M&SOM MANUFACTURING & SERVICE OPERATIONS MANAGEMENT
Vol. 11, No. 1, Winter 2009, pp. 90–108
ISSN 1523-4614 | EISSN 1526-5498 | 09 | 1101 | 0090

informs®
DOI 10.1287/msom.1070.0198

Multimarket Facility Network Design with Offshoring Applications

Lauren Xiaoyuan Lu
Kenan-Flagler Business School, University of North Carolina at Chapel Hill,
Chapel Hill, North Carolina 27599, lauren_lu@unc.edu

Jan A. Van Mieghem
Kellogg School of Management, Northwestern University, Evanston, Illinois 60208,
vanmieghem@kellogg.northwestern.edu

Moving production to low-wage countries may reduce manufacturing costs, but it increases logistics costs and is subject to foreign trade barriers, among others. This paper studies a manufacturer's multimarket facility network design problem and investigates the offshoring decision from a network capacity investment perspective. We analyze a firm that manufactures two products to serve two geographically separated markets using a common component and two localized final assemblies. The common part can be transported between the two markets that have different economic and demand characteristics. Two strategic network design questions arise naturally: (1) Should the common part be produced centrally or in two local facilities? (2) If a centralization strategy is adopted, in which market should the facility be located? We present a transportation cost threshold that captures costs, revenues, and demand risks, and below which centralization is optimal. The optimal location of commonality crucially depends on the relative magnitude of price and manufacturing cost differentials but also on demand size and uncertainty. Incorporating scale economies further enlarges the centralization's optimality region.

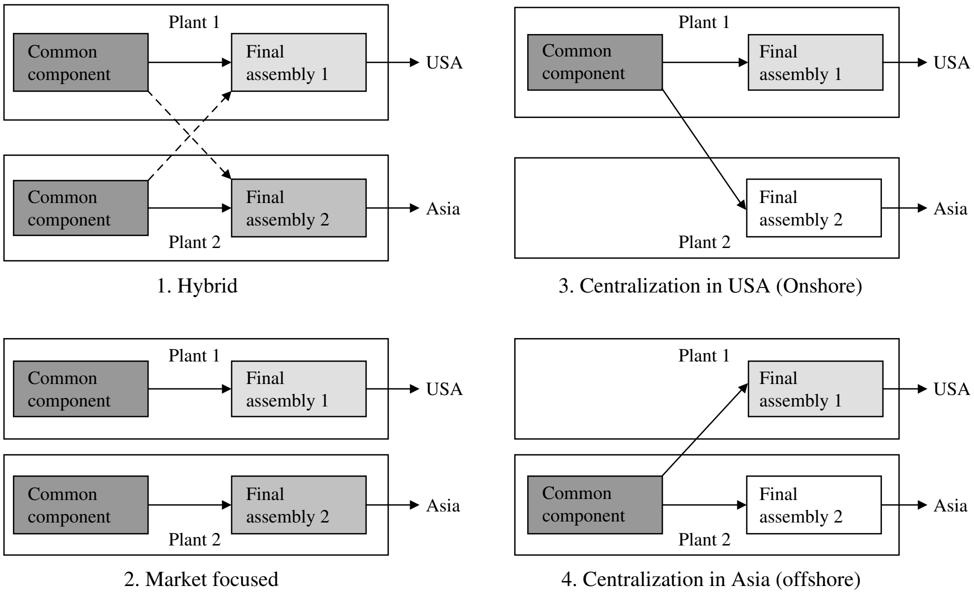
Key words: capacity investment; newsvendor network; location; transshipment; commonality
History: Received: October 17, 2005; accepted: July 23, 2007. Published online in *Articles in Advance* April 17, 2008.

1. Introduction

Global manufacturing firms often have production facilities around the world that serve each major market. Moving production facilities to low-wage countries provides an opportunity for labor cost reduction. However, this offshore manufacturing strategy increases logistics costs and is subject to foreign trade barriers, among others. Capturing these decision factors, this paper studies a manufacturer's multimarket facility network design problem and investigates the value of offshoring from a network capacity investment perspective.

Specifically, we examine the operations strategy of a firm that manufactures two products to serve two geographically separated markets using a common component and two localized final assemblies. The common part can be transported between the two markets that have different economic and demand characteristics. The associated transportation costs account for shipping the common parts (intermediate goods) between the two markets, as well as for foreign trade barriers such as tariffs and duties. For our 2-product 2-market model with commonality, four supply network strategies are possible, as illustrated in Figure 1. The U.S. market boasts higher sale prices while the other market, Asia, enjoys lower manufacturing costs. A multinational car manufacturer is a motivating example for our model when localized car models serve local markets but share a common engine. For example, Toyota recently started to produce 2.4-liter engines in its joint venture in China and planned to export two-thirds of the output to Japan and the U.S. The engines are shared by Camrys sold in China, Japan, and the U.S., and also by minivans sold in Europe and Japan. Toyota plans to invest as much as $2.5 billion in China by 2010 and currently has no plans to export cars from China because of enormous local demand (Webb 2004, Webb and

Figure 1 Four Possible Configurations of a Multimarket Facility Network



Treece 2004). We are interested in understanding how the economic and demand characteristics drive the strategic facility decision of engine production.

As shown in Figure 1, the hybrid (Strategy 1) and the market-focused (Strategy 2) configurations source the common component locally, while the other two configurations (Strategy 3 and 4) centralize it in a single market. Obviously, the market-focused configuration can be replicated, and thus is dominated by the hybrid configuration. For the common component, we restrict attention to the two geographically separated markets as the only location options. This restriction highlights the key trade-offs in the location decision but precludes some interesting questions such as whether it is better to locate the common component at a hub, which can economically supply both markets. The network design problem comes down to two strategic questions: The first is whether the common parts should be produced in a single facility or in two local facilities. If a centralized facility strategy is adopted for the common component, the second question is where should such a facility be located?

We use newsvendor network methodology to analyze the model under both deterministic and stochastic demand. Our main findings are as follows. In the simple base case of deterministic demand, the centralization decision solely depends on transportation and manufacturing costs. If the unit transportation cost is higher than the unit manufacturing cost differential between the two markets, it is optimal to adopt the market-focused configuration and produce common parts in both markets. Otherwise, it is optimal to centralize commonality in Asia to save manufacturing costs.

In the more realistic case that demand is uncertain during network planning, centralization becomes more attractive due to the benefits of demand pooling and the embedded ex-post revenue maximization option to allocate capacity to the more profitable market. Even centralization in the United States may emerge as the optimal configuration when price differential and demand uncertainty are high. This finding underscores the importance of analyzing the network design problem under stochastic demand: Not only do optimal network configurations change under stochastic demand, but the transportation cost threshold is refined to capture demand uncertainty in addition to economic characteristics.

The changes in network strategy due to demand uncertainty can be explained by two factors: differences in transportation costs and the value of the revenue maximization option. We show that transportation costs are typically lowest with local sourcing and decrease in demand correlation. However, when market prices differ substantially, U.S. centralization can become optimal because its transportation costs can be lower than those of the hybrid network, which must invoke transshipment to satisfy U.S. demand to reap higher profits in addition to local sourcing.

We also find that revenue maximization benefits are typically equivalent under hybrid, U.S.-centralization, and Asia-centralization. The equivalence holds when market prices differ substantially and transportation is inexpensive. Then U.S. demand has priority over Asia and cheap transshipment allows hybrid and Asia-centralization to satisfy as much U.S. demand as U.S.-centralization does. However, when market prices are similar or transportation is expensive, local demand takes priority. Because the U.S. market still has an (albeit small) price advantage, U.S.-centralization enjoys larger revenue benefits, which increases in demand correlation. Differences in transportation costs and revenue maximization benefits thus explain why and when the less intuitive U.S.-centralization can be optimal. An example in §4.2 will further illustrate this.

In contrast to much of the related facility network design literature, the contributions of this paper must be found in refining network design strategies to capture uncertain demand and the revenue effect, i.e., the option to maximize revenue by contingent capacity allocation to the high-price market. Strengthening the results from previous literature,[1] we provide analytical conditions under which the centralization and market-focused configurations arise as boundary solutions of the facility planning problem. Specifically, we prove that U.S.-centralization, or onshoring, can become optimal when markets have substantial price differences and highly correlated demands. In addition, the hybrid configuration may outperform centralization and market-focused configurations. We believe that providing the ex-post transshipment option to both locations is important to the flexibility of the manufacturing network, as demonstrated by the concept of "chaining" in Jordan and Graves (1995). Eliminating one transshipment activity breaks the chain and can significantly lower network flexibility. Furthermore, the generality of our model encompasses all possible configurations of the multimarket facility network formulated here and allows for analyzing the location decision of commonality. Finally, our coverage of stochastic demand ordering and economies of scale (EoS) through fixed capacity costs seem to be novel analytical techniques in a newsvendor network.

[1] See our literature review for detailed discussions on a closely related paper, Kulkarni et al. (2005).

2. Literature Review

2.1. Operations Strategy

Configuring the right multiplant facility network plays an important role in a firm's operations strategy. Hayes and Wheelwright (1984) illustrate four approaches for formulating a multiplant facility strategy: physical facilities analysis, geographical network analysis, functional needs and corporate philosophy analysis, and product-process focus analysis. They argue that these approaches represent different perspectives and should be used in a proper combination. Our analysis combines the geographical network and product-process focus approaches. The geographical network analysis is often observed when transportation costs constitute a significant portion of total production cost. This paper illustrates the pivoting role of transportation cost in choosing centralized versus localized commonality strategy. The product-process focus approach is based on the concept of operational focus proposed by Skinner (2006) and recently modeled by Van Mieghem (2008). Firms may choose to focus their facilities according to volumes, product, process, or service. Similar in spirit, our model incorporates two products with different demand characteristics, two geographically separated markets with distinct economic characteristics, and two processes with different purposes: common component manufacturing versus dedicated assembly. We illustrate how these elements interact and drive the optimal network decisions.

2.2. Facility Location and Network Design

Our research falls within the vast literature on facility location and supply chain network design. Snyder (2006) presents a recent and broad review of facility location research. Our paper follows the stream that deals with facility decisions in a global context. We categorize and summarize the related literature into four groups of papers according to their research methodologies (an extended review is in the online appendix).

