# HOW DOES RISK POOLING

# IMPACT

# MANUFACTURING NETWORK CONFIGURATION?

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## Abstract

A firm's choice between setting up a plant network is influenced by a number of factors including demand fluctuations across its portfolio of products, logistics costs and service level requirements. Generally speaking *product plant networks* offer the benefits of consolidated production and reduced transshipment costs as the product is manufactured complete under one roof and shipped to the market. On the other hand, *process plant networks* allow intensive dedication to process expertise and economies of scale. In this paper we show that besides these benefits, process plant networks offer significant risk pooling advantages under a wide range of conditions. The modeling of this problem is motivated by a real network configuration problem faced by a major telecommunications manufacturer based in North America. We solve a two-stage problem. In the first stage, we decide on the capacity acquired in each of the two types of plant networks. In the second stage, production and shipping decisions, constrained by capacity acquired, result in specific costs and customer service levels. This approach enables us to develop boundary conditions for the optimal solution. We demonstrate that even without accounting for economies of scale advantages, firms may prefer the process plant network configuration due to the risk pooling benefits offered. We quantify this advantage, derive it analytically for general demand distributions and also derive closed-form solutions for the case of uniformly distributed demand.



**Keywords: Network Configuration, Process and Product Plant Networks, 2-stage Optimization, Operations Strategy**

# How Does Risk Pooling Impact Manufacturing Network Configuration?

## 1. Introduction

Configuration of a multi-plant network to deliver products and services to markets is a difficult problem faced by many firms (Hayes and Wheelwright, 1984). Sometimes an organization can consolidate all processes for a specific product (or product line) under one roof. Such a **product plant network strategy** relies on the logic of focus – consolidating all processes for a product or a category of products under one roof results in direct savings associated with the replacement of "external" logistics (for example, co-ordination and delivery costs from feeder plants, contractors and suppliers) with "internal" logistics (internal co-ordination and delivery among departments that are in proximity of each other). However, the firm loses economies of scale at the component level. For example, common component production for several end-products is now disbursed across multiple facilities. Such examples can also be found in the service sector. For example, a health care organization operating two "specialist" hospitals may have to duplicate support services (components) such as radiology labs and patient data files across both hospitals thereby losing economies of scale.

Alternatively, firms may develop a **process plant network strategy** wherein they consolidate component manufacturing at feeder plants and ship these components to other plants. The health care organization may chose to setup a single radiology facility for both hospitals; it accrues logistics losses in the form of additional costs (to bring the reports to the hospital in a timely fashion) or customer inconvenience (if patients are asked to travel to the radiology lab for testing after visiting the hospital). Figure 1 depicts the two alternative strategies. In a product plant network strategy, plants 1 and 2 process both components (C1 and C2) required to make the product. In the process plant network strategy, plant 1 focuses on making component C1 and plant 2 focuses on component C2. Both plants possess the requisite amount of assembly capacity to put the components together. It is the choice between these two network configurations that we consider in this paper.

INSERT FIGURE 1 HERE

Our research is motivated by the manufacturing structure of a major telecommunications firm in North America. This firm has two manufacturing facilities for manufacturing telecommunication-switching devices. The switching device has two main components, frames and printed circuit boards (PCBs), and is manufactured in two main stages: fabrication of components and final assembly of components (frames and PCBs) in to the telecommunication-switching device. Their two plants are process-focused - one is dedicated to the production of frames and the other to the production of PCBs (see Figure 2). At this firm, assembly is done at both plants for shipping to geographically distinct markets. Frames are manufactured at Plant 1 and then a certain fraction of these are shipped from Plant 1 to Plant 2 for assembly; similarly, the required fraction of total PCBs manufactured at Plant 2 is shipped to Plant 1 for assembly. Much of the assembly is manual.

INSERT FIGURE 2 HERE

The differences in the manufacturing processes for making frames and PCBs allow the firm to focus on the unique processes required for each component. It also enjoys other benefits associated with consolidating all component production under one roof – scale economies, affordability of better technology due to high volumes, and critical mass in process support and development. However, the firm incurs higher shipping costs in its current configuration as well as yield problems arising as a result of shipping. The response time for a customer order is increased as production schedules and shipments across the plants have to be reconciled and sometimes orders cannot be filled as they wait for a shipment from another plant. It is for these reasons that the firm was considering the alternative shown in Figure 2 – a product plant network. This would require developing the capacity to manufacture both components in both plants. This investment in production capability at both plants for both components should reduce shipping costs and generate greater responsiveness/flexibility to market [see Doerr and Magazine (2000)]. An excellent discussion of the pros and cons of product versus process focus within plants in a network can be found in Hayes and Wheelwright (1984, p.91).

The case raises several important questions about network configuration decisions. Network configuration decisions include strategic choices of allocating manufacturing activity and process competence to a set of (network of) plants. This includes deciding on the scope and focus of plants with regard to component production, assembly, and supply etc., sometimes referred to as the plant charter. Which configuration should a firm choose – a process plant network or a product plant network? *(Note: A third alternative for the firm would be to produce both components at both plants and also ship components from one plant to the other. We do not consider this alternative in this paper. Our rationale for doing this is that such cross-shipment would reduce the product plant network to a process plant network under certain conditions making the comparison uninteresting.)* What would be the important tradeoffs in the choice of selecting a particular network configuration? Also, how should the firm decide on the allocation of component level production to multiple plants? In this paper we focus on the risk pooling benefits offered by the process plant network and demonstrate that such benefits are significant. This finding is significant in that it alerts firms to explicitly consider such benefits in making strategic configuration decisions.

In the next section we summarize the literature pertinent to the problem. In section 3 we present a simple example demonstrating the conditions under which substantial risk pooling benefits would accrue. In section 4 we present analytical models that allow us to explicitly capture the risk pooling benefits associated with process plant networks. In this paper, we do not attend to the issues related to economies of scale and capacity flexibility associated with alternative configuration choices since our intention is to show that under certain conditions, risk pooling benefits in process plants outweigh the incremental logistics burden imposed; scale economies and flexibility would no doubt enhance these benefits. Section 5 presents numerical computations from the models developed in Section 4 with uniform demand distribution and derives key insights into the nature of tradeoffs in network configuration. Section 6 concludes the paper with qualitative recommendations and some suggestions for future research.

## 2. The Manufacturing Network Configuration Problem: Literature Review and Synthesis

Several authors have addressed issues related to strategic design choices available to firms with multiple facilities in a network. Schmenner (1982) and Cohen and Lee (1989) defined and evaluated the strategic implications of process and product plant networks. Schmenner (1982) identifies four distinct multi-plant configuration strategies prevailing among Fortune 500 companies in the United States - plant charters are based on products, market areas, processes or general configurations. For example, a product network configuration would dictate that the firm produces entire products (product lines) under one roof. Cohen and Lee (1989) extend this work and formulate several plant charter strategies in global manufacturing networks:

- Regionalization Strategy, which focuses plant activity on the needs of a geographic region,
- Consolidation Strategy, which allows plants to manufacture for disparate markets with disparate processes under one roof,

- Product Focus Strategy, which establishes plants based on products or product lines,
- Process Focus Strategy, which establishes plants based on specific processes in the product value chain, and
- Vertical Integration Strategy, which assimilates vertically-integrated, processes under one roof.

Moon (1989) and Cohen and Moon (1990, 1991) address issues related to plant configuration strategies incorporating economies of scale and scope as well as inbound and outbound transportation costs. They develop single period, deterministic mixed integer programming models for plant product mix loading and offer policies for optimal configuration of a set of capacitated plants. Scale economies in production are approximated by piecewise linear functions. They find that the cost savings of focusing each plant on few products must be traded off against inbound and outbound transportation costs. Cohen and Moon (1990) investigate the impact of scale economies, scope economies and supply chain transportation costs on network configuration and distribution policy. They formulate a mixed integer non-linear programming model and develop insights on the impact of changes in a firm's cost environment on its supply chain structure. These papers do not consider the effect of demand uncertainty or the impact of long term average operational costs on the configuration decisions.

Li and Tirupati (1995) examine an investment-planning problem, which deals with the choice of technology and capacity additions to satisfy prescribed service levels in the presence of product families with dynamic demands. They consider scale economies at the plant level and attempt to minimize the total investment costs in dedicated and/or flexible capacity for two products with uniformly distributed demands. Li and Tirupati mention that one of the key features of their research is the coupling between operational and strategic planning decisions, which are made at different levels of the organizational hierarchy. They specifically consider the impact of operating policies on configuration decisions. They show that ignoring the effects of operating policies can lead to significant cost penalties.

Flexible process technology can also induce a change in the "optimal" scale at any stage in a firm's value chain. Benjaafar (1995) demonstrates the impact of flexible technology and argues that facility pooling (making multiple products under one roof) is justified when setup costs/times are low. Bish, Muriel and Biller (2001) consider a two plant- two-product setting to demonstrate that such flexibility on one hand increases sales, but may increase the variability of upstream components and their inventory levels. They suggest that

(1) *fully flexible* policies, that change production levels every period may not be as effective (as compared to partially flexible policies which change the capacity allocation in the medium term) since, while they increase sales levels somewhat, the accompanying increase in upstream inventory levels is prohibitive;

(2) *distributed* policies, which split production of each product between two plants, result in lower logistics costs but require higher component inventories (when compared to *prioritized* policies which focus production of each product in one plant) .

