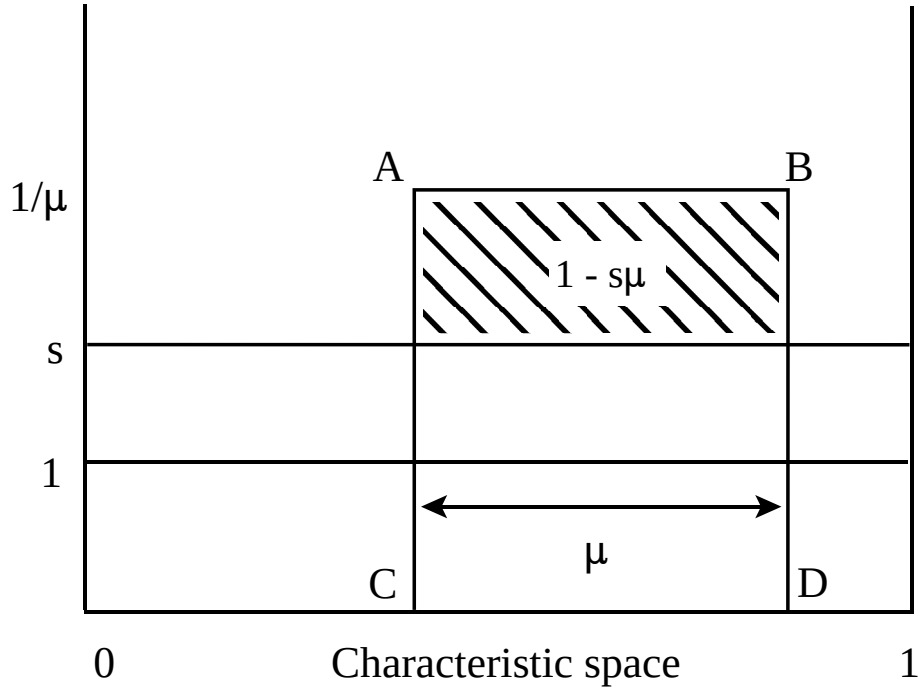



Figure 3: Demand for characteristics

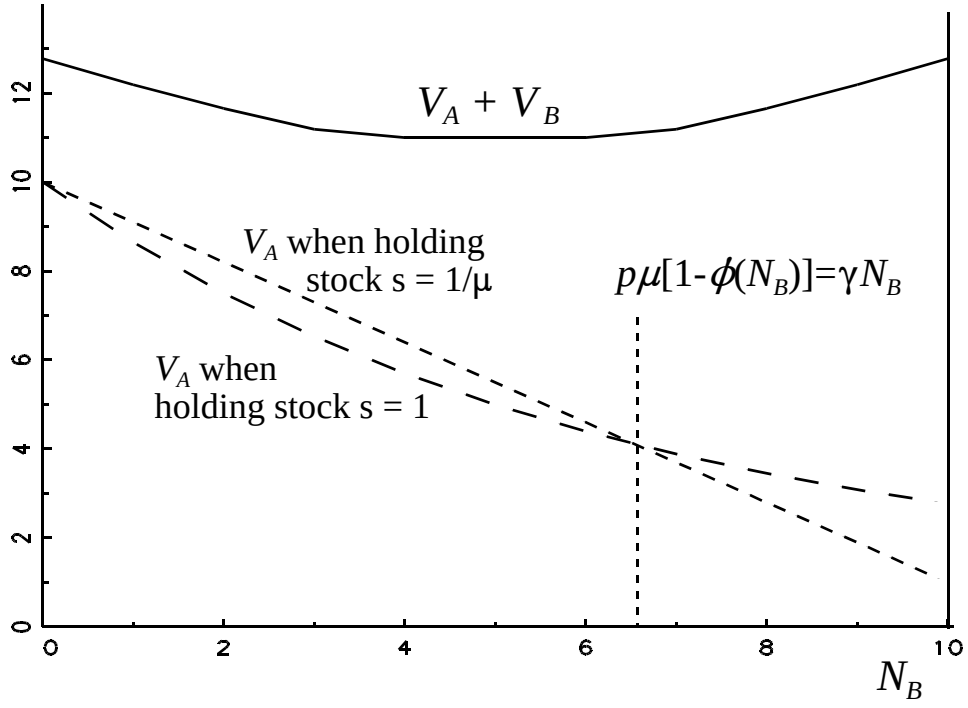



Figure 4: Inventory choice

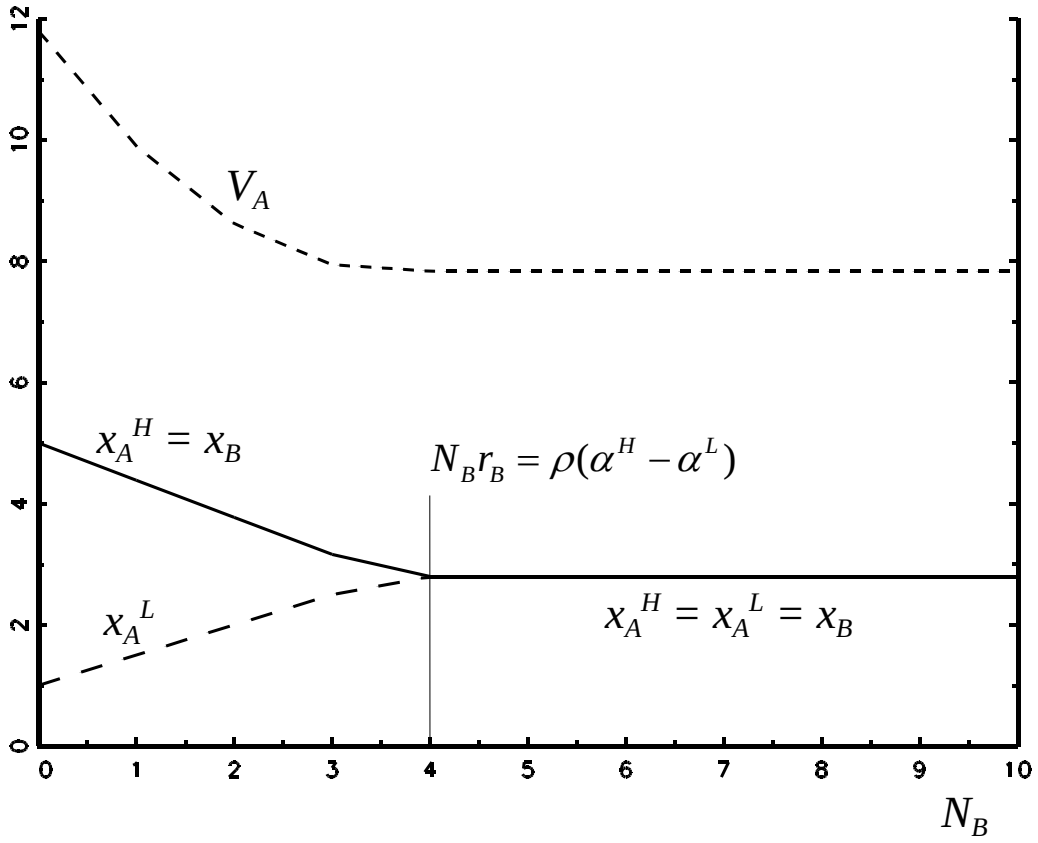



Figure 5: Demand level uncertainty

**Appendix:**

Figure 1: $r_A = r_B = 1$, $\sigma = 5$, $p = 1.5$, $\tau = 1.5$, $N = 10$.

Figure 2: $v_A^0 = 1$, $\delta p + \beta w_A = 1.5$, $q = 0.9$.

Figure 4: $r_A = r_B = 1$, $\mu = 0.1$, $\gamma = 0.1$, $\bar{p}\phi(k) = 10 * 0.85^k$

Figure 5: $r_A = r_B = 1$, $\rho = 0.45$, $\alpha^H = 20$, $\alpha^L = 12$, $\beta = 1$

Section 5: Similar results hold if mismatched components are randomly assigned to profits, in which case the expected value of assembly at *A* is:

$$V_A = \bar{p} \sum_{k=0}^{N_B} \phi(k) \binom{N_B}{k} (s\mu)^{N_B - k} (1 - s\mu)^k - (s - 1)\gamma N_B - N_A r_A - N_B r_B.$$

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