2.2.1. Mathematical Programming. One of the seminal papers that formulate global manufacturing strategic planning as a mathematical programming problem is Cohen and Lee (1989). Their model can capture a large number of factors affecting resource deployment decisions in a multicountry model, such as regional demand requirements, sourcing constraints, interplant transshipments, taxation, and tariffs. In a global setting, firms' manufacturing decisions are significantly affected by international trade barriers and regulations, as demonstrated by Arntzen et al. (1995), Munson and Rosenblatt (1997), and Kouvelis et al. (2004). A common feature of these mathematical programming formulations is that the decision framework is deterministic, i.e., no demand, financial, production, or regulatory uncertainties.

2.2.2. Stochastic Programming. Some papers explicitly model uncertainty in the global manufacturing environment using a stochastic programming approach. Santoso et al. (2005) propose a model and a solution algorithm for solving large-scale stochastic supply chain design problems. Others specifically evaluate the benefit of operational flexibility embodied in owning international operations, e.g., Kogut and Kulatilaka (1994), Huchzermeier and Cohen (1996), Kouvelis et al. (2001), and Kazaz et al. (2005).

2.2.3. Newsvendor Networks. This stream of papers use parsimonious newsvendor models to generate managerial insights pertaining to demand risk in general and specifically the value of transshipment, e.g., Robinson (1990) and Rudi et al. (2001). Van Mieghem and Rudi (2002) present a systematic approach to study network design in a newsvendor setting, which was adopted by Kulkarni et al. (2004, 2005). The latter is closely related to our model and numerically determines the better of two predetermined network configurations for a multiplant network with commonality: process plant (corresponding to our U.S.-centralization) and product plant (corresponding to our market-focused configuration). Four major distinctions separate our work from Kulkarni et al. (2005). First, we enlarge the feasible configuration set and endogenize the location of common component by incorporating Asia-centralization and the most general configuration, i.e., the hybrid. Second, we let the optimal network configuration emerge from optimization and provide analytical optimality conditions. Third, instead of using numerical sensitivity analysis, we analytically demonstrate the impact of economic and demand characteristics on optimal network configurations. Last, we explain how differences in transportation costs and revenue maximization benefits determine optimal network design under demand uncertainty and demonstrate how this can even lead U.S.-centralization to be optimal.

2.2.4. Conceptual and Empirical Approaches. A group of papers draw on extensive interviews and case studies to examine the strategies and trends in facility location selections: Schmenner (1979), Bartmess and Cerny (1993), Bartmess (1994), MacCormack et al. (1994). Other papers conduct empirical studies on facility strategies of large manufacturing firms, e.g., Schmenner (1982) and Brush et al. (1999).

2.3. Commonality, Dual Sourcing, and Offshoring Literature

This is also relevant to our work. Commonality is about assembling multiple products from common components and product-specific components, according to Van Mieghem (2004). Multiproduct firms often use commonality to add flexibility to their existing production networks. Kulkarni et al. (2005) examine the trade-offs between risk pooling and logistics cost for two extreme configurations (process versus product) of commonality in a multiplant network. In contrast to Kulkarni et al. (2005), we endogenize the location decision of commonality and allow different centralization configurations to arise from optimization. Our work also studies the choice between single sourcing (centralization) and dual sourcing (hybrid) strategies for commonality. Other sourcing strategies are studied by Anupindi and Akella (1993), Yazlali and Erhun (2004), Tomlin and Wang (2005), and Tomlin (2006). Finally, our research belongs to the growing literature on offshoring. Related literature is mostly found in the international business and popular management journals, e.g., Ferdows (1997), Markides and Berg (1988), Farrell (2004, 2005). Related economics literature focuses on the impact of offshoring on domestic labor markets (Feenstra and Hanson 1996, Baily and Lawrence 2004).

3. Model

Consider a firm that uses four resources to produce two products. In the capacity portfolio $K = (K_1, K_2, K_3, K_4)$, K_i captures end-product localization capacity in market $i = 1, 2$ while K_{i+2} represents common component capacity in market i. Thus, Resources 1 and 2 are product-dedicated while transshipment allows Resources 3 and 4 to be shared by the two products with demand vector $D \in \mathbb{R}^2_+$. The firm sells a single product in each geographically separated market and has the option to configure its production network as illustrated in Figure 2. The dedicated resources are exogenously chosen to be located in the market they serve. Transshipment of common parts between the two markets is available at a positive cost. (Though it can be easily incorporated into the model, we assume that dedicated component manufacturing is costless for the convenience of notation.)

Following the convention set by Van Mieghem and Rudi (2002), we let $p = (p_1, p_2)$ where p_i is the per unit sale price of product i; $c_M = (c_{M,1}, c_{M,2})$ where $c_{M,i}$ is the per unit common component manufacturing cost in market i; $c_T = (c_{T,1}, c_{T,2})$ where $c_{T,i}$ is the total transportation cost of one unit of common part from market i to market j including associated tariffs and duties; $c_K = (c_{K,1}, c_{K,2}, c_{K,3}, c_{K,3})$ is the constant marginal capacity investment cost. For expositional simplicity, we assume common component capacity cost is identical for both markets, but relax this later. We also assume that any currency exchange rates are fixed, so that all prices and costs can be denominated in a single currency. Three price and cost differentials arise naturally

$$\Delta p = p_1 - p_2, \qquad \Delta c_M = c_{M,1} - c_{M,2},$$
$$\Delta c_T = c_{T,1} - c_{T,2}.$$

The processing network of Figure 2 has four contingent activities: x_i is the number of common parts used locally in market i, while x_{i+2} is the number of common parts transshipped from market i. The net values of the four processing activities are denoted by v

$$v_1 = p_1 - c_{M,1}, \qquad v_2 = p_2 - c_{M,2},$$
$$v_3 = p_2 - c_{M,1} - c_{T,1}, \qquad v_4 = p_1 - c_{M,2} - c_{T,2}.$$

To eliminate trivialities, we assume positive net values so that production and transshipment are ex-post profitable. In addition, it is economically justified to produce both end products, which means investment in the dedicated resources is always positive.

The firm is an expected profit optimizer so that the optimal capacity strategy K and contingent activities $x(K, D)$ emerge from a two-stage optimization problem. Let $V(K)$ denote the expected firm value given capacity investment K. The optimal expected firm value is

$$V^* = \max_{K \in \mathbb{R}^4_+} \mathbb{E}\pi(K, D) - C(K),$$

where the optimal operating profit is

$$\pi(K, D) = \max_{x \in \mathbb{R}^4_+} \; v'x$$
$$\text{subject to } Ax \le K, \quad R_D x \le D,$$

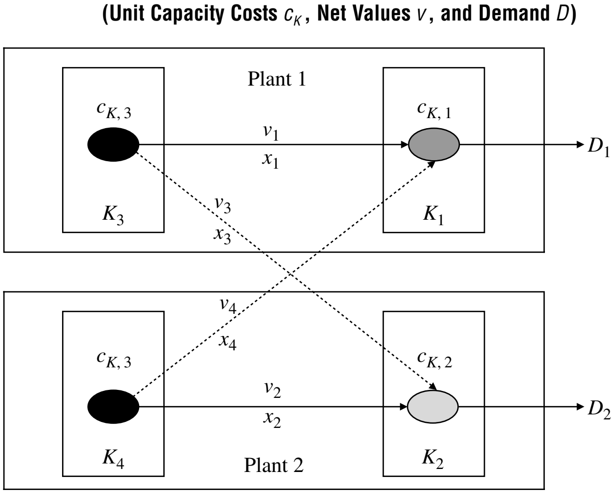
where primes denote transposes and the consumption and output matrices are

$$A = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}, \qquad R_D = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}.$$

We first assume the capacity cost function is linear, i.e., $C(K) = c_K' K$, but later add a fixed cost to study EoS. Finally, to compare the optimal value of the four network configurations, we denote

- V_{hyb} = optimal value of the hybrid configuration, which is the most general and hence optimal strategy: $V_{\text{hyb}} = V^*$;

Figure 2 Graphical Representation of Our Newsvendor Network with Volume Decisions (Capacity K and Allocation x) and Data (Unit Capacity Costs c_K, Net Values v, and Demand D)



- V_{mkt} = optimal value of the market-focused configuration, where $x_3 = x_4 \equiv 0$;
- V_{on} = optimal value of the configuration centralizing commonality in Market 1, where $K_4 \equiv 0$;
- V_{off} = optimal value of the configuration centralizing commonality in Market 2, where $K_3 \equiv 0$.

In general, $V^* = V_{\text{hyb}} \geq \max\{V_{\text{mkt}}, V_{\text{on}}, V_{\text{off}}\}$ with equality meaning that a boundary solution is optimal. In this way, the optimal network strategy emerges from optimization. Finally, all proofs are in the online appendix.

4. Optimal Network Configurations

We focus on two key components of the optimal solution to the network design problem. First, is it optimal for the firm to adopt a centralization strategy for the common component? Second, if centralization of commonality is optimal, in which market should the facility be located? To highlight the first-order cost drivers, we start with the deterministic demand setting before tackling the stochastic model.

4.1. Deterministic Demand

Because the common component capacity cost is identical for both locations, the investment decision comes down to evaluating the economic attractiveness of the alternative processing activities for each product. Without imposing any assumption, there are 24 (=4!) possible orderings of the four net values, but their definitions imply an interdependence, $v_4 \geq v_1 \Rightarrow v_2 \geq v_3$, which eliminates 6 orderings. The remaining 18 are divided into two groups, one of which is the mirror image of the other. Due to symmetry in results, our subsequent analysis focuses on the 9 orderings displayed in Table 1. The four processing activities are categorized into basic and "discretionary," as described by Van Mieghem and Rudi (2002). The discretionary processing activities are only used in stochastic settings to deal with deviations from the expected scenario. Proposition 1 provides the conditions under which each of the 9 cases occurs and the corresponding optimal network configuration.