Karmarkar and Kekre (1989) use investment and operational costs to compare the performance of flexible and dedicated facilities. Operational aspects of the impact of flexible technology on issues such as operational costs, product variety, setup time, batch sizes, queuing delays are offered in Benjaafar and Gupta (1998), and Li and Qui (1996). An insightful analysis of the multi-plant capacity choice problem can be found in Jordan and Graves (1995). They develop principles for configuring a pre-existing network of plants for near-optimal process flexibility at a fraction of the cost for total flexibility. The work of Harrison and Van Mieghem (1999), Van Mieghem (1998), and Van Meghem (1999) are relevant too, although they are primarily in a single plant context. Harrison and Van Mieghem (1999) develop a multi-period model for investing in resources within a single plant. They factor in demand uncertainty and derive qualitative insights into the invest-stay put-disinvest decision across multiple periods. They develop the structure of optimal policies and some approximate solutions.

Pressure for delivery time and responsiveness in many industries has led firms to reassess the manufacturing network structure from a strategic perspective (Raturi et al. 1990). Product plant networks, with all processes for a product being performed under one roof, offer the obvious advantages of quick delivery. Unlike the process plant network, no time is lost in transporting components to assembly facilities. Benjaafar and Gupta (1997) evaluate the scale versus scope argument for minimal product flow times for a multi-product multi-facility problem. They conclude that the effect of product variety on manufacturing performance (flow time) is not monotonic: increased capacity and flexibility can sustain product variety up to a limit. Thereafter, there is a general degradation in performance with increased product variety.

Finally, the issues raised in Jaikumar and Upton (1993) merit attention. Making a persuasive argument for smaller plants due to the emergence of flexible capacity as well as the information technology to co-ordinate the stages of a value chain, Jaikumar and Upton conclude that "these factors serve to substantially de-emphasize economies of scale and reduce absolute cost outlay at the plant level". In an almost eerie prediction, they forecast the rise of contract manufacturing, greater levels of outsourcing, and a transition to distinctive competency centered on flexibility and not size. Their arguments clearly suggest the need for better insight into the configuration alternatives. Their arguments on risk pooling also apply to the process plant network. To quote,

> *The pooling effect of the market better insulates capacity buyers from fluctuations in demand. Since products are diversified, it will often be the case that when one capacity purchaser's demand is high (for his/her particular product) another's may be low. The pooling effect enables capacity purchasers to take advantage of the disparate temporal requirement for flexible capacity and avoid the cost of capacity constrained operation and low asset utilization that often face firms to which capacity is dedicated.*

Sometimes, risk pooling benefits are derived as a result of *backward and forward* linkages created in the process plant network. Consider the example of a leather goods manufacturer who traditionally does not enjoy high *internal* economies of scale (Junius 1997). Let us assume that there are two main components for her product; the leather shell and the steel (bolts, clips etc.). If the manufacturer were to configure her network as a process plant network then she would be able to hedge against supply side uncertainty by consolidating safety stocks and avail of labor market pooling as well as other agglomeration (scale) benefits in component production. For example, procurement of leather shell raw materials will be consolidated and shipped to just one facility. Also the process plant network will be able to better hedge against demand variations due to consolidated production. It is this phenomenon of risk pooling that we attempt to capture in this paper.

Based upon our review of the literature, “pure” (i.e. sans scale economies) risk pooling benefits of process plants have not been analyzed and quantified in a simple and insightful framework, especially in the context of network configuration. There is evidence from the supply chain management literature that such risk pooling benefits can often be substantial. For example, the research with Hewlett Packard clearly demonstrates the benefits of relocate the "localization" step in the product assembly process from the factory to the various distribution centers (Lee and Billington, 1993**)**. This transition is similar to the process plant network strategy as the factory focuses on component (printer) production. We believe that investigating the risk pooling benefits in strategic plant configuration decision would fill an important gap in the research literature as well provide relevant guidelines to firms. We next demonstrate with a simple example that even in the absence of economies of scale, process plants may be preferred in situations where significant risk pooling savings accrue. Such capacity risk pooling advantages overcome the incremental logistics costs incurred in process plants.

## 3. Risk Pooling Benefit of Process Plant Networks: A Simple Demonstration

Consider two alternative structures of our major telecommunications equipment manufacturing firm in Figure 2. Let us assume that the final product demand in each of two markets is random and i.i.d., and follows a discrete distribution in the following three scenarios: Low Variance, Medium Variance and High Variance. We want to evaluate conditions under which the risk pooling benefits accumulated at the component level by the process plant networks outweigh the additional logistics costs incurred to ship components.

INSERT TABLE 1 HERE

Marginal capacity acquisition costs are the same in both product and process plant network (differences in scale economies can be modeled using different capacity costs in these two scenarios). For the sake of the illustrative example in this section, we assume that component capacity acquired is at the same level in both plant networks. This assumption is of course relaxed when we solve the two-stage optimization problem in the next section. However, this assumption allows us to focus on the Expected Total Cost as a combination of just penalty cost for shortage in the market, and the shipping cost which is incurred in the process plant network. Thus, we restrict our attention in this section to the following two costs:

s = cost of shipping a single unit of component (C1 or C2 in Figure 2) from plant 1 to plant 2 or vice-versa; this cost incurred only for the process plant network; and,

p = unit penalty cost for shortages in the market; this parameter also models an implicit service level.

In our variable definition, we separate the capacity acquired by component type and market, in order to capture service level by markets as well as evaluate the consequences of consolidated versus distributed capacity. The decision variables follow from Figure 2:

$x_1$ = units of component C1 manufactured at plant 1 for Market A.

$$x_2 = \begin{cases} \text{units of component C1 manufactured and shipped from plant 1 to plant 2 for Market B (for Process Plants)} \\ \text{or} \\ \text{units of component C1 manufactured at plant 2 for Market B (for Product Plants)} \end{cases}$$

$$y_1 = \begin{cases} \text{units of component C2 shipped from plant 1 for Market A (for Product Plants)} \\ \text{or} \\ \text{units of component C2 manufactured and shipped from plant 2 to plant 1 for Market A (for Process Plants)} \end{cases}$$

$y_2$ = units of component C2 manufactured at from plant 2 for Market B.

We assume, as for the telecommunications equipment firm, that each facility in a process plant network manufactures a single component (C1 or C2), acquires the second component from its sister plant, and does the final assembly for its respective market. In a product plant network, both components are produced at both plants, however assembly in again done by each plant for its respective market. Referring to Fig. 2 again, in a process plant network we acquire (x1+x2) units of capacity for component C1 in plant 1 and (y1+y2) units of capacity for component C2 in plant 2. In addition, we incur the cost of logistics by transporting (x2+y1) units of components at a cost of $s per unit. In a product plant network, we acquire (x1=y1) units of capacity of C1 and C2 respectively in plant 1 and (x2=y2) units of capacity in plant 2.

There is a critical ratio (CR=p/s) for which the process plant is at least as good as the product plant in terms of Expected Total Cost. The reason for this is the straightforward tradeoff between the two configurations. High shipping costs make process plant networks unattractive since such logistics costs are incurred only in the process plant network. High penalty cost for shortages make the product plant unattractive since it does not provide any capacity risk pooling at the component level; *ceteris paribus*, shortages in product plant networks are always higher.

Any ratio of (p/s) larger than this critical ratio (CR) would make the process plant network better than the product plant network. The critical ratios for the different values of capacity acquired can then be calculated as those values where Expected Total Costs for the process plant network are lower than that for the product plant network.

We provide an illustrative calculation and then summarize our findings for all possible combinations of demand and capacity acquisition scenarios. In Figure 2, let the capacity acquired for component production be 100 units for C1 and 100 units for C2 in each of the plants in a product plant network. Thus we have 400 units of component manufacturing capacity overall, and will satisfy a maximum of 100 units of demand of the final product in *each* market. Also, the capacity acquired for C1 and C2 in a process plant network will be 200 units each. Overall, the total capacity acquisition costs are the same in both network configurations. Table 2 illustrates the computations for various demand scenarios under these conditions.

INSERT TABLE 2 HERE

Table 3 summarizes the results of these computations for the three demand scenarios from Table 1, for a range of capacity acquisitions. The main result of the computations illustrated in Table 2 appears in the middle column of Table 3. We calculated the critical ratio (p/s) by comparing the expected total costs of the product and the process plant networks in these three scenarios with various values of penalty costs (p) and shipping costs (s). In the low and high capacity acquisition scenarios, this ratio is infinite suggesting that product plant networks are always better. However, when an intermediate amount of capacity is acquired (as would be the scenario in most firms), process plants have lower expected total costs when (p/s) ratios are greater that 29, 16 or 11. For example, with low variance in demand, the expected total cost of a process plant network is lower than that of a product plant network when the (p/s) ratio is greater than 29.

