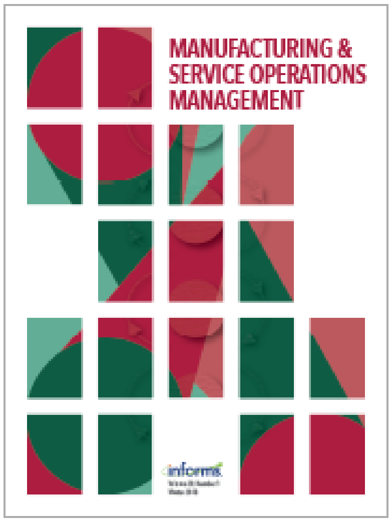

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Yimin Wang, Wendell Gilland, Brian Tomlin,

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Mitigating Supply Risk: Dual Sourcing or Process Improvement?

Yimin Wang
W. P. Carey School of Business, Arizona State University, Tempe, Arizona 85287, yimin_wang@asu.edu
Wendell Gilland
Kenan-Flagler Business School, University of North Carolina, Chapel Hill, North Carolina 27599, wendell_gilland@unc.edu
Brian Tomlin
Tuck School of Business, Dartmouth College, Hanover, New Hampshire 03775, brian.tomlin@tuck.darmouth.edu

Surveys suggest that supply chain risk is a growing issue for executives and that supplier reliability is of particular concern. A common mitigation strategy is for the buying firm to expend effort improving the reliability of its supply base. We explore a model in which a firm can source from multiple suppliers and/or exert effort to improve supplier reliability. For both random capacity and random yield types of supply uncertainty, we propose a model of process improvement in which improvement efforts (if successful) increase supplier reliability in the sense that the delivered quantity (for any given order quantity) is stochastically larger after improvement. We characterize the optimal procurement quantities and improvement efforts and generate managerial insights. For random capacity, improvement is increasingly favored over dual sourcing as the supplier cost heterogeneity increases, but dual sourcing is favored over improvement if the supplier reliability heterogeneity is high. In the random yield model, increasing cost heterogeneity can reduce the attractiveness of improvement, and improvement can be favored over dual sourcing if the reliability heterogeneity is high. A combined strategy (improvement and dual sourcing) can provide significant value if suppliers are very unreliable and/or capacity is low relative to demand.

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1. Introduction

In the McKinsey & Co. Global Survey of Business Executives (Muthukrishnan and Shulman 2006), 65% of respondents reported that their firm's supply chain risk had increased over the past five years. Moreover, the survey identified supplier reliability as one of the top three supply chain concerns for companies during their most recent strategic/operational planning cycle. Echoing this finding, a 2008 survey by the consulting company PRTM found that "companies named on-time delivery of critical products as well as overall product/supply availability as major risks when globalizing their supply chain" (Cohen et al. 2008).

A common, albeit implicit, thread in the growing academic literature on supply risk is that firms can take operational actions to mitigate their risk, for example, by dual sourcing or backup sourcing, but cannot or do not take actions to reduce the underlying delivery risk posed by a particular supplier (see, for example Tomlin 2006, Babich et al. 2007, Dada et al. 2007, Federgruen and Yang 2009a). In practice, firms can and do take actions to improve supplier reliability in lieu of or in addition to sourcing from multiple suppliers:

> Companies have developed numerous ways to minimize disruption related to quality and delivery issues. Increasing the frequency of on-site audits is the most commonly cited approach, followed by physical deployment of their company's resources within the supplier's location, increased inspection, and increased supplier training. Other risk mitigation strategies mentioned frequently include consistent dual sourcing strategies. (Cohen et al. 2008, p. 8)

Both Honda and Toyota devote significant resources to improving supplier performance in cost, quality, and order fulfillment reliability (Handfield et al. 2000, Liker and Choi 2004, Sheffi 2005): "Of the 310 people in Honda's purchasing department, fifty are engineers who work exclusively with suppliers" (Handfield et al. 2000, p. 44). Supplier improvement is practiced by other automotive companies, for example, Daimler, BMW, and Hyundai (Handfield et al. 2000, Wouters et al. 2007) and many nonautomotive companies such as Heineken, Intel, Kimberly Clark, and Siemens (Handfield et al. 2000, Wouters et al. 2007, SCQI 2009). Some companies single source and work with one supplier to improve performance, for example, Altera, Daewoo, and National Computer Resources (Morris 2006, Handfield et al. 2000). Other companies dual source and work with one or both suppliers to improve performance, for example, Honda and Toyota (Liker and Choi 2004). Still other companies dual source but do not collaborate with suppliers on process improvement (Krause and Ellram 1997, Krause 1999), with U.S. firms lagging behind Japanese firms in supplier improvement efforts (Krause et al. 2007).