Proposition 1 (Deterministic Demand). *If $c_{T,1} \leq -\Delta c_M$, centralizing commonality in Market 1 is optimal with capacity investment $K^* = (D_1, D_2, D_1 + D_2, 0)'$. If $c_{T,2} \leq \Delta c_M$, centralizing commonality in Market 2 is optimal with capacity investment $K^* = (D_1, D_2, 0, D_1 + D_2)'$.*

Table 1 **Optimal Network Configurations Under Deterministic Demand**

Net value ordering	Conditions	Basic activities	Discretionary activities	Optimal network configuration (K^*)
$v_1 \geq v_4 \geq v_2 \geq v_3$ $v_1 \geq v_2 \geq v_4 \geq v_3$ $v_2 \geq v_1 \geq v_4 \geq v_3$	$c_{T,1} \geq -\Delta c_M$ $c_{T,2} \geq \Delta c_M$	x_1, x_2	x_3, x_4	Market-focused (D_1, D_2, D_1, D_2)
$v_1 \geq v_3 \geq v_4 \geq v_2$ $v_1 \geq v_4 \geq v_3 \geq v_2$ $v_3 \geq v_1 \geq v_4 \geq v_2$	$c_{T,1} \leq -\Delta c_M$	x_1, x_3	x_2, x_4	Centralization: Market 1 $(D_1, D_2, D_1 + D_2, 0)$
$v_2 \geq v_4 \geq v_1 \geq v_3$ $v_4 \geq v_1 \geq v_2 \geq v_3$ $v_4 \geq v_2 \geq v_1 \geq v_3$	$c_{T,2} \leq \Delta c_M$	x_2, x_4	x_1, x_3	Centralization: Market 2 $(D_1, D_2, 0, D_1 + D_2)$

Otherwise, a market-focused configuration is optimal with capacity investment $K^* = (D_1, D_2, D_1, D_2)'$.

Proposition 1 demonstrates that it is optimal to centralize commonality in the low-cost market whenever the manufacturing cost advantage outweighs the transportation cost of centralization. Lemma 1 further characterizes the three net value orderings that give rise to the market-focused configuration. These three cases will become the center of our analysis under stochastic demand.

Lemma 1. *If $c_{T,1} > -\Delta c_M$ and $c_{T,2} > \Delta c_M$, three cases are possible:*

(i) *High price differential, meaning $\Delta p \geq c_{T,2}$ and thus $v_1 > v_4 \geq v_2 > v_3$.*

(ii) *Medium price differential, meaning $\max(\Delta c_M, -\Delta c_M - \Delta c_T) < \Delta p < c_{T,2}$ and thus $v_1 > v_2 > v_4 > v_3$.*

(iii) *Low price differential, meaning $-\Delta c_M - \Delta c_T \leq \Delta p \leq \Delta c_M$ and thus $v_2 \geq v_1 > v_4 \geq v_3$.*

4.2. Stochastic Demand

Though demand uncertainty complicates the network design problem, it is straightforward to show that the conditions for centralization to be optimal under deterministic demand extend to stochastic demand as stated in Proposition 2:

Proposition 2 (Stochastic Demand). *If $c_{T,i} \leq (-1)^i \Delta c_M$, centralizing commonality in market i is optimal, where $i \in \{1, 2\}$.*

This also implies that the common component that only provides discretionary activities remains valueless under demand uncertainty. While Proposition 2 is sufficient for our purpose, it also simplifies finding the specific optimal capacity levels when $c_{T,i} \leq$

$(-1)^i \Delta c_M$: set $K_{j+2} = 0$ (where $j \neq i$) and solve the three-dimensional optimal capacity problem.

For the remainder, we will focus on the less obvious cases illustrated in Lemma 1. Without loss of generality, we label Market 1 the high-price market, i.e., $p_1 \geq p_2$. To cast the model in the context of offshoring, we further assume that Market 1 has higher manufacturing costs, i.e., $c_{M,1} \geq c_{M,2}$, and call Market 2 the low-cost market. These two assumptions also ensure that the three interesting cases in Lemma 1 are nonempty sets.

With uncertainty, even expensive transshipment has an option value because it reduces ex post supply-demand mismatch costs and can increase revenues. Our analytic model is designed to increase understanding of this option value. Before delving into the general analysis, let us first consider a simple example to generate some intuition on the role of the three drivers in this network design: revenue maximization option, transshipment option, and manufacturing costs. Two three-point discrete demand distributions are sufficient for our purpose. When demand is perfectly negatively correlated, the realizations are $(1+\sigma, 1-\sigma)$, $(1, 1)$, $(1-\sigma, 1+\sigma)$ each with probability $\frac{1}{3}$, where $\sigma \in [0, 1]$ is a measure of demand volatility. When demand is perfectly positively correlated, the realizations are $(1+\sigma, 1+\sigma)$, $(1, 1)$, $(1-\sigma, 1-\sigma)$ each with probability $\frac{1}{3}$. Assume symmetric transportation costs for simplicity, i.e., $c_{T,1} = c_{T,2} = c_T$, and consider three networks: *Hybrid* with capacity $(1 + z\sigma, 1 + z\sigma, 0.5(1 + z\sigma), 0.5(1 + z\sigma))$, *Onshore* with capacity $(1+z\sigma, 1+z\sigma, 1+z\sigma, 0)$, and *Offshore* with capacity $(1+z\sigma, 1+z\sigma, 0, 1+z\sigma)$, where $z \in [0, 1]$ is a measure of service probability. It is reasonable to assume that total common component investment is higher than the lowest total demand, i.e., $1 + z\sigma > 2(1 - \sigma)$ so that $\sigma(2+z) > 1$. We keep investment in dedicated and common components equal across the three networks to focus attention on the impact of common component allocation. Table 2 shows the resulting expected revenues, transportation costs, and manufacturing costs.

With high Δp, expected revenues are identical across the three networks because cheap transshipment allows the high-price U.S. demand to be satisfied as much as possible. In contrast, with medium to low Δp, Onshore has the highest revenues while Offshore has the lowest. Moreover, the revenue advantage of Onshore is higher when demand is positively correlated and less volatile: Indeed, $\Delta R^{\text{on-hyb}}_{\rho=1} = \frac{1}{3}\Delta p > \Delta R^{\text{on-hyb}}_{\rho=-1} = \frac{1}{6}(3 - \sigma(2 + z))\Delta p$, indicating the value of revenue maximization of onshoring increases in demand correlation ρ while larger demand volatility σ decreases that revenue advantage. This pattern also holds if we compare Onshore against Offshore.

Hybrid achieves the lowest transportation costs in general with one surprising exception: Onshore incurs even lower transportation costs than Hybrid when the price differential is high and demand is positively correlated (notice that $\Delta \text{TC}^{\text{on-hyb}}_{\rho=1} = -\frac{1}{3}\sigma(1-z)c_T$). Substantial price difference induces the network to prioritize satisfying the demand of the high-price market. When this price priority is coupled with positive demand correlation, the service level of the other market is relatively low, letting Onshore save transportation costs. Further, the cost savings increase when demand volatility rises. Similarly, the transportation cost advantage of Onshore over Offshore increases in demand correlation. However, the cost savings decrease in demand volatility.

Finally as expected, Offshore incurs the lowest manufacturing costs while Onshore incurs the highest. The cost savings are higher under negatively correlated demand (notice that $\Delta \text{MC}^{\text{on-off}}_{\rho=-1} = (1+z\sigma)\Delta c_M > \Delta \text{MC}^{\text{on-off}}_{\rho=1} = \frac{2}{3}(2-\sigma+z\sigma)\Delta c_M$). The cost savings of offshoring increase (decrease) in demand volatility when demand correlation is negative (positive).

In summary, this example illustrates that the revenue maximization advantage and transportation cost savings of onshoring increase in demand correlation while the manufacturing cost savings of offshoring decrease in demand correlation. The impact of demand volatility depends on both network configuration and demand correlation. Next we formalize the intuition derived from this example by solving the stochastic capacity investment problem using the newsvendor network approach and assuming a random demand vector D with continuous bivariate distribution F. (We will use F_i to denote the marginal distribution of market i demand.)

Lemma 2. *If $c_{T,1} > -\Delta c_M$ and $c_{T,2} > \Delta c_M$, the optimal capacity investment vector satisfies $K^*_i \geq K^*_{i+2}$. Moreover, $K^*_{i+2} = 0$ implies $K^*_j = K^*_{j+2}$, where $i, j \in \{1, 2\}$ and $i \neq j$.*

Table 2 Expected Revenues (R), Transportation Costs (TC), and Manufacturing Costs (MC) of the Three Networks Depend on Price Differential Δp (H: High, M: Medium, L: Low) and Demand Correlation ρ for the Simple Example

	Δp		Hybrid	Onshore	Offshore
$\rho=-1$	H	R	$\frac{3-\sigma+z\sigma}{3}p_1+\frac{\sigma+2z\sigma}{3}p_2$	Same as left	Same as left
	M/L		$\frac{1+z\sigma}{2}(p_1+p_2)$	Same as above	$\frac{\sigma+2z\sigma}{3}p_1+\frac{3-\sigma+z\sigma}{3}p_2$
	H	TC	$\frac{0.5+\sigma+0.5z\sigma}{3}c_T$	$\frac{\sigma+2z\sigma}{3}c_T$	$\frac{3-\sigma+z\sigma}{3}c_T$
	M/L		$\frac{-1+2\sigma+z\sigma}{3}c_T$	Same as above	Same as left
	H/M/L	MC	$\frac{1+z\sigma}{2}(c_{M,1}+c_{M,2})$	$(1+z\sigma)c_{M,1}$	$(1+z\sigma)c_{M,2}$
$\rho=1$	H	R	$\frac{3-\sigma+z\sigma}{3}p_1+\frac{1-\sigma+z\sigma}{3}p_2$	Same as left	Same as left
	M/L		$\frac{2-\sigma+z\sigma}{3}(p_1+p_2)$	Same as above	$\frac{1-\sigma+z\sigma}{3}p_1+\frac{3-\sigma+z\sigma}{3}p_2$
	H	TC	$\frac{1}{3}c_T$	$\frac{1-\sigma+z\sigma}{3}c_T$	$\frac{3-\sigma+z\sigma}{3}c_T$
	M/L		Same as above	Same as left	
	H/M/L	MC	$\frac{2-\sigma+z\sigma}{3}(c_{M,1}+c_{M,2})$	$\frac{2(2-\sigma+z\sigma)}{3}c_{M,1}$	$\frac{2(2-\sigma+z\sigma)}{3}c_{M,2}$

Lemma 2 says that investment in the common component is weakly less than in the dedicated component in both markets. Van Mieghem (2007) provides two explanations: "excess" downstream capacity provides a "switching option" that requires an unbalanced capacity portfolio, and the resource pooling benefit (here brought by the ex post transshipment option). As common parts can be shared across markets, the need to invest in the common component in both markets is reduced. Moreover, Lemma 2 provides a simplification property for analyzing the centralization configurations, i.e., equal investment in the common and dedicated components.