INSERT TABLE 3 HERE

Why do the product plant networks dominate the process plant when capacity acquired is much higher than or lower than the average demand? With low capacity acquisition, demand is almost never satisfied and the incremental shipping cost of the process plant makes the configuration always unattractive. Similarly with high component capacity acquisition (600) all demand is satisfied and the process plant with its incremental shipping cost is never able to better the results from a product plant network. But when component capacity acquired exactly satisfies average final product demand (100), then p/s value greater than 29, 16 or 11 in the 3 respective demand scenarios result in lower total expected cost for the process plant network. We thus conclude that risk pooling benefits from consolidating component production are maximal when,

- penalty costs for shortages are high (high p/s ratio)
- shipping cost for components is low (high p/s ratio)
- variability of demand is high (since the critical ratio p/s becomes smaller).

If we consider scale economies in component production in addition, the critical ratios in the above table would be smaller. This example amply demonstrates the conditions for risk pooling favoring process plant networks.

**4. A Two-stage Optimization Model for the Network Configuration Problem**

In order to formally develop the scenarios where process plant networks offer substantial risk pooling benefits, we model a two-market, single-product, two-component, two-plant scenario (Figure 2) as a two stage optimization problem. *Our intention is to compare the costs associated with product versus process plant networks when the firm makes an optimal capacity acquisition decision.* We compare the capacity acquired (and the resulting costs) in process and product plant networks with a single period, two-stage scenario. The stages are chronologically ordered within the single period. In this case, the firm acquires capacity in the face of uncertain demand in Stage 1. This is a centralized decision taken at the corporate level that accounts for the distribution of demands across both markets as well as the resulting costs from this chosen configuration. In Stage 2, demand is observed and the firm assembles and ships to the two markets based on the respective demand and constrained by the acquired capacity vector.

We make some additional assumptions in order to assess the capacity acquisition, shortage and shipping cost implications derived from product versus process plant networks. Most of these assumptions can be relaxed at the expense of complicating the models and analysis; at this stage, a key goal is parsimony in model development. We summarize the key assumptions and the rationale here.

1. We develop single period, two-stage stochastic model. Capacity acquisition is treated as a long-term decision and we are interested in capturing the significant differences across product and process plant networks in the long-term average costs given the capacity decisions. We do not consider holding costs as we have a single period model and no inventory exists.

2. Cost of capacity acquisition is modeled using marginal costs (defined as the cost per unit of capacity acquired) as in Cachon and Lariviere (1999), Fine and Freund (1990), Li and Tirupati (1995) and Van Mieghem (1998, 1999). We ignore the impact of economies or diseconomies of scale and scope. Our intention here is to show that *there exists a significant trade-off between configuration options in the presence of risk pooling alone.* Economies of scale would only accentuate this tradeoff and lead to the selection of process plant networks in many more scenarios.

3. We assume two markets with independent, random demands for the end products. The demand distributions are known and are stationary. The models and results are developed with general distributions; however, closed form solutions to this decision problem are obtained (in Section 5) with demand following a uniform distribution.

Further, there is no demand for components alone (for example, for service parts and replacements).

4. The objective is to minimize total cost including the capacity acquisition costs, cost of shipping component (in a process plant), and penalty costs associated with shortages. The cost of shipping includes losses due to 'shipping damage' and other incidentals that were quite significant in the case of the telecommunications firm.

The following variables are used in the formulation. Let $K_i$ denote the total capacity acquired at plant i. Also,

$x_1$ = units of component C1 shipped from plant 1 for Market 1.

$$x_2 = \begin{cases} \text{units of component C1 shipped from plant 1 for Market 2. (for Process Plants)} \\ \text{or} \\ \text{units of component C2 shipped from plant 2 for Market 2. (for Product Plants)} \end{cases}$$

$$y_1 = \begin{cases} \text{units of component C2 shipped from plant 1 for Market 1. (for Product Plants)} \\ \text{or} \\ \text{units of component C2 shipped from plant 2 for Market 1. (for Process Plants)} \end{cases}$$

$y_2$ = units of component C2 shipped from plant 2 for Market 2.

**4.1 Two-stage Model for a Process Plant Network**

The formulation of the two-stage problem for the process plant can be written as:

Stage 1:

$$W(K^*) = \underset{K \in R_+^2}{Min.}\ W(K)$$

Stage 2:

$$\Pi = Min. \quad s\,(y_1 + x_2) + p\sum_{i=1}^{2}\left(D_i - Min(x_i, y_i)\right)$$

$$St. \quad x_1 + x_2 \le K_1$$
$$y_1 + y_2 \le K_2$$
$$x_i \le D_i,\ y_i \le D_i\ \forall i$$

where, $W(K) = E\,\Pi + \sum_{i=1}^{2} c_i K_i$, $\Pi$ represents the Stage-2 objective function and $K^*$ represents the optimal capacity acquisition *vector*.

The quantities of the two components will never be unequal (i.e. $x_i = y_i$). This result can be verified by examining the Stage-2 linear program's objective function. Thus $K^*$, the optimal capacity acquisition, is a single value and no longer a 2-vector. The unique optimal capacity acquisition for the two-stage Process Plant model is given as $K^* = F_D^{-1}[1 - \frac{c_1 + c_2}{p - s}]$ where, $D=D_1+D_2$, represents the two-fold convolution of demands in the two markets and $F_D$ represents the cumulative distribution function of the convolution. Appendix I derives this result. This result is intuitively verified by a cursory glance of the objective function coefficients – optimal capacity acquired is monotonically increasing in (p-s) and decreasing in ($c_1+c_2$). This can be verified easily; as well as the result that optimal capacity acquisition is less sensitive to the second stage penalty and shipping costs than the first stage capacity acquisition costs, i.e. $\frac{\partial K^*}{\partial C} > \frac{\partial K^*}{\partial a}$ where, $C=c_1+c_2$ and $a$ = (s-p). As in the newsvendor problem, one would expect that the capacity acquisition decision would be more sensitive to the marginal capacity acquisition costs. This result is similar to the conclusions of Cohen and Moon (1991), regarding a firm's cost environment change and the impact on its supply chain configuration.

Our result stresses the need for considering the impact of operational decisions, *explicitly* in the capacity acquisition decision (i.e. a two stage analysis of the network problem). Without the consideration of operational decisions on shipping quantities, one would acquire capacity independently for plant 1 and plant 2 (Single-stage analysis) and the optimal capacity acquisition would be given as

$$K^* = \sum_{i=1}^{2} F_i^{-1}[1 - \frac{c_1 + c_2 + s}{p_i}].$$

Appendix I derives this result. To compare the single stage solution in contrast with the two stage solution consider a simple numerical example with s = 2, $c_1 = 4$, $c_2 = 3$, $D_1 \sim U(0, 3000)$,

$D_2$ ~ U(0,1000) and p = 15. Then the newsvendor type solution to the problem would suggest a critical fractile of [(1-(4+3+2)/15 ] or 40%. With the demand distribution given above, this would result in an optimal capacity acquisition of 1200 (=.4*3000) for market 1 and 400 (=.4*1000) for market 2. However, for the 2-stage formulation, the solution is quite different (see Table 4 for results).

INSERT TABLE 4 HERE

In Table 4, the difference in expected total costs reflects the impact of not explicitly considering the effect of operational decisions in the strategic configuration problem. In fact, this difference can be shown to be equal to $\left(p-s\right)\int_{K_{1-S}^{*}}^{K_{2-S}^{*}} D\ f\left(\cdot\right) dD$, where

$K^{*}_{1\text{-}S} = \sum_{i=1}^{2} F_i^{-1}[1-\frac{c_1+c_2+s}{p_i}]$ and $K^{*}_{2\text{-}S} = F_D^{-1}[1-\frac{c_1+c_2}{p-s}]$ and D represents the two-fold demand convolution. The value of information and capacity risk pooling is clearly suggested in the reduction in the expected total cost for the two-stage formulation. Why do we acquire more capacity in this situation? With the pooling of demand information from the two markets, we are exposed to reduced demand risk and hence we can afford to provide a higher service level. Note that the service level in this example increases from 40% to about 47.1% coverage. Such service levels are not uncommon for capacity decisions if one considers the fact that most firms plan capacity to meet the average demand (50% coverage).

### 4.2 Two-stage Model for a Product Plant network

In the case of the product plant network we have the following two-stage problem.

Stage 1:

$$W(K_i^*) = \underset{K_i \in R_+^1}{Min.}\ W(K_i)$$

Stage 2:

$$\Pi_i = Min.\ p\,(D_i - x_i)$$
$$St.\quad x_i \le K_i$$
$$x_i \le D_i$$

where i=1,2 denotes markets 1 and 2 respectively and $W(K_i) = E\,\Pi_i + (c_1 + c_2)K_i$. The unique optimal capacity acquisition for the two-stage Product Plant model is given as

$K_i^* = F_{D_i}^{-1}[1 - \frac{c_1 + c_2}{p_i}]$ where i = 1,2 denotes markets 1 & 2 respectively and FDi represents the distribution function for demand in market i.

### 4.3 Comparing the Performance of Product and Process Plant Networks

Proposition 1 quantifies the difference in expected total costs of product and process plant networks since one of our primary goal is to decide which configuration provides lower long-term configuration and average operating costs.