This paper examines both the process improvement strategy—that is, exerting effort to increase supplier reliability—and dual sourcing strategy in the context of a single-product newsvendor with unreliable suppliers. We explore both the random capacity and random yield models of supplier reliability and propose a model of process improvement in which the firm can exert effort to improve the reliability of a supplier. The effort may or may not succeed, but if it does, then the supplier is more reliable in the sense that the delivered quantity (for any given order quantity) is stochastically larger after improvement. As both the improvement and dual sourcing strategies are observed in practice, the objective of this work is not to determine which strategy is inherently superior, but rather to identify the circumstances that favor a particular strategy and to determine if and when firms should deploy both strategies simultaneously. A particular focus is the exploration of whether and how characteristics of the supply base (cost structure, reliability, degree of heterogeneity in supplier cost structures and reliabilities, etc.) influence the strategy preference.

In addition to fully characterizing the optimal improvement effort and sourcing quantities, we establish a number of important managerial insights, including the following. If the two suppliers differ in at most one dimension, such as cost or reliability, then increasing heterogeneity (weakly) increases the expected profit for both the improvement and dual sourcing strategies. If supply uncertainty is of the random capacity type, then (all else being equal) improvement is preferred over dual sourcing as supplier cost heterogeneity increases, but dual sourcing is favored if reliability heterogeneity is high. In contrast, if supply uncertainty is of the random yield type, then (all else being equal) cost heterogeneity can (under certain conditions) favor dual sourcing, and high reliability heterogeneity typically favors improvement. For both the random capacity and random yield models, if suppliers are identical, dual sourcing is more likely to be preferred in a low-cost supply base, but improvement is more likely to be preferred in a low-reliability supply base. Deploying the combined strategy of improvement and dual sourcing can add significant value if capacity and reliability are both low.

The rest of this paper is organized as follows. Section 2 surveys the relevant literature, and §3 presents the underlying model. For the random capacity model, we characterize and contrast the improvement and dual sourcing strategies in §4 and §5, respectively. We consider the combined strategy in §6. Section 7 examines the random yield model. Section 8 concludes. All proofs can be found in the online appendix.

2. Literature

There exists a large stream of literature that studies unreliable supply. This literature models reliability in three different but related ways: random capacity (Ciarallo et al. 1994, Erdem 1999), random yield (Gerchak and Parlar 1990, Parlar and Wang 1993, Anupindi and Akella 1993, Agrawal and Nahmias 1997, Swaminathan and Shanthikumar 1999, Federgruen and Yang 2009a), and random disruption (Parlar and Perry 1996, Gürler and Parlar 1997, Tomlin 2006, Babich et al. 2007). Financial default is another element of supply risk and has recently been explored by Babich et al. (2007) and Swinney and Netessine (2008).

In the random capacity model, the delivered quantity is the lesser of the order quantity and the realized supplier capacity (and the capacity is independent of the order size). In the (proportional) random yield model, the delivered quantity is a random fraction of the order quantity, and the supplier's capacity is typically assumed to be infinite. Therefore, the random capacity model differs from the random yield model primarily in two aspects: whether the delivered quantity is directly proportional to the order quantity and whether capacity is limited. In the random disruption model, a supplier is either active or inactive and a firm can only place orders when the supplier is active. The random disruption model can be seen as a special case of the proportional random yield model, where the realized yield is either 100% or 0%. We note that Dada et al. (2007) investigate a supplier selection problem using a more general model of supplier reliability. Their focus is to identify supplier rankings in selecting a subset of suppliers. All the above papers treat a supplier's reliability as exogenous; therefore, the improvement strategy is not considered.