As illustrated in Figure 1, two centralization strategies are possible: centralization in Market 1 and in Market 2. Given the equal investment property stated in Lemma 2, let the two boundary solutions $\bar{K}=(\bar{K}_1,\bar{K}_2,\bar{K}_1,0)$ and $\underline{K}=(\underline{K}_1,\underline{K}_2,0,\underline{K}_2)$ represent the two centralization configurations, respectively. With demand uncertainty, both strategies may become optimal under certain conditions that hinge on the price differential and demand volatility. Different centralization configurations may arise for the three cases in Lemma 1. To specify the optimal strategies for the high and medium Δp cases, it is useful to introduce the following transportation cost threshold defined by the "upper" boundary solution $\bar{K}$

$$\bar{c}_T=\frac{\Delta p\bar{P}_3-\Delta c_M-c_{K,1}}{1-\bar{P}_3}, \tag{1}$$

where $\bar{P}_3=\Pr(D_1>\bar{K}_1)$. (The online appendix shows its derivation.) Proposition 3 states the optimal network configuration for the high and medium Δp cases.

Proposition 3. *For the high and medium price differential cases, the optimal investment strategy depends on* $c_{T,1}$:

(i) *If* $c_{T,1}<\bar{c}_T$, *it is optimal to centralize commonality in Market* 1;

(ii) *If* $c_{T,1} \geq \bar{c}_T$, *it is optimal to invest in commonality in both markets;*

(iii) *Market-focused configuration is a special case of* (ii) *in which activities* x_3 *and* x_4 *are identically zero, and its capacity vector* $\tilde{K} = (\tilde{K}_1, \tilde{K}_2, \tilde{K}_1, \tilde{K}_2)$ *is optimal if and only if*

$$\Pr(D_1 > \tilde{K}_1, D_2 > \tilde{K}_2) > \max\left\{a*\left(\frac{c_{K,1}+c_{K,3}}{v_1} - \frac{c_{K,1}}{v_4}\right), \frac{c_{K,2}+c_{K,3}}{v_2} - \frac{c_{K,2}}{v_3}\right\},$$

where

$$\tilde{K}_1 = F_1^{-1}\left(\frac{v_1 - c_{K,1} - c_{K,3}}{v_1}\right), \quad \tilde{K}_2 = F_2^{-1}\left(\frac{v_2 - c_{K,2} - c_{K,3}}{v_2}\right),$$

$$a = \frac{v_4}{v_2} \text{ (or 1) for high (or medium) } \Delta p.$$

Under deterministic demand, onshoring can never be optimal because $c_{T,1} \leq -\Delta c_M$ can never be satisfied. In contrast, demand uncertainty makes centralization in the high-price market more attractive under the conditions given in Proposition 3. Also notice that with medium to high price differentials, Proposition 3 implies that it is never optimal to centralize commonality in the low-cost market. Further, the high and medium Δp cases share the same set of strategies and transportation cost threshold (though the derivations are different as shown in the proof). The market-focused configuration may arise, but only as a subset solution of the hybrid strategy, depending on how likely the capacity constraint $\tilde{K}$ is reached simultaneously for both products. When the likelihood is sufficiently large, the value of the transshipment option to alleviate the ex post demand-capacity mismatch decreases to zero and thus the market-focused configuration becomes optimal. To specify the optimal strategies when the price differential is low, we need another transportation cost threshold defined by the "lower" boundary solution $\underline{K}$

$$\underline{c}_T = \frac{\Delta c_M - \Delta p \underline{P}_3 - c_{K,2}}{1 - \underline{P}_3}, \tag{2}$$

where $\underline{P}_3 = \Pr(D_2 > \underline{K}_2)$.

Proposition 4. *For the low price differential case, the optimal investment strategy depends on* $c_{T,2}$:

(i) *If* $c_{T,2} < \underline{c}_T$, *it is optimal to centralize commonality in Market* 2.

(ii) *If* $c_{T,2} \geq \underline{c}_T$, *it is optimal to invest in commonality in both markets.*

(iii) *Market-focused configuration is a special case of* (ii) *in which activities* x_3 *and* x_4 *are identically zero, and its capacity vector* $\tilde{K} = (\tilde{K}_1, \tilde{K}_2, \tilde{K}_1, \tilde{K}_2)$ *is optimal if and only if*

$$\Pr(D_1 > \tilde{K}_1, D_2 > \tilde{K}_2) > \max\left\{\frac{c_{K,1}+c_{K,3}}{v_1} - \frac{c_{K,1}}{v_4}, \frac{c_{K,2}+c_{K,3}}{v_2} - \frac{c_{K,2}}{v_3}\right\},$$

where

$$\tilde{K}_1 = F_1^{-1}\left(\frac{v_1 - c_{K,1} - c_{K,3}}{v_1}\right), \quad \tilde{K}_2 = F_2^{-1}\left(\frac{v_2 - c_{K,2} - c_{K,3}}{v_2}\right).$$

Together Propositions 3 and 4 highlight the importance of capturing the revenue impact in stochastic network planning: *A substantial price difference coupled with demand uncertainty are the key conditions to argue against offshoring*. Notice that a common feature shared by the two propositions is that the transportation cost thresholds depend on demand distributions and thus the optimality of centralization depends on demand volatility. Moreover, notice that a positive transportation cost threshold requires either $\Delta p > \Delta c_M$ in the case of $\bar{c}_T$, or $\Delta p < \Delta c_M$ in the case of $\underline{c}_T$. These two opposite conditions underscore the pivotal role of the price differential in network decisions: When the transportation cost is relatively inexpensive, depending on the price differential it may be optimal to centralize common component in either the high-price market or in the low-cost market, but not both.

5. Impact of Costs and Prices

5.1. Impact of Costs and Prices on the Optimal Network Configuration

The previous two propositions identify the transportation cost thresholds below which centralization strategies are optimal. Next we analyze how economic characteristics such as price, manufacturing cost, and capacity investment cost, affect network decisions. The pivotal role of the price differential in network decisions is manifested in its association with the specific centralization strategy as shown earlier. Here we also answer other interesting questions: (1) Does centralization in the high-price market become more attractive when the price differential increases? (2) Does centralization in the low-cost market become more attractive when the manufacturing cost differential increases? (3) How does the optimal network configuration change with the capacity investment cost? Since the transportation cost thresholds determine the optimal network configuration, we can answer these questions by finding out how $\bar{c}_T$ and $\underline{c}_T$ are affected by a change in any of the economic characteristics.

We will focus on $\bar{c}_T$ (the analysis on $\underline{c}_T$ is similar). The change of $\bar{c}_T$ w.r.t. parameter y is given by the total derivative

$$\frac{d\bar{c}_T}{dy} = \underbrace{\frac{\partial \bar{c}_T}{\partial y}}_{\text{Direct Effect}} + \underbrace{\frac{\partial \bar{c}_T}{\partial \bar{P}_3}\frac{d\bar{P}_3}{dy}}_{\text{Indirect Effect}}.$$

Decomposing the total effect of parameter y on $\bar{c}_T$ enables a better understanding of the countervailing forces that affect the attractiveness of centralization. Determining the sign of $\partial\bar{c}_T/\partial y$ is straightforward. However,

$$\operatorname{sign}\left(\frac{\partial \bar{c}_T}{\partial \bar{P}_3}\frac{d\bar{P}_3}{dy}\right) = \operatorname{sign}\left(\frac{\partial \bar{c}_T}{\partial \bar{P}_3}\right)\times \operatorname{sign}\left(\frac{d\bar{P}_3}{d\bar{K}_1}\right)\times \operatorname{sign}\left(\frac{d\bar{K}_1}{dy}\right),$$

where

$$\operatorname{sign}\left(\frac{\partial \bar{c}_T}{\partial \bar{P}_3}\right) = 1, \qquad \operatorname{sign}\left(\frac{d\bar{P}_3}{d\bar{K}_1}\right) = -1.$$

Therefore determining the sign of the indirect effect comes down to determining the sign of $d\bar{K}_1/dy$, which is derived analytically in the online appendix. The signs of direct, indirect, and total effects of all the economic parameters are summarized in Table 3.

We selectively discuss the effects of some parameters. For example, the third column in Table 3 shows how the costs and prices may impact the decision to maintain U.S.-centralization, indicated by the change of $\bar{c}_T$. An increase in Asian price decreases $\bar{c}_T$ and thus the attractiveness of onshoring. In contrast, an increase in Asian manufacturing or dedicated component investment cost enhances the attractiveness of centralization in the United States, as manifested by the increase of $\bar{c}_T$. The same holds true for the common component investment cost. The other three

Table 3 **Impact of Costs and Prices on the Transportation Cost Thresholds**

	$\bar{c}_T$			$\underline{c}_T$		
Parameter	Direct	Indirect	Total	Direct	Indirect	Total
p_1	+	−	+/−	−	−	−
p_2	−	−	−	+	−	+/−
$c_{M,1}$	−	+	+/−	+	0	+
$c_{M,2}$	+	0	+	−	+	+/−
$c_{K,1}$	−	+	+/−	0	+	+
$c_{K,2}$	0	+	+	−	+	+/−
$c_{K,3}$	0	+	+	0	+	+

changes, i.e., U.S. price, manufacturing cost, or dedicated component investment cost, lead to ambiguous change in $\bar{c}_T$. This ambiguity reflects the inherent trade-offs in centralization. For example, in the case of p_1, the positive direct effect is induced by increased service level of the U.S. market. The negative indirect effect is caused by the decreased service level of the Asian market, which can be shown from the optimality conditions.

Our result on the investment cost of the common component confirms and generalizes that of Kulkarni et al. (2005, §4.2, Figure 5) i.e., centralization strategy remains optimal for larger values of transportation costs when the investment cost of common component increases. Kulkarni et al. (2005) base their result on observations from numerical analysis assuming uniform demand distributions and comparing process plant (corresponding to our centralization) with product plant (corresponding to our market-focused) configuration. Ours is a general analytical result for the less restrictive model formulated here.

5.2. Impact of Costs and Prices on the Optimal Value and Capacity Investment

Now we study the impact of the economic parameters on optimal network value and capacity investment. The total capacity investment in common component is denoted by $K_{\text{com}} = K_3 + K_4$.

Property 1. *The optimal expected firm value V^* is a nonincreasing convex function of c_K with gradient $\nabla_{c_K} V^* = -(K_1^*, K_2^*, K_3^*, K_4^*)' \le 0$. Moreover, the optimal value V^* is an increasing convex function of p with gradient $\nabla_p V^* = \mathbb{E}(x_1^* + x_4^*, x_2^* + x_3^*)' > 0$.*

The sensitivity terms of K^* on any of the economic parameters can be calculated following the approach in Van Mieghem (1998). (Calculation of those sensitivity terms are available upon request.) Here we employ a different approach to characterize the impact, drawing on the concepts of supermodularity and increasing differences.