**Proposition 1[1]: The difference in the optimal expected total costs (ETC) between the process and the product plant network is given as,**

**a.** $\Delta ETC = p\sum_{i=1}^{2} \int_{D_i \le K_i^*} D_i\ f_i(\cdot)\,dD_i - (p - s)\int_{D \le K^*} D\ f(\cdot)\,dD$

**b.** $\dfrac{\partial^2 \Delta ETC}{\partial s^2} = -\dfrac{(c_1 + c_2)}{(p - s)^3\, f(K^*)}$

**c.** $\dfrac{\partial^2 \Delta ETC}{\partial p^2} = \dfrac{(c_1 + c_2)^2}{p^3}\left( \sum_{i=1}^{2} \dfrac{1}{f_i(K_i^*)} - \dfrac{1}{\left(1 - \dfrac{s}{p}\right)^3 f(K^*)} \right)$

It is important to note that Proposition 1 does not assume any particular demand density functions. Further analysis yields 1b and 1c. We observe that the difference in the expected total costs is strictly concave in the shipping costs. Such a conclusion cannot be reached for 1c, since it cannot be signed in general. This has important implications, as we shall see later. The importance of Proposition 1 becomes more evident when we discuss Figures 4 and 5 in the numerical illustration in the next section. Proposition 1 is a key result of our paper. It allows us to develop the exact solutions to the difference in the total costs under varying assumptions on the distribution of demand across the two markets, and the level of correlation in the demand for the two markets. The results for optimal capacity acquisition for the process plant network do not make any assumption about independence of demand. If demands are N ($\mu_1 + \mu_2$ , $\sigma_1^2 + \sigma_2^2 + 2 \rho \sigma_1 \sigma_2$ ), then the expression for optimal capacity acquisition, $K^* = F_D^{-1}[1 - \frac{c_1 + c_2}{p - s}]$, is given as,

$$K^* = \mu_1 + \mu_2 + \sqrt{s_1^2 + s_2^2 + 2 r s_1 s_2}\, \Phi^{-1}[1 - \frac{c_1 + c_2}{p - s}].$$

For the product plant network, the optimal capacity acquisition in the presence of demand correlation would result from:

$$\textbf{Min:}\ (c_1 + c_2)\sum_{i=1}^{2} K_i + \sum_{i=1}^{2} p \int_{0}^{\infty}\int_{K_i}^{\infty} (D_i - K_i)\, f(D_1, D_2)\, dD_1\, dD_2$$

The optimal capacity acquisition is then given as,

$$K^* = H_1^{-1}[1 - \frac{c_1 + c_2}{p_1} | D_2] + H_2^{-1}[1 - \frac{c_1 + c_2}{p_2} | D_1]$$

where, $f(D_1, D_2)$ represent the joint density function of the demands in the two markets, whereas, $h_i(\cdot|D_j)$ and $H_i(\cdot|D_j)$ represent the conditional density and distribution functions respectively for i=1,2 , j=1,2 and i?j. If demands are assumed to be $N(\mu_1 + \mu_2 , \sigma_1^2 + \sigma_2^2 + 2 \rho \sigma_1 \sigma_2 )$, as assumed earlier for the Process plant model, then for the Product plant model,

$$K^* = \mu_1 + \rho\ (d_2 - \mu_2)\ \sigma_1/\sigma_2 + \sigma_1 \sqrt{1-r^2}\ \Phi^{-1}[1-\frac{c_1+c_2}{p_1}]$$

$$+\ \mu_2 + \rho\ (d_1 - \mu_1)\ \sigma_2/\sigma_1 + \sigma_2 \sqrt{1-r^2}\ \Phi^{-1}[1-\frac{c_1+c_2}{p_2}]$$

where $d_i$ represents a realization of the random demand $D_i$.

## 5. Numerical Examples with Uniform Demand Distribution

In this section we illustrate the results from the previous section by first demonstrating the general functional form of the difference in the expected total costs of the two configurations when demand is independent and uniform. We then show several numerical examples that give us insight into the nature of risk pooling benefits under varying parameter specifications.

### 5.1 Results for a Two-stage Model for a Process Plant Network with Uniform Demand

So far we have not imposed any specific distribution requirements for our results. With Uniform demands $D_i \sim U(0,\beta_i)$ assuming that $b_1 \geq b_2$ we can derive closed form solutions to the optimal capacity decision for a process plant network. This makes it easy to demonstrate the sensitivity of the optimal capacity acquisition to key cost and demand parameters as well as improves the ability to conduct a sensitivity analysis to help the decision maker evaluate what-if scenarios for the long-term capacity acquisition problem. The unique optimal capacity acquisition for the two-stage Process Plant model when demands are distributed as $D_i \sim U(0, \beta_i)$, give some interesting insights and a rather simple formula.

**Lemma 1: The optimal capacity acquisition for a process plant network with uniform demand can be given as**

$$K^* = \sqrt{2b_1b_2\left(1-\frac{c_1+c_2}{p-s}\right)} \qquad when, (p-s)(1-\frac{b_2}{2b_1}) < (c_1+c_2) \le (p-s)$$

$$K^* = \frac{b_2}{2} + b_1\left(1-\frac{c_1+c_2}{p-s}\right) \qquad when, (p-s)(\frac{b_2}{2b_1}) < (c_1+c_2) \le (p-s)(1-\frac{b_2}{2b_1})$$

$$K^* = b_1 + b_2 - \sqrt{2b_1b_2\left(\frac{c_1+c_2}{p-s}\right)} \qquad when,\ 0 \le (c_1+c_2) \le (p-s)(\frac{b_2}{2b_1})$$

$$K^* = b_1 + b_2 \qquad when, (c_1+c_2) = 0$$

A simple example is used to illustrate the solutions to the process plant network problem. Consider a firm with (p-s)=$13. Table 5 illustrates the capacity acquisition decision for this firm given the varying values of ($c_1$+ $c_2$). When $ß_1$=3000 and $ß_2$=1000, then $ß_2$ /$2ß_1$=0.167 and (1-$ß_2$/$2ß_1$)=0.833.

INSERT TABLE 5 HERE

As can be seen from Table 5, decreasing costs of acquiring capacity result in increases in optimal capacity acquired until we cover the maximum demand in both markets (4000 units). Note that the service levels in this example range from about 17% to 47% to 76% to 100% with decreasing cost of capacity. Figure 3 plots the optimal capacity acquired by the process plant as a function of the cost of capacity. Note that under a wide range of conditions, 0.167(p-s) < ($c_1$+ $c_2$) = 0.833(p-s), the optimal capacity acquired is linear in $ß_1$ and $ß_2$. This is a robust result even under different distribution assumptions. For example, we have verified that when demand is normally distributed in Market 1 or Market 2 or both markets, the results for the optimal capacity acquired do not change significantly. It is easily verified from Figure 3 that when the cost of capacity is 0, the firm acquires capacity to cover the maximum demand (4000 units). When the cost of capacity is equal to (p-s)=13, the firm acquires 0 capacity. This highlights the importance of establishing which “zone” the plant network operates in – the definition of these zones depends not just on the cost parameters (p, s, $c_1$ and $c_2$) but also on the relative demand served in each market (ratio of $ß_2 /2ß_1$).

INSERT FIGURE 3 HERE

From now on, for all the computations we assume that the costs of capacity and the demand distributions are given as: $c_1$ = \$4/unit, c2= \$3/unit, $D_1$ ~U (0, 3000), $D_2$~U (0,1000).

In Figure 4 we plot, for the process plant network, the variation in optimal capacity acquisition "K" with variation in penalty costs, at different levels of shipping cost "s". The slope of the curves is given as $\frac{\partial K}{\partial p} = \frac{(c_1 + c_2)}{(p-s)^2 f(K)}$. We note that the optimal capacity acquired is very sensitive to changes in the penalty costs at lower levels as opposed to when penalty costs are relatively high. This is because after a certain point, *almost* 100 % service levels (but *never* equal to 100%) are achieved by the acquired capacity and hence shortage penalties do not contribute much to the total cost. This is equivalent to saying that a "newsboy" is ordering a large fractile of the demand distribution; hence lost sales do not have much effect on the ordering policy. As shipping costs increase, lower levels of capacity are acquired.

INSERT FIGURE 4 HERE

For the process plant network, we also assess the variation in optimal capacity acquired with variation in shipping costs at different levels of penalty costs "p" (see Figure 5). The slope of the curves is given as $\frac{\partial K}{\partial s} = -\frac{(c_1 + c_2)}{(p - s)^2 f(K)}$. Once again we observe that at higher levels of the penalty cost "p", the optimal capacity acquisition is less sensitive to variation in the cost of shipping. Figures 4 and 5 demonstrate the tradeoff between penalty costs (increases capacity acquired) and shipping costs (decreases capacity acquired) for a given cost of capacity. When penalty costs are high, the marginal effect of shipping cost on the capacity acquired is reduced. Thus process plant networks in fashion goods (where penalty costs are high), or in other environments where contribution margins of products are large, are less prone to shipping cost effects.