There is an extensive empirical and case-based literature on supplier development (e.g., Leenders and Blenkhorn 1988; Krause 1997; Krause et al. 1998, 2007; Krause 1999; Handfield et al. 2000; Krause et al. 2007; Wouters et al. 2007, and references therein). Handfield et al. (2000, p. 37) define supplier development as "any activity that a buyer undertakes to improve a supplier's performance and/or capability to meet the buyer's short-term or long-term supply needs." Delivery reliability (quantity and time) is an important motive for supplier development: "The need for supplier development resulted from supplier problems that threatened to delay, or even bring to a standstill, the buying firm's production" (Krause et al. 1998, p. 45). Krause (1997) classifies development activities into three types: (a) enforced competition, that is, multiple sourcing; (b) incentives, that is, a promise to the supplier of current or future benefits such as a higher price or volume; and (c) direct involvement in which the buying firm expends "resources to help the supplier increase its performance" (Krause 1997, p. 15). A recent working paper by Federgruen and Yang (2009b) explores enforced competition in a random yield setting, where suppliers compete on the mean and variability of production yield. As part of their exploration of joint marketing and inventory decisions, Liu et al. (2009) investigate the value of higher reliability and examines a case in which a retailer pays a higher unit price for higher reliability. This is an example of incentives. Neither Federgruen and Yang (2009b) nor Liu et al. (2009) review the supplier development literature or adopt the classification or terminology of Krause (1997), but we use the classification to position the research.

Our paper explores direct involvement as the mechanism for developing a supplier's delivery reliability performance. There is empirical evidence that direct involvement may be a more effective mechanism for improving reliability: in their study of supplier development in the United States, Krause et al. (2007, p. 540) found that "performance outcomes in quality, delivery and flexibility appear to depend more on direct involvement supplier development than cost performance outcomes." Zhu et al. (2007) study a buying firm's quality improvement effort at its supplier. Their focus is to contrast supplier- and buyer-initiated quality improvement efforts in a single supplier and buyer setting with deterministic demand. They conclude that buyer-initiated quality improvement is important to achieve higher product quality.

Our paper is also related to the process improvement literature, but the focus is quite different from the main thrust of that body of work, namely, the design and control of improvement efforts. Typically the process improvement literature can be categorized into two different streams. The first stream primarily focuses on finding the optimal control policies to improve the production process while minimizing operating costs (Porteus 1986, Fine and Porteus 1989, Marcellus and Dada 1991, Dada and Marcellus 1994, Chand et al. 1996), where process improvement is typically measured in effective capacity (Spence and Porteus 1987), amount of defects (Marcellus and Dada 1991), or general cost of failures (Chand et al. 1996). The second stream of literature focuses on the interaction of process improvement with the firm's knowledge creation and learning curve (Fine 1986; Zangwill and Kantor 1998; Carrillo and Gaimon 2000, 2004; Terwiesch and Bohn 2001). This stream establishes theoretical foundations for the evaluation of process improvement benefits. None of the above process improvement papers considers diversification or dual sourcing strategies.

In summary, the existing supply-uncertainty literature typically focuses on sourcing or inventory strategies for managing supply risk rather than on reliability improvement. The supplier development literature suggests that supplier reliability can be improved and that direct involvement, that is, exertion of effort by the buying firm, may be the most effective mechanism. The process improvement literature focuses on the relative effectiveness of certain process improvement efforts or particular policies for process improvement but does not typically consider a firm's procurement strategy. Our work contributes to the existing literature by exploring and comparing both dual sourcing and direct-involvement reliability improvement.

3. Model

In this section, we first introduce the basic features of the model, then describe our model of supplier reliability and process improvement, and conclude by formulating the firm's problem. Throughout the paper we adopt the convention that $y^+ = \max(0, y)$, $\mathsf{E}[\cdot]$ is the expectation operator, and ∇_x denotes a partial derivative with respect to x. We occasionally also use $'$ to denote derivatives when there is no possibility of ambiguity. The terms "increasing," "decreasing," "larger," and "smaller" are used in the weak sense throughout this paper.

3.1. Basic Features

We study a newsvendor model in which the firm sells a single product over a single selling season. Let $F(\cdot)$ and $f(\cdot)$ denote the distribution and density function of the demand X, respectively. Also, let r, v, and p denote the product's per unit revenue, salvage value, and penalty cost (for unfilled demand), respectively. The firm can source from two suppliers, $i = 1, 2$. Suppliers are unreliable in that the quantity y_i delivered by supplier i is less than or equal to the quantity q_i ordered by the firm. Reliability is further defined below. For a given order quantity q_i and realized delivery quantity y_i, the firm incurs a total supplier-i procurement cost of $(\eta_i q_i + (1 - \eta_i) y_i) c_i$, where c_i is the supplier-i unit cost and $0 \leq \eta_i \leq 1$ is the supplier-i committed cost. The committed cost η_i reflects the fact that, as discussed in Tomlin and Wang (2005), firms at times incur a fraction of the procurement cost for undelivered product.