Property 2. *The expected firm value $V(K)$ is supermodular in (K_1, K_2, K_3, K_{com}) and has increasing differences in $(K_1, K_2, K_3, K_{com}, y)$, where $y = -c_K$ or p_1. Moreover, the expected firm value is supermodular in (K_1, K_2, K_4, K_{com}) and has increasing differences in $(K_1, K_2, K_4, K_{com}, y)$, where $y = -c_K$ or p_2.*

Complementarity among K_1, K_2, and K_{com} is not surprising given that the network is a connected "chain" so that a capacity increase in one type of resource should be accompanied by an increase in any other type of resource within the network. However, the supermodularity property cannot be established for (K_1, K_2, K_3, K_4) because of the substitution effect between K_3 and K_4. When perturbed by a change in the economic environment, the system needs to be adjusted towards optimality, and the adjustment may not be monotone at all facilities. Nevertheless, some monotonicities can be established.

Property 3. *K_1^*, K_2^*, K_3^*, and K_4^* are monotone decreasing in any marginal capacity cost $c_{K,i}$, $i = 1, 2, 3$. K_1^*, K_2^*, K_{com}^* are monotone increasing in p_i, $i = 1, 2$. K_3^* is monotone increasing in p_1. K_4^* is monotone increasing in p_2.*

The monotonicity of K_1^*, K_2^*, K_{com}^* in both c_K and p is not surprising due to the complementarity property stated in Property 2. However, K_3^* and K_4^* may be increasing or decreasing in p_2 and p_1, respectively. When p_2 increases, the incentive to invest more in K_2 obviously increases. What is less obvious is the increased incentive to invest more in K_3 because some of the capacity can be used towards the production of Product 2 ex post. However, if p_2 becomes large enough so that Δp becomes less than Δc_M, centralization in Asia will become more attractive as demonstrated earlier, thus leading to a decrease in K_3.

Not only do economic characteristics impact network decisions, demand characteristics also interact with economic characteristics in determining the optimal network configurations. We discuss the impact of demand characteristics in the next section.

6. Impact of Demand Size and Uncertainty

We have shown that the optimality of centralization is independent of demand uncertainty when the transportation cost is lower than the manufacturing cost differential. However, the dependence emerges when transportation is more expensive. For this case, we analyze the impact of demand size, volatility and correlation on the optimal network configuration.

6.1. Demand Size

When centralizing commonality in market i is optimal for a given demand size, we expect it to remain optimal when market i grows. The less obvious case is when the demand size of the other market changes. The next proposition illustrate how these changes affect the optimal network configuration.

Proposition 5. *Suppose market demands are independent and have a finite mean. Let D_i and D_i' denote two demand distributions of market i. Suppose D_i' has first-order stochastic dominance over D_i (i.e., $F_{D_i'}(\cdot) \leq F_{D_i}(\cdot)$).*

(i) *If centralization of commonality in Market* 1 (*or* 2) *is optimal for (D_1, D_2), it remains optimal for (D_1', D_2) (or (D_1, D_2')).*

(ii) *If centralization of commonality in Market* 1 (*or* 2) *is optimal for (D_1, D_2') (or (D_1', D_2)), it remains optimal for (D_1, D_2).*

(iii) *If centralization of commonality in Market* 1 (*or* 2) *is optimal for (D_1, D_2), there exists a $\bar{\mu}_2$ (or $\bar{\mu}_1$) such that when $\mathbb{E}(D_2') > \bar{\mu}_2$ (or $\mathbb{E}(D_1') > \bar{\mu}_1$) the centralization strategy is never optimal for (D_1, D_2') (or (D_1', D_2)).*

The insight from the propositions is that, in contrast to the deterministic case, market size matters in network design under demand uncertainty. Because every unit of deterministic demand can be satisfied, increasing demand size scales up the network proportionally and thus has no impact on the optimal network configuration. However, when demands are stochastic, demand-capacity mismatch causes the optimal network value to be nonlinear in demand size because of risk pooling and the revenue maximization option. Indeed, the trade-off between the revenue maximization benefits, transportation costs, and manufacturing costs is affected by demand size. Specifically, suppose centralizing commonality in market i

is optimal for a given demand size. When the size of market j increases, centralization in market i remains optimal until market j grows so large that the expected transportation costs outweigh either the benefits of revenue maximization or manufacturing cost reduction, making the hybrid strategy dominant among the centralization strategies.

Relating the result to the context of offshoring, suppose centralization in Asia is optimal given current global demand. If Asian demand grows larger, ceteris paribus, centralization in Asia stays optimal. If we instead suppose centralization in the United States is optimal given current global demand, when Asian demand grows larger, localization of commonality becomes optimal. Therefore, given the likelihood that growth rates in Asia will continue to surpass those in the United States, we expect to see configurations that centralize commonality in the United States gradually disappear, while more configurations arise that localize commonality or centralize commonality in Asia.

6.2. Demand Volatility and Correlation

Our stochastic analysis highlights the fact that the facility network design decision not only depends on the relative demand size, but also on volatility and correlation. Van Mieghem and Rudi (2002) prove that for bivariate normally distributed demands D the optimal value V^* is increasing in the mean μ and decreasing in any variance term Σ_{ii}. In other words, for normally distributed demands, because its capacity is capped from above, demand volatility degrades the expected value of a network. Further, if $\pi(K, D)$ is submodular in D, then V^* is decreasing in any covariance term Σ_{ij}. Submodularity of π in D can be established for the high Δp case.

Property 4. *For the high Δp case, the operating profit $\pi(K, D)$ is submodular in D.*

Property 4 implies that increased market correlation decreases the network value when market 1's price is substantially higher than Market 2. This result is specific to normal demand distributions. Now we analyze general continuous demand distributions.

Proposition 6. *Let product demands be perfectly negatively correlated: $P(\{D_1 + D_2 = k > 0\}) = 1$.*

(i) *For the high and medium Δp cases,*

$$\bar{c}_T = c_{T,1}\left\{1 + \frac{(v_1 - v_3)(c_{K,2} + c_{K,3} - v_2)}{v_1 - (c_{K,1} + c_{K,2} + c_{K,3})}\right\}.$$

Moreover, it is optimal to centralize commonality in market 1 if and only if $v_1 > c_{K,1} + c_{K,2} + c_{K,3}$ and $v_2 < c_{K,2} + c_{K,3}$.

(ii) *For the low Δp case,*

$$\underline{c}_T = c_{T,2}\left\{1 + \frac{(v_2 - v_4)(c_{K,1} + c_{K,3} - v_1)}{v_2 - (c_{K,1} + c_{K,2} + c_{K,3})}\right\}.$$

Moreover, it is optimal to centralize commonality in market 2 if and only if $v_2 > c_{K,1} + c_{K,2} + c_{K,3}$ and $v_1 < c_{K,1} + c_{K,3}$.

This proposition highlights the nonobvious role of price and manufacturing cost differentials in determining the optimal network configuration. Notice that the sufficient and necessary conditions for the optimality of centralization imply that $v_1 - v_2 > c_{K,1}$ and $v_2 - v_1 > c_{K,2}$ for (i) and (ii), respectively. This suggests that centralization becomes dominant only when the profit advantage of the centralizing market is sufficiently high.

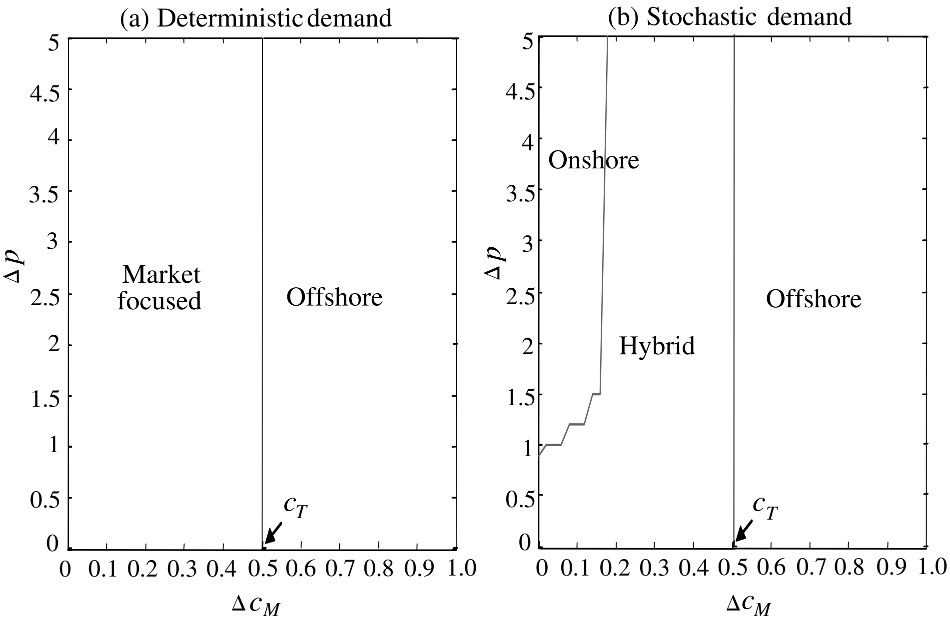
When demands are perfectly positively correlated, a closed-form expression for the transportation cost thresholds is not obtainable. Nevertheless, some structural properties of the optimal capacity vector exist.

Proposition 7. *Let demands be perfectly positively correlated: $P(\{D_1 = D_2\}) = 1$. For the medium and low Δp cases, if $(c_{K,1} + c_{K,3})/v_1 < (c_{K,2} + c_{K,3})/v_2$, then $0 \le K_4^* \le K_2^* < K_3^* = K_1^*$; if $(c_{K,1} + c_{K,3})/v_1 = (c_{K,2} + c_{K,3})/v_2$, then $K_1^* = K_2^* = K_3^* = K_4^*$; if $(c_{K,1} + c_{K,3})/v_1 > (c_{K,2} + c_{K,3})/v_2$, then $0 \le K_3^* \le K_1^* < K_4^* = K_2^*$.*

The structural properties of the optimal capacity vector indicate a weakened value of the ex post transshipment option. Notice that $K_i^* = K_{i+2}^*$ holds for either $i = 1, 2$, or both. It follows that all units of product i are produced locally at market i even though common component capacity at market j could be positive.

It is well known that the newsvendor critical fractile solution crucially depends on the distribution over the entire support and that the optimal capacity level can be below, at, or above the mean of the demand. Hence, general results on how capacity changes with demand variability are hard to establish. We use numerical analysis to illustrate the impact of demand volatility and correlation on capacity investment.