INSERT FIGURE 5 HERE

### 5.2 Network Configuration Choice with Uniform demand

From Proposition 1a we obtain an expression for the difference in Expected Total Costs (ETC) for the Product and Process plant configurations when demands are uniformly distributed. The difference in optimal ETCs between the two-stage process and product plant networks when demands are distributed as $D_i \sim U(0, ß_i)$ is useful in understanding the impact of the cost vector on the choice of alternate network configurations.

**<u>Lemma 2</u>: The difference in the optimal expected total cost (ETC) between a process and a product plant network with uniform demand distribution can be given as**

$$\Delta ETC = \frac{p}{2}\sum_{i=1}^{2}\frac{(K_i^*)^2}{b_i} - (p-s)\frac{(K^*)^3}{3b_1 b_2} \qquad when, (p-s)(1-\frac{b_2}{2b_1}) < (c_1+c_2) \le (p-s)$$

$$\Delta ETC = \frac{p}{2}\sum_{i=1}^{2}\frac{(K_i^*)^2}{b_i} - (p-s)\left(\frac{(K^*)^2}{2b_1} - \frac{b_2^{\,2}}{6b_1}\right) \qquad when, (p-s)(\frac{b_2}{2b_1}) < (c_1+c_2) \le (p-s)(1-\frac{b_2}{2b_1})$$

$$\Delta ETC = \frac{p}{2}\sum_{i=1}^{2}\frac{(K_i^*)^2}{b_i} \qquad when,\ 0 \le (c_1+c_2) \le (p-s)(\frac{b_2}{2b_1})$$

$$+(p-s)\left(\frac{(K^*)^3}{3b_1b_2} + \left(\frac{b_1}{2b_2} - \frac{(K^*)^2}{2b_1b_2}\right)(b_1+b_2) - \frac{b_1^{\,2}}{3b_2} - \frac{b_1}{2} + \frac{b_2^{\,2}}{6b_1}\right)$$

$$\Delta ETC = \frac{p}{2}\sum_{i=1}^{2}\frac{(K_i^*)^2}{b_i} \qquad when, (c_1+c_2) = 0$$

In Figure 6 we plot the difference in expected total costs (process plant network – product plant network) against the shipping costs, for 3 values of shortage penalty costs. Thus values above the x-axis represent situations where product plants are preferred. The curves represent concave functions, with the level of concavity diminishing as "p" increases. This is in accordance with Proposition 1b. In all three curves the process plant network is more attractive at lower levels of shipping costs. This is quite intuitive. However, what is more interesting, and not so intuitive is that as penalty costs increase (say from 10 to 20), the process plant network remains attractive for *larger* values of the shipping cost. Conventional thinking about process plants is driven by economies of scale thinking. This result explicitly quantifies the risk pooling advantages of process plants with respect to increased level requirements, without convoluting these advantages with economies of scale benefits. Risk pooling advantages of process plants provide sound market responsiveness logic; and under certain conditions, as demonstrated above, represent the better choice, even without scale economies.

INSERT FIGURE 6 HERE

Figure 7 plots the difference in expected total costs against the penalty costs, while fixing the shipping costs at various levels. The values of other parameters remain the same as assumed earlier. We notice that at low values of shipping cost (say s=1), the process plant network remains attractive over the entire range of penalty costs above $13 per unit. This would mean that at certain levels of shipping costs, the Process plant is clearly the more attractive option. However, what is more interesting is the shape of the curves at low shipping costs. The difference in expected total costs is represented as a convex function (not observable in the graph but numerical values validate this). The *difference* increases, becomes maximum (which is actually the minimum of the convex function) and then decreases again. In fact, for s=1.44, the Product Plant dominates over the early region of penalty costs, then the Process Plant takes over and later the Product plant again becomes more attractive.

INSERT FIGURE 7 HERE

This behavior may be explained as follows. For cases such as s = 1.44, at low levels of penalty costs, the shipping cost penalties outweigh the risk pooling gains. The firm would choose the product plant network to avoid the added logistics costs. Now, as the penalty cost increases, the firm would want to benefit from the risk pooling advantages provided by the process plant network. However, as the penalty cost crosses some critical threshold level, the firm would then expect to be better off acquiring a large amount of capacity and focusing on each market separately, thus resorting to the product plant network once again. This has interesting implications with regard to the joint consideration of penalty, shipping costs and demand uncertainty in plant network configuration decisions. With uncertain demand, it is important that firms consider the joint effects of implicit service levels and shipping costs especially if the relative levels of both costs are such that a clear-cut dominance of one configuration strategy over another is not evident.

To reiterate, our main conclusions are as follows. First, conventional thinking about process plants suggest that they are very attractive when a firm can achieve economies of scale in component production; however, we show that process plant configuration is also advantageous to firms with sufficient demand uncertainty to warrant risk pooling in component manufacturing. These firms would also typically have low shipping costs per unit and desire high service levels (high penalty costs of not shipping). Second, firms that have an agenda to provide intermediate service levels (when compared to standard industry benchmarks) should also consider the process plant network strategy. At very high and very low shortage cost per unit, product plant network strategies tend to dominate. These generalizations are based on the results shown above; ideally the firm should investigate such nuances in their own industry. We also conclude that in the presence of uncertain demand, it is important to consider the shape of the entire demand distribution as well as the joint effect of service level and shipping costs. Table 6 provides an itemized summary of our results.

INSERT TABLE 6 HERE

## 6. Conclusions and Future Research

The focus on the level of specialization (core competence) has recently led to the tremendous growth in contract manufacturing. In the cellular phone industry, as much as 70% of manufacturing is outsourced to contract manufacturers, with the same contract manufacturer often supplying competing firms. The process plant network evolving in this industry allows the players at the component level to focus on a "narrower" expertise base, deliver economies of scale through consolidation, as well as hedge upstream firms (contract manufacturers) from variations across product lines and markets in the industry. These risk pooling benefits have significant impacts on a firm's decision to consolidate component production.

We have illustrated with the help of a two-stage optimization model as well as numerical examples that the strategic choice between alternate plant network configurations is a difficult decision that must account for such risk pooling benefits. Using a motivating example of a real manufacturing firm, we first assess the long-term capacity acquisition problem using two-stage models, which explicitly consider the impact of operational decisions and the risk pooling advantage provided by the process plant network. We find that the choice of network configuration (product versus process plant network) can fluctuate depending upon the level of demand uncertainty and the cost parameters. Our results as well as our computations with numerical examples suggest the following.

First, compared to two-stage models, traditional single-stage formulations underestimate the capacity required in the network. Second, process plants provide greater advantages when logistics costs are low, and/or the demand variance is high. Third, the impact of the cost structure on the network configuration choice is not intuitive in some cases. For example, implicit service level requirements strongly affect the choice of network configuration, but this choice is affected in complicated ways by the level of demand uncertainty and logistics costs. Finally, we provide guidelines to the sensitivity of this choice to the parameters; this clearly suggests that some parameters must be estimated more accurately by the firm than others.

Our research results suggest that even in the absence of scale economies, firms gain significant benefits by choosing process networks and deriving risk pooling advantages thereof. Obviously, significant scale economies would tip the scale further towards choosing process plant networks. The rampant growth of contract manufacturing in telecommunications equipment provides empirical evidence justifying this argument.

Current tendencies of firms such as using contract manufacturing, outsourcing and managing globally dispersed facilities make it vital that firms evaluate their plant network strategy critically. We have not comprehensively researched the many implications of alternative strategies in networks – instead we focus on the cost and service level implications. One immediate area of future research is to investigate the more complex implications of alternative network strategies using metrics such as response time to customers, levels of inventory and ability to deliver customized products. Process and component commonality in the product structure and its impact on the network configuration choice can also be investigated. This would be interesting since it would be a combined look at risk pooling from the perspective of a common component (inventory) and network structure. Multi-period models, in which the firm has a strategic planning horizon, can also be constructed and optimal policies derived with multi-stage decisions within each period. Finally, the consideration of supply side uncertainty in the network configuration problem would be interesting.

## Appendix I: Deriving Optimal K* for Process and Product Plant Networks

*Consider first, a single-stage optimization problem for the Process plant.*
***Single-stage (Process Plant)***

***Min:*** $s(x_2 + y_1) + c_1(x_1+x_2) + c_2(y_1+y_2) + P$
***St :*** $x_i$ , $y_i$ ³ 0, " *i*

*where,* $P = \sum_{i=1}^{2} p_i \int_{\mathrm{Min}(x_i,\, y_i)}^{\infty} (x_i - \mathrm{Min}(x_i , y_i))\, f_i(x_i)\, dx_i$

***An optimal solution will have the property*** $x_i = y_i$
***Proof:*** *It is sufficient to consider the two cases below.*

*Case 1: (*$x_i^*$ ³ $y_i^*$*)*
*Let [*$x_1^*, y_1^*, x_2^*, y_2^*$*] be an optimal solution such that* $x_i^*$ ³ $y_i^*$ *. Let the optimal objective function be Z*. Now, consider another feasible solution, [*$y_1^*, y_1^*, y_2^*, y_2^*$*]. Let the objective function value with this solution be Z. We have,* $Z^* - Z = s(x_2^* - y_2^*) + c_1 (x_1^* - y_1^*) + c_1 (x_2^* - y_2^*)$
*Since Z* - Z is greater than or equal to zero, Z is an optimal solution.*

*Case 2: (*$x_1^*$ ³ $y_1^*$ *and* $x_2^*$ £ $y_2^*$*)*
*Let [*$x_1^*, y_1^*, x_2^*, y_2^*$*] be an optimal solution such that* $x_1^*$ ³ $y_1^*$ *and* $x_2^*$ £ $y_2^*$*. Let the optimal objective function be Z*. Now, consider another feasible solution, [*$y_1^*, y_1^*, x_2^*, x_2^*$*]. Let the objective function value with this solution be Z. We have,* $Z^* - Z = c_1 (x_1^* - y_1^*) + c_1 (y_2^* - x_2^*)$
*Since Z* - Z is greater than or equal to zero, Z is an optimal solution.*

*The first order optimality conditions for the above model are given as,*

$$(s+c_1+c_2) - p_1[1-F_1(x_1)] = 0 \qquad (1)$$

$$(s+c_1+c_2) - p_2[1-F_2(x_2)] = 0 \qquad (2)$$

*where,* $F_i(x_i^*)$ *is the cumulative distribution function for demand. Solving (1) and (2) above, we get,*

$$p_1[1-F_1(x_1^*)] = p_2[1-F_2(x_2^*)] \qquad (3)$$

*Based on (1) and (2) it is easy to see that the optimal solution is,*

$$K^* = \sum_{i=1}^{2} F_i^{-1}[1 - \frac{c_1 + c_2 + s}{p_i}] \, .$$

*The Two-stage optimization model for the Process Plant can be written as:*
***Two-Stage Process Plant Model***

Stage 1:

$$W(K^*) = \underset{K \in R_+^2}{Min.} \; W(K)$$

Stage 2:

$$\Pi = Min. \quad s\,(\,y_1 + x_2) + p \sum_{i=1}^{2} \left(D_i - Min(x_i, y_i)\right)$$

$$St. \quad x_1 + x_2 \le K_1$$

$$y_1 + y_2 \le K_2$$

$$x_i \le D_i, \; y_i \le D_i \; \forall i$$

*where,* $W(K) = E\,\Pi + \sum_{i=1}^{2} c_i K_i$ *, and P represents the Stage-2 objective function and* $K^*$ *represents the optimal capacity acquisition vector.*

*We note that* $x_i = y_i$ *which results in a unitary capacity acquisition vector K. Upon differentiating the objective function w.r.t K we get the first order condition as,*

$$P(D_1 + D_2 > K) - \frac{c_1 + c_2}{p - s} = 0 \qquad (4)$$

*where,* $D=D_1+D_2$*, represents the convolution of demands. Let* $F_D$ *represents the cumulative distribution function of the convolution and f(.) its probability density function. Then we have the optimal capacity acquisition given as,*

$$K^* = F_D^{-1}[1 - \frac{c_1 + c_2}{p - s}]$$

*What remains to be proven is uniqueness and optimality of the solution given by (4). This is easily verified since the second derivative of the objective function w.r.t K is given as,*

$$\nabla^2 W(K) = (p - s)\, f(K) > 0$$

*Let* $a = (s-p)$ *and* $(c_1+c_2) = C$*. Then differentiating the optimal K* w.r.t.* $a$ *and C we get,*

$\frac{\partial K^*}{\partial C} = \frac{1}{a\ f(K^*)}$ *and* $\frac{\partial K^*}{\partial a} = \frac{-C}{a^2\ f(K^*)}$*. Based upon our assumption that* $(p-s) > (c_1 + c_2)$ *it is easy to see that* $\frac{\partial K^*}{\partial C} > \frac{\partial K^*}{\partial a}$.

## References


BENJAAFAR, S. AND D. GUPTA. "Scope Versus Focus: Issues of Flexibility, Capacity and Number of Production Facilities," *IIE Transactions* 30 (5), 1998.

BISH, E.K., A.MURIEL AND S. BILLER "Managing Flexible capacity in a Make-to-order Environment," *Working papers, Report on NSF Contract DMI-0010357,* September 2001

CACHON, G. P. AND M. A. LARIVIERE "Capacity Choice and Allocation: Strategic Behavior and Supply Chain Performance," *Management Science* 45 (8), 1999.

COHEN, M. A. AND H. L. LEE. "Resource Deployment Analysis of Global Manufacturing & Distribution Networks," *Journal of Manufacturing and Operations Management* 2, 1989.

COHEN, M. A. AND R. HALPERIN. "Optimal Technology Choice in a Two-stage-Stochastic Environment," *Journal of Operations Management.* 6 (3,4), 1986.

COHEN, M. A. AND S. MOON. "Impact of Production Scale Economies, Manufacturing Complexity and Transportation Costs on Supply Chain Facility Networks," *Journal of Manufacturing and Operations Management* 3, 1990.

COHEN, M. A. AND S. MOON. "An Integrated Plant Loading Model with Economies of Scale and Scope," *European Journal of Operational Research* 50 (3), 1991.

DIETER, E. "From Partial to Systemic Globalization: International Production Networks in the Electronics Industry," Berkeley Roundtable on the International Economy, University of California at Berkeley. (Working Paper # 98), 1997.

DOERR, K AND M. J. MAGAZINE. "Design, coordination and control of hybrid factories: Research issues from an exploratory field study," *International Journal of Operations and Production Management,* 20 (1), 2000.

FINE, C. H. AND R. M. FREUND. "Optimal Investment in Product Flexible Manufacturing Capacity," *Management Science* 36 (4), 1990.

HAYES, R. H. AND S. C. WHEELWRIGHT. "Restoring Our Competitive Edge," *New York: John Wiley and Sons*, 1984.

HARRISON, J. M. AND J. A. VAN MIEGHEM. "Multi-Resource Investment Strategies: Operational Hedging Under Demand Uncertainty," *European Journal of Operational Research* 113 (1), 1999.

RAMACHANDRAN, J. AND D. M. UPTON, "The coordination of global manufacturing", in "Globalization, Technology and Competition: The Fusion of Computers and Telecommunications", Edited by Stephen P. Bradley, Jerry A. Hausman and Richard L. Nolan, Harvard Business School Press, Boston, MA., 1993.

KARMARKAR, U. S. AND S. KEKRE. "Manufacturing Configuration and Mix Flexibility," *Journal of Manufacturing Systems* 6 (4), 1989.

LI, S. AND QUI J. "Models for Capacity Acquisition Decisions Considering Operational Costs," *International Journal of Flexible Manufacturing Systems* 8, 1996.

LEE, H.L. AND C. BILLINGTON. "Material management in decentralized supply chains," *Operations Research*, 41:835-847, 1993.

LI, S. AND TIRUPATI D. "Technology Choice with Stochastic Demands and Two-stage Capacity Allocation : A Two-Product Analysis," *Journal of Operations Management* 12 (3,4), 1995.

MOON, S. "A Profit Maximizing Plant-Loading Model with Demand Fill-Rate Constraints," *Journal of Operational Research Society* 40 (11), 1989.

RATURI, AMITABH, JACK MEREDITH, JEFFREY CAMM AND DAVID MCCUTCHEON. "Coping with the Build to Forecast Environment, Journal of Operations Management, Vol 9 No 2, 1990.

SCHMENNER, R. W. "Multiplant Manufacturing Strategies Among the Fortune 500," *Journal of Operations Management* 2 (2), 1982.

SCHMENNER, R. W. "Making Business Locations Decisions," *Englewood Cliffs, New Jersey: Prentice Hall* 1982

VAN MIEGHEM, J. A. "Investment Strategies for Flexible Resources," *Management Science* 44 (8), 1998.