Figure 3 **Optimal Network Configurations Under Deterministic and Stochastic Demand for** $p_1 = 20$, $c_{M,1} = 1$, $c_T = 0.5$, $c_K = (0.5, 0.5, 13.5, 13.5)$, $\mu = (1, 0.1)$, $\gamma = 1$, $\rho = 1$



7. Numerical Analysis

The analysis in the previous sections illustrates how the optimal network configuration is impacted by economic and demand characteristics but has two limitations. First, we are only able to determine the signs of the effects rather than their magnitude. Second, unlike network values, we cannot draw a general conclusion on how demand volatility affects network configuration and capacities. To strengthen our analysis in these two aspects, we present numerical examples using optimization with simulated bivariate normal demands with means $\mu = (\mu_1, \mu_2)$ and covariance matrix

$$\Sigma = \gamma \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix},$$

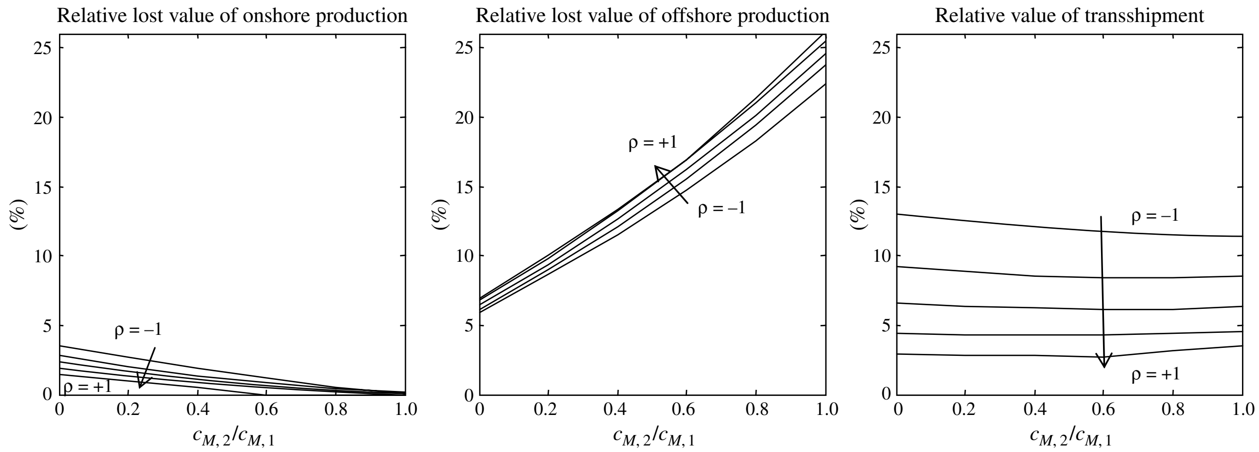
where $\sigma_i = \mu_i CV_i$ and CV_i is the coefficient of variation of demand i, γ is a standard deviation multiplier, and ρ is the correlation coefficient. We set $CV = (0.3, 0.4)$ as constant for all subsequent examples but may vary μ, γ, and ρ. For simplicity, we assume $c_{T,1} = c_{T,2}$ and use c_T to denote the transportation cost. To compare the performance of the four network configurations described in the introduction, we define relative lost value of onshore production $= (V^* - V_{\text{on}})/V_{\text{on}}$; relative lost value of offshore production $= (V^* - V_{\text{off}})/V_{\text{off}}$; relative value of transshipment $= (V^* - V_{\text{mkt}})/V_{\text{mkt}}$.

Figure 3 illustrates how optimal network configurations change under demand uncertainty in the complete space of price and manufacturing cost differentials.[2] In the deterministic case, network decisions are solely driven by cost considerations (i.e., offshoring is optimal when the transportation cost is lower than the manufacturing cost differential) and only market-focused and offshoring may become optimal. In contrast, onshoring may become optimal under stochastic demand, as illustrated in the right panel of the figure. Demand uncertainty makes onshoring more attractive when the price difference is substantial and the manufacturing cost difference is small.

Offshoring decisions are often driven by significant labor cost advantages in the foreign market. Figure 4 shows that for a high Δp case, an increase in the manufacturing cost in the foreign market, as measured

[2] We hold p_1 and $c_{M,1}$ fixed and vary p_2 and $c_{M,2}$. This ensures monotonic changes in the attractiveness of the network configurations. Recall that $\bar{c}_T$ is monotone decreasing in p_2 and monotone increasing in $c_{M,2}$.

Figure 4 Network Values as a Function of Manufacturing Cost Ratio



Note. Parameterized by correlation for $p = (20, 14)$, $c_{M,1} = 1$, $c_T = 1.5$, $c_K = (1, 1, 10, 10)$, $\mu = (1, 0.2)$, $\gamma = 1$.

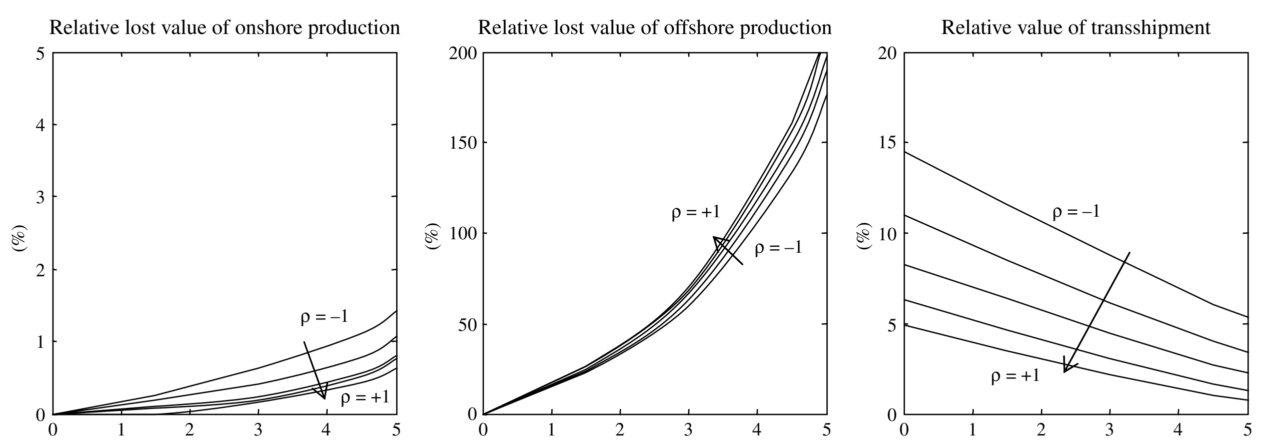
by the ratio $c_{M,2}/c_{M,1}$, increases the attractiveness of onshoring, which becomes optimal when the correlation of demands approaches 1. The impact of this cost change on the value of transshipment is rather flat, meaning a similar impact on both market-focused and hybrid configurations. Notice that Figure 4 assumes a large high-price market: $\mu_1 = 5\mu_2$. The hybrid configuration remains optimal, however, even when $c_{M,2}/c_{M,1} = 1$ if $\mu_1 = \mu_2 = 1$ (not shown). Therefore, low volume in the low-cost market contributes to the attractiveness of onshoring.

Figure 5 shows the impact of transportation cost on the network values for the same parameter values of Figure 4 except that we now fix $c_{M,2}/c_{M,1} = 1$ but vary c_T. As expected, more expensive transportation leads to lower value of centralization and transshipment.

7.1. Demand Correlation

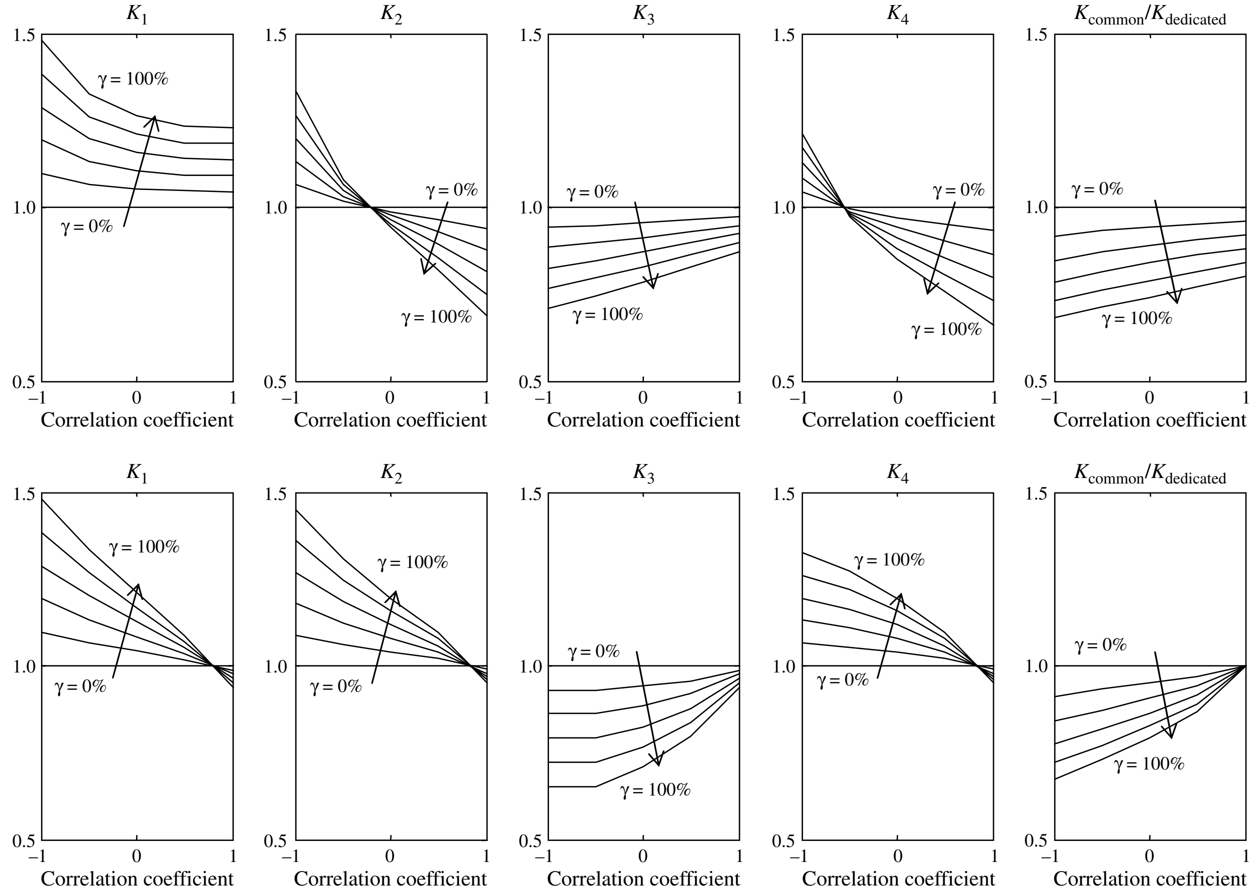
In Figures 4 and 5, the value of transshipment decreases in demand correlation, which implies that the hybrid configuration incurs lower transportation costs as demand correlation increases. Consistent with our example in §4.2, the two figures also illustrate that the attractiveness of onshoring (embodied in the revenue maximization option and transportation

Figure 5 Network Values as a Function of Transportation Cost



Note. Parameterized by correlation for $p = (20, 14)$, $c_M = (1, 1)$, $c_K = (1, 1, 10, 10)$, $\mu = (1, 0.2)$, $\gamma = 1$.