VAN MIEGHEM, J. A. "Coordinating Investment, Production and Subcontracting," *Management Science* 45 (7), 1999.

| Table 1: Three Scenarios for Demand Distribution<br>(Fractions in the table represent the probabilities) | | | |
|---|---|---|---|
| Demand | **50** | **100** | **150** |
| Low variance | 1/4 | 1/2 | 1/4 |
| Medium variance | 1/3 | 1/3 | 1/3 |
| High variance | 2/5 | 1/5 | 2/5 |

**Table 2: Illustrative Calculations**

Demand Environment : Medium Variance,

Component Capacity Acquired : Process Plant – 200 units of C1 (C2) at plant 1 (2)

Product Plant – 100 units of C1 & C2 each, at each plant.

| Market 1 Demand | Market 2 Demand | Joint Probability of Demand | Cost in Process Plant Network | Cost in Product Plant Network |
|---|---|---|---|---|
| 50 | 50 | 1/9 | 100s | 0 |
| 50 | 100 | 1/9 | 150s | 0 |
| 50 | 150 | 1/9 | 200s | 50p |
| 100 | 50 | 1/9 | 150s | 0 |
| 100 | 100 | 1/9 | 200s | 0 |
| 100 | 150 | 1/9 | 200s + 50p | 50p |
| 150 | 50 | 1/9 | 200s | 50p |
| 150 | 100 | 1/9 | 200s + 50p | 50p |
| 150 | 150 | 1/9 | 200s + 100p | 100p |
| Expected Total Cost | | | (1600s + 200p)/9 | 100p/3 |

**Table 3: Critical Ratio (p/s) for Various Values of Demand Variance**

| Total Component Capacity Acquired | 200 | 400 | 600 |
|---|---|---|---|
| Low variance | ∞ | 29 | ∞ |
| Medium variance | ∞ | 16 | ∞ |
| High variance | ∞ | 11 | ∞ |

| **Table 4: Comparing the Single stage and Two-stage analysis for a process plant network** | | |
|---|---|---|
| | Expected Total cost (ETC) | Optimal capacity ( $K^*$ ) |
| Newsboy Analysis $K^* = \sum_{i=1}^{2} F_i^{-1}[1 - \frac{c_1 + c_2 + s}{p_i}]$ | \$23202.6 | 1600 |
| Two-stage Analysis for Process Plant $K^* = F_D^{-1}[1 - \frac{c_1 + c_2}{p - s}]$ | \$23026.7 | 1885 |

| **Table 5: Capacity Acquisition for a Process Plant Under Varying Conditions** Conditions: (p-s)=13, ß$_1$=3000, ß$_2$=1000 | | | |
|---|---|---|---|
| Capacity cost | Parameter conditions | Optimal $K^*$ expression | Value of $K^*$ |
| $(c_1 + c_2)=12$ | $(c_1 + c_2)>0.833(p-s)$ | $K^* = \sqrt{2 b_1 b_2 \left(1 - \frac{c_1 + c_2}{p - s}\right)}$ | 679 |
| $(c_1 + c_2)=7$ | $(c_1 + c_2)=0.833(p-s)$ <br> $(c_1 + c_2)>0.167(p-s)$ | $K^* = \frac{b_2}{2} + b_1 \left(1 - \frac{c_1 + c_2}{p - s}\right)$ | 1885 |
| $(c_1 + c_2)=2$ | $(c_1 + c_2)=0.167(p-s)$ <br> $(c_1 + c_2)>0$ | $K^* = b_1 + b_2 - \sqrt{2 b_1 b_2 \left(\frac{c_1 + c_2}{p - s}\right)}$ | 3039 |
| $(c_1 + c_2)=0$ | | $K^* = b_1 + b_2$ | 4000 |

| Table 6: Summary of Key Results | | |
|---|---|---|
| | Process Plant Network | Product Plant Network |
| Sensitivity of Optimal Capacity Acquisition to Shipping Cost ($s$) | High $s$ ? low capacity acquisition; increasing with higher penalty costs. | No sensitivity to $s$ |
| Sensitivity of Optimal Capacity Acquisition to Penalty Cost ($p$) | High $p$ ? high capacity acquisition; increasing with lower shipping costs. Asymptotic at Very High values of $p$ irrespective of level of $s$. | Analysis not conducted |
| Optimal Network Configuration Choice | Always with very low $s$ <br> Over intermediate range of $p$ for low $s$ <br> With increasing demand variance | With very high and very low $p$ for intermediate $s$ <br> Always with high $s$ |

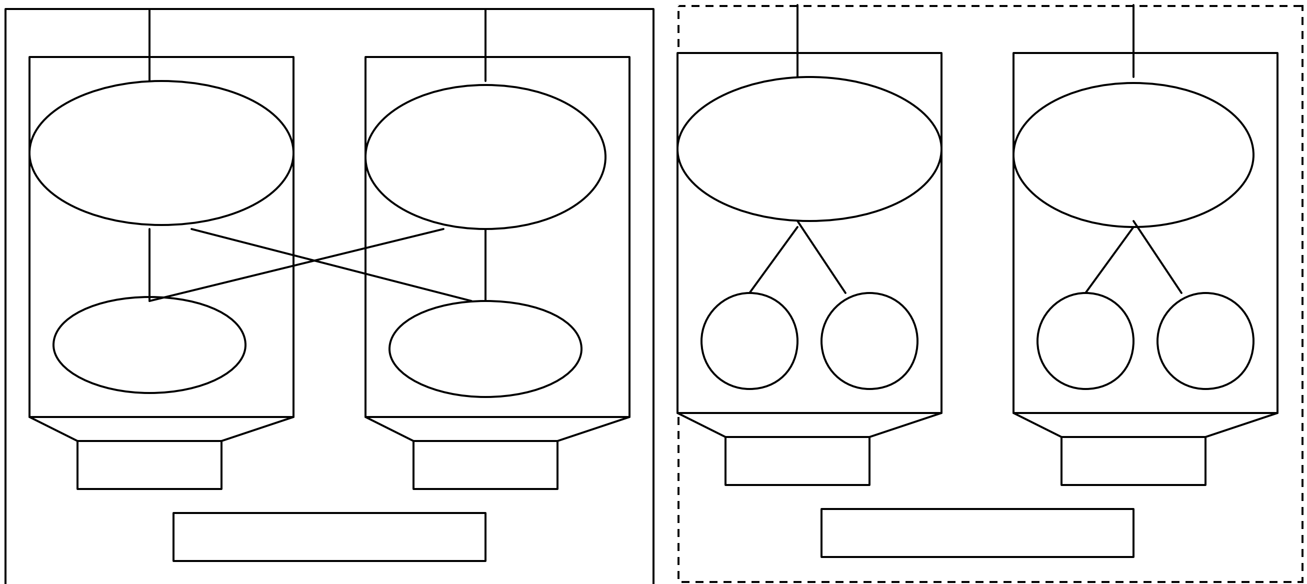
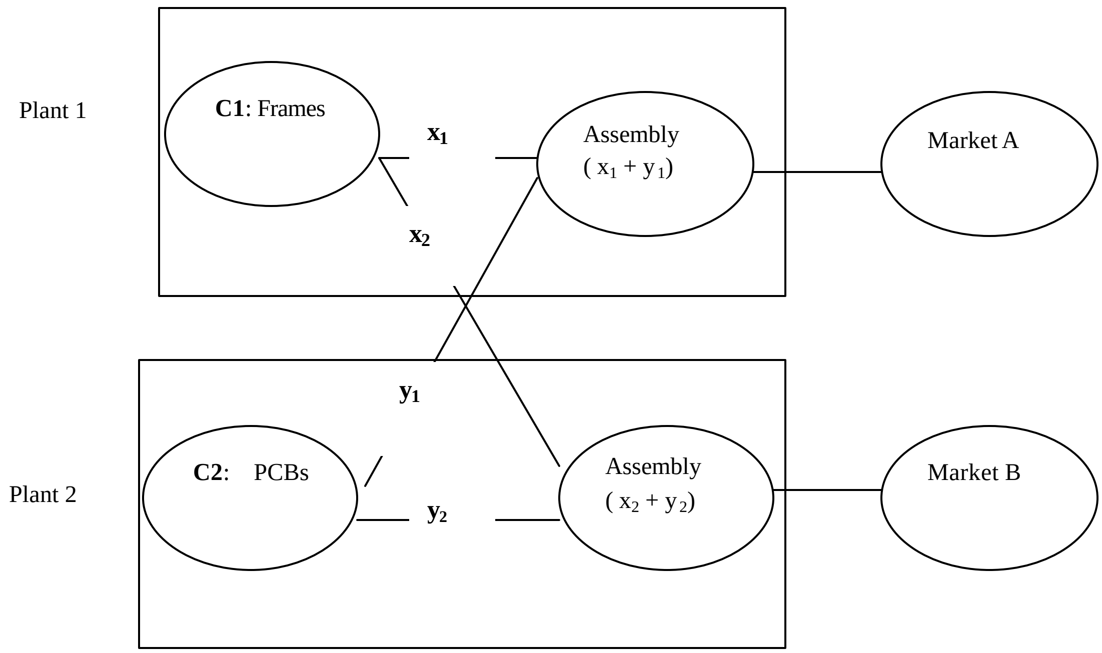
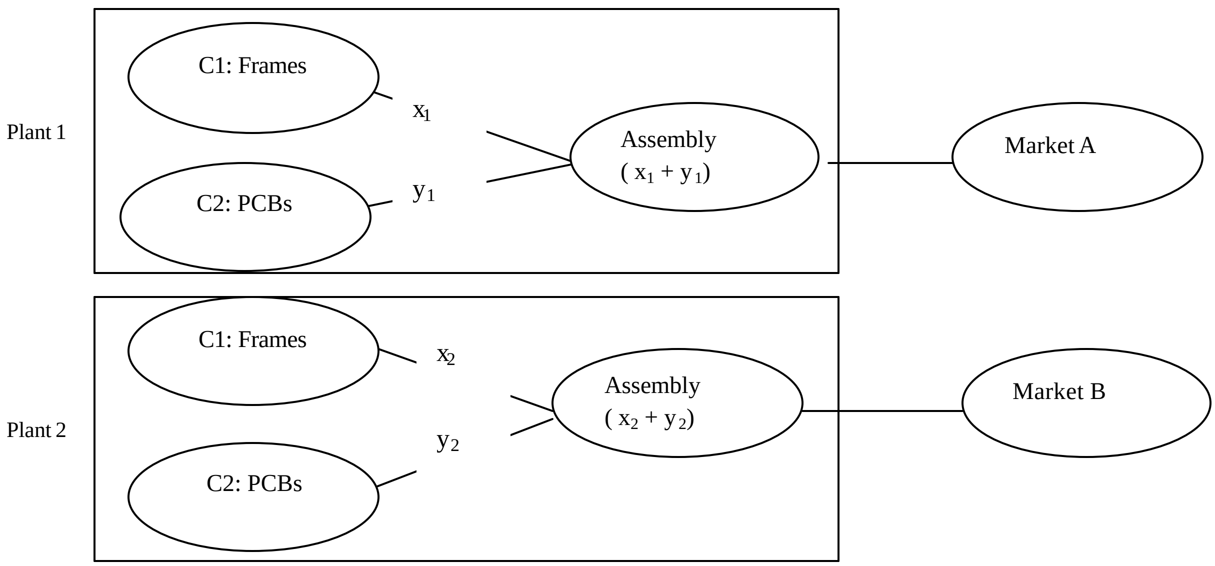