Figure 6 Network Capacity Investment as a Function of Correlation



Notes. Parameterized by standard deviation multiplier γ for $p_1 = 20$, $c_M = (1, 0)$, $c_T = 1.3$, $c_K = (1, 1, 10, 10)$, $\mu = (1, 1)$. (top) high Δp: $p_2 = 14$; (bottom) low Δp: $p_2 = 20$.

cost savings) increases in correlation while that of offshoring (embodied in manufacturing cost savings) decreases in correlation.

Figure 6 details the impact of correlation and volatility on network investment for high and low Δp. Demand sizes are kept equal for the two markets to illustrate that similar forces are at play as in the previous two examples even though in this example the hybrid configuration always dominates the others. Except K_3, all capacities decrease in demand correlation, consistent with the notion that the value of network production (i.e., demand pooling) decreases in demand correlation. Under high Δp, increasing K_3 enhances the revenue maximization benefit, which increases in demand correlation. Under low Δp, increasing K_3 is also profitable, but for a different reason: The manufacturing cost savings from investing in K_4 decreases in demand correlation. The investment in K_2 and K_4 is impacted differently by demand volatility in the two cases: Under high Δp, there exists a correlation coefficient threshold above which K_2 and K_4 decrease in demand volatility, while under low Δp they almost always increase in demand volatility. In the former case, because of the high price in Market 1, the revenue maximization effect dominates, making investment in Market 1 more profitable as demand volatility increases. In the latter case, no price advantage is present and thus the manufacturing cost effect dominates, making investment in Market 2 more attractive as demand volatility goes up.

Finally, in both cases of Figure 6, total investment in the common component increases in demand correlation compared to that in dedicated components. Under low Δp, the capacity ratio of common component to dedicated component even increases to 1 and thus operational hedging through capacity imbalance disappears. This is consistent with Van Mieghem (2007) and reflects that the risk pooling benefit of commonality decreases to zero as demand correlation approaches 1 in the absence of the revenue maximization option.

8. Extensions

We consider two extensions: (1) generalizing our model to asymmetric capacity cost of common component; and (2) exploring the impact of EoS by incorporating fixed cost of investment.

8.1. Asymmetric Capacity Cost of Common Component

Until now we have assumed that the capacity costs of the common component in both markets are identical. The difference in real estate, labor costs, and exchange rates, however, can lead to asymmetric capacity cost of common component in geographically separated markets. To generalize our results, we derive structural properties assuming $c_{K,3} \neq c_{K,4}$. It is useful to define $\Delta c_K = c_{K,3} - c_{K,4}$.

Proposition 8. *Under deterministic demand,*

(i) *If* $c_{T,1} \leq -\Delta c_M - \Delta c_K$, *centralizing commonality in Market* 1 *is optimal;*

(ii) *If* $c_{T,2} \leq \Delta c_M + \Delta c_K$, *centralizing commonality in Market* 2 *is optimal;*

(iii) *Otherwise, the market-focused configuration is optimal.*

Under stochastic demand,

(i) *If* $c_{T,1} \leq -\Delta c_M - \Delta c_K$ *and* $\Delta c_K \leq 0$, *centralizing commonality in Market* 1 *is optimal;*

(ii) *If* $c_{T,2} \leq \Delta c_M + \Delta c_K$ *and* $\Delta c_K \geq 0$ *centralizing commonality in Market* 2 *is optimal.*

Proposition 8 states the conditions under which the centralization configurations are optimal under deterministic and stochastic demand. The results are rather general and cover previous results (setting $\Delta c_K = 0$ reduces Proposition 8 to Propositions 1 and 2). Notice that the optimality condition under stochastic demand requires lower common component capacity cost in the centralizing market. Consider the condition $c_{T,1} \leq -\Delta c_M - \Delta c_K$, which is equivalent to $v_2 - v_3 \leq -\Delta c_K$. When $\Delta c_K \leq 0$, $v_2 - v_3$ is the upper bound of profit gain of moving one unit of common component from Markets 1 to 2 while $-\Delta c_K$ is the associated capacity cost increase. The inequality condition implies that investing in any amount of common component in Market 2 would be suboptimal. If, however, $\Delta c_K \geq 0$, the optimal network configuration becomes less obvious and depends on the demand distribution and thus has to be solved from optimization. This is because even though the profit gain of moving one unit of common component from Market 2 to 1, as measured by $v_3 - v_2$, is greater than the capacity cost increase Δc_K, the expected profit gain may be lower than Δc_K, making investment in Market 2 common component profitable.

Table 4 applies Proposition 8 to the nine cases of net value ordering. The top three cases central to our previous analysis share similar structural properties

Table 4 Optimal Network Configurations Depend on Net Values and Capacity Costs of the Common Component

Ordering	$c_{K,3} = c_{K,4}$	$c_{K,3} > c_{K,4}$	$c_{K,3} < c_{K,4}$
$v_1 \geq v_4 \geq v_2 \geq v_3$ $v_1 \geq v_2 \geq v_4 \geq v_3$ $v_2 \geq v_1 \geq v_4 \geq v_3$	$K_i^* \geq K_{i+2}^*$ $K_{i+2}^* = 0 \Rightarrow K_j^* = K_{j+2}^*$ $i, j \in \{1, 2\}, i \neq j$	$K_1^* \geq K_3^*$ $K_4^* = 0 \Rightarrow K_1^* = K_3^*$	$K_2^* \geq K_4^*$ $K_3^* = 0 \Rightarrow K_2^* = K_4^*$
$v_1 \geq v_3 \geq v_4 \geq v_2$ $v_1 \geq v_4 \geq v_3 \geq v_2$ $v_3 \geq v_1 \geq v_4 \geq v_2$	Centralization: Market 1	See Proposition 8	Centralization: Market 1
$v_2 \geq v_4 \geq v_1 \geq v_3$ $v_4 \geq v_1 \geq v_2 \geq v_3$ $v_4 \geq v_2 \geq v_1 \geq v_3$	Centralization: Market 2	Centralization: Market 2	See Proposition 8

as before, yet are less restrictive. The behavior of the remaining six cases depends on which market has the capacity cost advantage. On the one hand, the results under the symmetric cost assumption are carried over under the asymmetric cost assumption when the centralizing market has cost advantage in capacity investment. For example, when Market 2 has lower capacity cost (i.e., $c_{K,3} > c_{K,4}$), centralization in Market 2 remains optimal. On the other hand, certain configurations may become optimal even though they are never optimal under the symmetric cost assumption. For example, when Market 2 has sufficiently high investment cost (i.e., $c_{T,1} \le -\Delta c_M - \Delta c_K$) and sufficiently low manufacturing cost (i.e., $c_{T,2} \le \Delta c_M$), centralization in Market 1 becomes optimal for the bottom three cases in Table 4, which only give rise to centralization in Market 2 when both markets have identical capacity cost of the common component. This implies that when the common component capacity cost increases in the low-wage countries the optimality region of onshoring is enlarged.

8.2. Fixed Cost of Investment

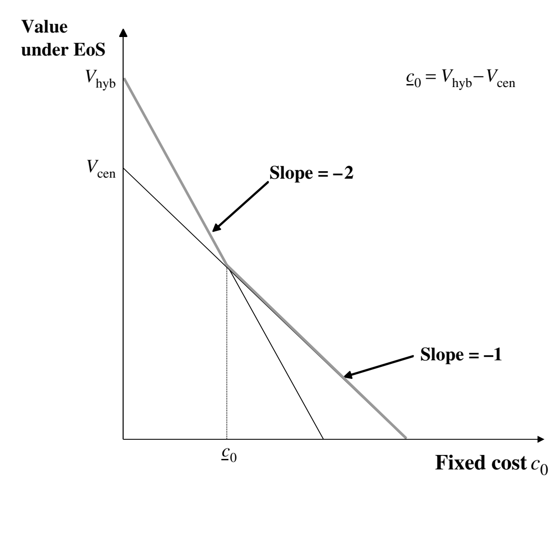
Our analysis until now has focused on the risk pooling and revenue maximization benefits of centralization. We now examine a third benefit: EoS, an important driver in investment decisions that, similar to demand volatility, increases the value of centralization. To analyze EoS in our model, we use the concave affine cost function $C(K) = c_0 1_{\{K>0\}} + c'_K K$. We only add a fixed cost to the common component as the capacity decision hinges on whether to invest this resource in both markets. Although the inclusion of fixed cost makes the cost function discontinuous at zero and complicates first-order conditions, we identified a simple condition to check whether centralization is optimal.

Let $V_{\text{cen}} = \max(V_{\text{on}}, V_{\text{off}})$. If there is no fixed cost, the optimization problem remains the same as before. When the fixed cost increases, the marginal investment decision remains unchanged for a range of fixed cost, in other words, the optimal capacity vector is determined by the same first-order conditions as before. But the optimal values of the centralization and hybrid configurations decrease at different rates. V_{hyb} decreases with slope -2 while V_{cen} decreases with slope -1 because the decentralized network has two common component facilities while the centralized network has only one. When the fixed cost is sufficiently high, the benefit of scale economies becomes dominant and makes centralization optimal. The outer envelope of the two downward-sloping lines in Figure 7 represents how the optimal network value changes with the fixed cost. It follows from the graph that the fixed cost threshold, denoted by $\underline{c}_0$ (where the kink is located) is exactly the difference between V_{hyb} and V_{cen}.