**Figure 1: Contrasting Product and Process Plant Network Strategy**

**Figure 2: Structure and Variables in Alternative Network Configurations**

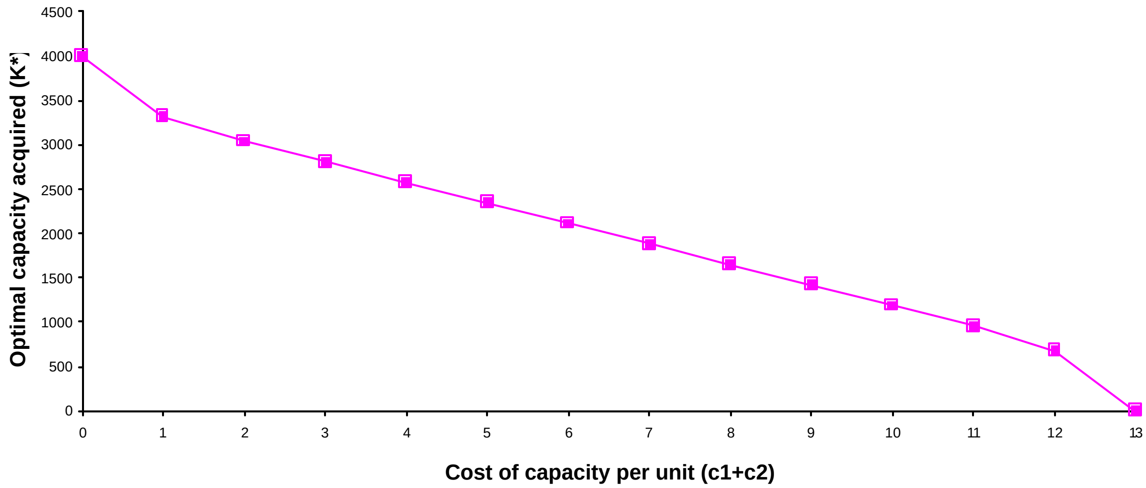



**Process Plant Network**




**Product Plant Network**

**Figure 3: Optimal Capacity Acquired (Process Plant) as a Function of Cost of Capacity**



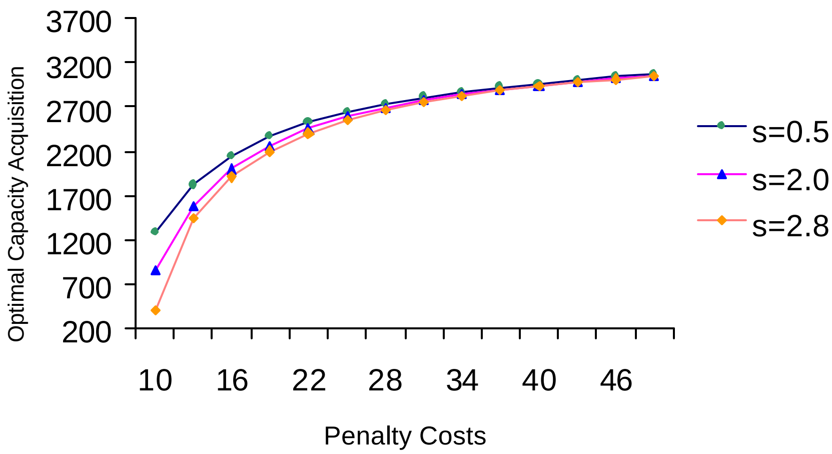




**Figure 4: Sensitivity of Optimal Capacity to Penalty Costs for Process Plants**

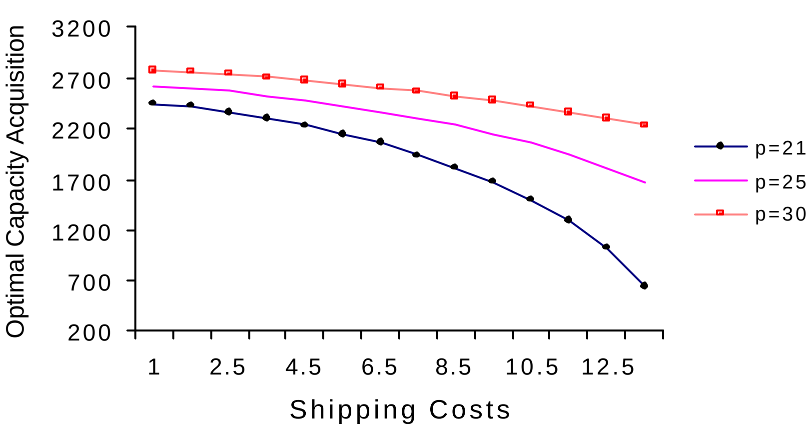



**Figure 5: Sensitivity of Optimal Capacity to Shipping Costs for Process Plants**

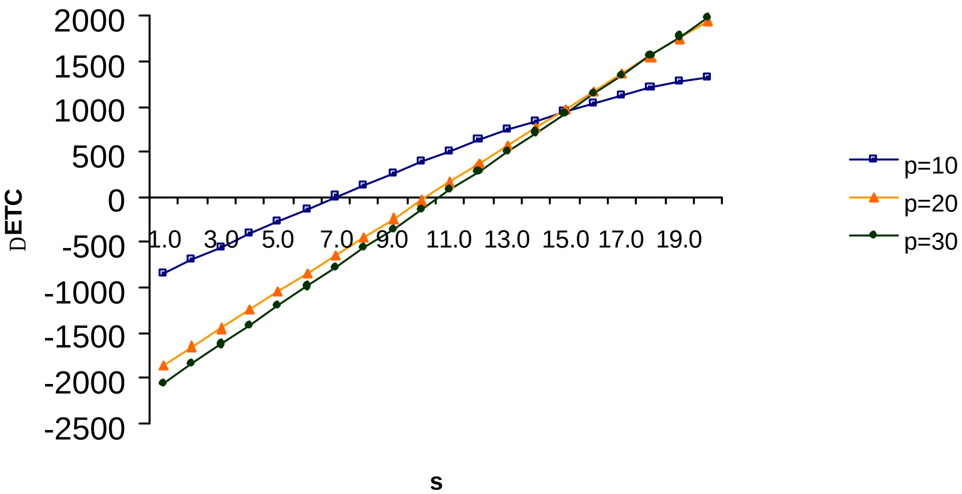



**Figure 6: Difference in Expected Total Costs (Process plant-Product Plant) versus Shipping Costs**

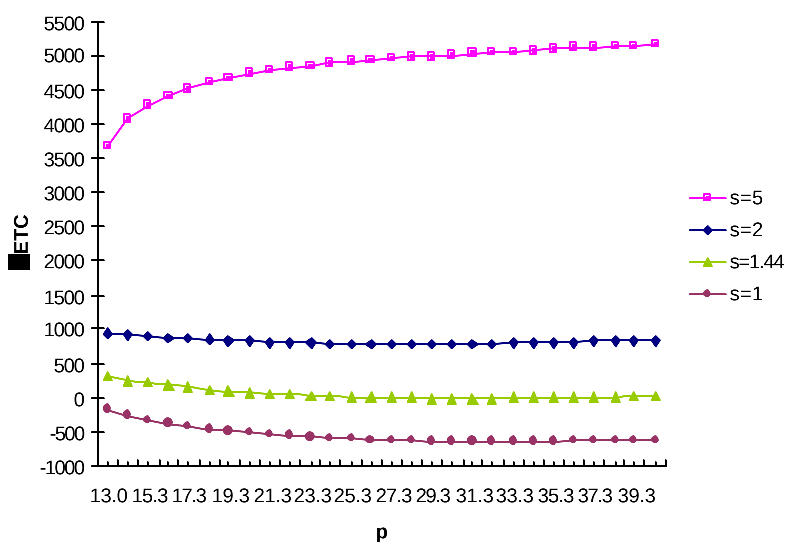



**Figure 7: Difference in Expected Total Costs v/s Penalty Costs**

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[1] All proofs for the propositions in this paper are available from the authors upon request.