Given an affine concave cost structure, we can decompose the optimization problem with EoS into three: one with the hybrid and two with the centralized configurations. The latter two problems can be solved using the newsvendor network approach illustrated earlier but with reduced dimensionality. Further, our intuition is confirmed that EoS only increases the optimality region of centralization: if centralization is optimal without EoS, the optimal configuration remains after EoS is incorporated. If, however, centralization is suboptimal, the hybrid configuration remains optimal as long as the fixed cost is smaller than the threshold $\underline{c}_0$.

It is important to point out that the optimal location of centralized commonality becomes dependent on demand characteristics in the presence of EoS. Recall that, without EoS, the potential optimal location of centralization is determined solely by the relative magnitude of price and manufacturing cost differentials (under symmetric capacity cost of common component). High and medium Δp cases sup-

Figure 7 Impact of Fixed Cost on Optimal Network Values



port centralization in the high-price market while low Δp puts centralization in the low-cost market. In a more realistic situation where capacity investment involves a significant fixed cost, the performance of both centralized configurations need to be evaluated against the hybrid configuration. Since V_{on} and V_{off} are impacted by demand size and volatility, the optimal location of centralization is impacted by those demand characteristics as well.

9. Conclusions, Managerial Insights, and Limitations

We have presented an analytic model to study sourcing and location decisions of commonality in multimarket facility networks. As a special case, the model allows us to analyze the offshoring decision from a network capacity investment perspective. The model in this paper belongs to the broad class of newsvendor networks but has a distinct focus on network design in the presence of interplant transshipment. Although the model is kept simple for analytical tractability, it captures three key factors in facility network planning: cost, revenue, and demand. Our main objective is to show how uncertainty may change the operations network strategy relative to intuitive, deterministic thinking based on cost only. We demonstrate that centralizing common component production in the high-price (but high-cost) market, or onshoring, can be optimal under certain conditions.

We translate our results into managerial insights on offshoring: (1) When the manufacturing cost reductions of offshoring outweigh transportation costs (including tariffs and duties), centralizing the common component in low-wage countries is optimal, as expected. Otherwise, the optimal network strategy is more complex and depends on price ratios (revenue impact) as well as cost, market size and uncertainty. (2) Centralizing the common component onshore becomes more attractive when the domestic price advantage outweighs the manufacturing cost disadvantage and when demand is positively correlated, i.e., high-price product with volatile correlated demand. (3) Demand volatility affects the centralization versus localization decision, but the optimal location of centralization, in the absence of fixed costs of capacity investment, is independent of demand characteristics. It is determined by the relative magnitude of the price and the manufacturing cost differential. (Recall that the high and medium price differential cases only support onshoring while the low price differential case only supports offshoring.) However, with the fixed costs, both decisions depend on demand characteristics of the two markets. (4) We provide the transportation cost thresholds to serve as an indicator of the attractiveness of centralization.

Though commonality is a key component of our model, it is worth noting that most of the managerial insights hold for any flexible manufacturing system (no distinction between common component versus dedicated component). A simpler yet equally important network question is where flexible manufacturing system should be located. Our analysis can be applied directly to answer this question. As telecommunication and transportation costs decreased and international trade barriers were lifted over the last decade, many companies in developed countries have moved production to low-wage countries. Our study leads to insights that can guide managers in evaluating the cost and benefit of offshoring. The key point is that it is crucial to incorporate the revenue effect and the global demand characteristics into their decision framework, in addition to understanding the cost structure of the global manufacturing network.

The limitation of our work lies in three aspects. First, while we capture many relevant first-order global parameters including exchange rates and tariffs, we focus on demand risk while keeping all other elements deterministic. The interaction between exchange rate risk and demand risk has been explored in the literature. A recent paper by Ding et al. (2007) shows that buying financial option contracts on the currency exchange rate impacts not only the magnitude of capacity levels but also the desired location and number of production facilities. Second, leadtime is not captured because our model has no explicit time dimension. In reality, capacity investment is followed by many demand and production periods. Significant transshipment leadtimes may increase the the implied demand volatility, making transshipment a less effective operational hedge. The conjectured result is that localization and even onshoring may then become more attractive. Last, transshipment of end product is not considered, yet that is not restrictive when localized end products are not substitutable.

Electronic Companion

An electronic companion to this paper is available on the *Manufacturing & Service Operations Management* website (http://msom.pubs.informs.org/ecompanion.html).

References

Anupindi, R., R. Akella. 1993. Diversification under supply uncertainty. *Management Sci.* **39**(8) 944–963.

Arntzen, B. C., L. F. Escudero, T. P. Harrison, L. L. Trafton. 1995. Global supply chain management at digital equipment corporation. *Interfaces* **25** 69–93.

Baily, M. N., R. Z. Lawrence. 2004. What happened to the great U.S. job machine? The role of trade and electronic offshoring. *Brookings Papers Econom. Activity* **2** 211–284.

Bartmess, A. 1994. The plant location puzzle. *Harvard Bus. Rev.* **72**(March–April) 20–22.

Bartmess, A., K. Cerny. 1993. Building competitive advantage through a global network of capabilities. *California Management Rev.* **35** 78–103.

Brush, T. H., C. A. Maritan, A. Karnani. 1999. The plant location decision in multinational manufacturing firms: An empirical analysis of international business and manufacturing strategy perspectives. *Production Oper. Management* **8**(2) 109–132.

Cohen, M. A., H. L. Lee. 1989. Resource deployment analysis of global manufacturing and distributions networks. *J. Manufacturing Oper. Management* **2** 81–104.

Ding, Q., L. Dong, P. Kouvelis. 2007. On the integration of production and financial hedging decisions in global markets. *Oper. Res.* **55**(3) 470–489.

Farrell, D. 2004. Beyond offshoring: Assess your company's global potential. *Harvard Bus. Rev.* **82** 82–90.

Farrell, D. 2005. Offshoring: Value creation through economic change. *J. Management Stud.* **42**(3) 675–683.

Feenstra, R. C., G. H. Hanson. 1996. Globalization, outsourcing, and wage inequality. *Amer. Econom. Rev.* **86**(2) 240–245.

Ferdows, K. 1997. Making the most of foreign factories. *Harvard Bus. Rev.* **75** 73–88.

Hayes, R. H., S. C. Wheelwright. 1984. *Restoring Our Competitive Edge*: *Competing Through Manufacturing*. John Wiley & Sons, New York.

Huchzermeier, A., M. A. Cohen. 1996. Valuing operational flexibility under exchange rate risk. *Oper. Res.* **44**(1) 100–113.

Jordan, W. C., S. C. Graves. 1995. Principles on the benefits of manufacturing process flexibility. *Management Sci.* **41**(4) 577–594.

Kazaz, B., M. Dada, H. Moskowitz. 2005. Global production planning under exchange-rate uncertainty. *Management Sci.* **51**(7) 1101–1119.

Kogut, B., N. Kulatilaka. 1994. Operating flexibility, global manufacturing, and the option value of a multinational network. *Management Sci.* **40**(1) 123–139.

Kouvelis, P., K. Axarloglou, V. Sinha. 2001. Exchange rates and the choice of ownership structure of production facilities. *Management Sci.* **47**(8) 1063–1080.

Kouvelis, P., M. J. Rosenblatt, C. L. Munson. 2004. A mathematical programming model for global plant location problems: Analysis and insights. *IIE Trans.* **36** 127–144.

Kulkarni, S., M. J. Magazine, A. S. Raturi. 2004. Risk pooling advantages of manufacturing network configuration. *Production Oper. Management* **13**(2) 186–199.

Kulkarni, S., M. J. Magazine, A. S. Raturi. 2005. On the trade-offs between risk-pooling and logistics costs in a multi-plant network with commonality. *IIE Trans.* **37** 247–265.

MacCormack, A. D., L. J. Newman III, D. B. Rosenfield. 1994. The new dynamics of global manufacturing site location. *Sloan Management Rev.* **35**(Summer) 69–80.

Markides, C. C., N. Berg. 1988. Manufacturing offshore is bad business. *Harvard Bus. Rev.* **66**(September–October) 113–120.

Munson, C. L., M. J. Rosenblatt. 1997. The impact of local content rules on global sourcing decisions. *Production Oper. Management* **6**(3) 277–190.

Robinson, L. W. 1990. Optimal and approximate policies in multiperiod, multilocation inventory models with transshipments. *Oper. Res.* **38**(2) 278–295.

Rudi, N., S. Kapur, D. F. Pyke. 2001. A two-location inventory model with transshipment and local decision making. *Management Sci.* **47**(12) 1668–1680.

Santoso, T., S. Ahmed, M. Goetschackx, A. Shapiro. 2005. A stochastic programming approach for supply chain network design under uncertainty. *Eur. J. Oper. Res.* **167** 96–115.

Schmenner, R. W. 1979. Look beyond the obvious in plant location. *Harvard Bus. Rev.* **57**(January–February) 126–132.

Schmenner, R. W. 1982. Multiplant manufacturing strategies among the fortune 500. *J. Oper. Management* **2**(2) 77–86.

Skinner, W. 1974. The focused factory. *Harvard Bus. Rev.* **52**(3) 113–121.

Snyder, L. V. 2006. Facility location under uncertainty: A review. *IIE Trans.* **38** 537–554.

Tomlin, B. 2006. On the value of mitigation and contingency strategies for managing supply-chain disruption risks. *Management Sci.* **52**(5) 639–657.

Tomlin, B., Y. Wang. 2005. On the value of mix flexibility and dual sourcing in unreliable newsvendor networks. *Manufacturing Service Oper. Management* **7**(1) 37–57.

Van Mieghem, J. A. 1998. Investment strategies for flexible resources. *Management Sci.* **44**(8) 1071–1078.

Van Mieghem, J. A. 2004. Note: Commonality strategies: Value drivers and equivalence with flexible capacity and inventory substitution. *Management Sci.* **50**(3) 419–424.

Van Mieghem, J. A. 2007. Risk mitigation in newsvendor networks: Resource diversification, flexibility, sharing, and hedging. *Management Sci.* **53**(8) 1269–1288.

Van Mieghem, J. A. 2008. *Operations Strategy*: *Principles and Practice*. Dynamic Ideas, Belmont, MA.

Van Mieghem, J. A., N. Rudi. 2002. Newsvendor networks: Inventory management and capacity investment with discretionary activities. *Manufacturing Service Oper. Management* **4**(4) 313–335.

Webb, A. 2004. U.S. will get China engines. *Automotive News* **79**(6111) 16.

Webb, A., J. Treece. 2004. Toyotas sold in U.S. may get Chinese engine. *Automotive News* **78**(6082) 6.

Yazlali, O., F. Erhun. 2004. Managing demand uncertainty with dual supply contracts. Working paper, Stanford University, Stanford, CA.