3.2. Supplier Reliability and Process Improvement

We consider two models of supplier reliability in this paper—random capacity and random yield. For ease of exposition, we focus attention on the random capacity model and then later, in §7, establish that many key results can also be proven for the random yield model.

Let K_i denote supplier i's design capacity, that is, the maximum production it can achieve. Supplier i's effective capacity is less than or equal to its design capacity for various reasons, such as random production technology malfunctions, raw material shortages, or utility interruptions. Let $\xi_i \geq 0$ denote supplier i's realized capacity loss. Then supplier i's effective capacity is $(K_i - \xi_i)^+$. For a given order quantity q_i, supplier i's delivery quantity is then given by $y_i = \min\{q_i, (K_i - \xi_i)^+\}$. The firm can exert effort to improve a supplier's reliability. A natural model of reliability improvement is one in which the effective capacity is (first-order) stochastically larger after improvement.[1] To formalize this, we associate a reliability index a_i with supplier i. For a given value of a_i, we let $G_i(\cdot, a_i)$ and $g_i(\cdot, a_i)$ denote the distribution and density function of the capacity loss ξ_i, respectively. An increase in the reliability index, say from a_i to $\hat{a}_i$, implies increased reliability in the sense that $G_i(\cdot, a_i) \leq G_i(\cdot, \hat{a}_i)$. We assume that the capacity-loss distribution[2] is continuous and that the capacity losses are independent.

[1] In their investigation of how supplier reliability influences order quantities in the two-supplier case, Dada et al. (2007) assume that a higher reliability is associated with a stochastically higher effective capacity, although they do not use this exact language (see p. 22).

[2] If the supplier capacity loss ξ_i is exponentially distributed with parameter λ, reliability improvement corresponds to an increase in λ. For a normal distribution with parameter (μ, σ), reliability improvement corresponds to a decrease in μ. For a Weibull distribution with parameter (α, β), reliability improvement corresponds to a decrease in β. For a uniform distribution $(0, b)$, reliability improvement corresponds to a decrease in b. In each of the above four cases, the reliability index a_i is given by λ, $1/\mu$, $1/\beta$, and $1/b$, respectively.

Let supplier i's initial reliability index be given by a_i^0. The firm can exert effort, for example, knowledge transfer or equipment investment (Krause 1997, Krause et al. 1998), to increase supplier i's reliability index. However, improvement efforts can and do fail (Krause et al. 1998, Krause 1999, Handfield et al. 2000). If the firm exerts an effort level of $z_i \geq 0$, then supplier i's capability improves to $a_i(z_i) \geq a_i^0$ with probability θ_i and remains at a_i^0 with probability $1-\theta_i$. Unless otherwise stated, we assume that the firm's improvement cost is linear in its effort; that is, it costs the firm $m_i z_i$ to exert effort z_i to improve supplier i. All results in the paper extend directly to the case where the firm's improvement cost is convexly increasing in z_i. Consistent with the process improvement literature, we assume $a_i(z_i)$ is concavely increasing in z_i, with $a_i(0) = a_i^0$. In effect, then, there are declining returns to improvement efforts. Note that we focus exclusively on the reliability benefit of process improvement and ignore any additional benefits, such as unit procurement cost reductions or improved payment terms. Additional side benefits from process improvement will only serve to increase its attractiveness as a strategy.

In summary, suppliers are unreliable in that they suffer a random capacity loss. Supplier i's capacity loss, ξ_i, depends on its reliability index a_i, which in turn depends on the firm's improvement effort z_i.

3.3. Problem Formulation

We now describe the firm's problem. The firm first decides its improvement efforts $\mathbf{z} = (z_1, z_2)$ and then, after observing the success or failure of these efforts, determines the order quantities $\mathbf{q} = (q_1, q_2)$. The firm's problem can therefore be formulated as a two-stage stochastic program. In the second stage, knowing the realized supplier reliability indices $\mathbf{a}^r = (a_1^r, a_2^r)$, which determine the distribution functions for the capacity losses (ξ_1, ξ_2), the firm's objective is to determine $\mathbf{q} \geq 0$ so as to maximize its expected profit; that is, $\mathsf{E}_{\xi(\mathbf{a}^r), X}[\pi(\mathbf{q})]$, where

$$\pi(\mathbf{q}) = -\sum_i (\eta_i q_i + (1-\eta_i) y_i) c_i + r \min\left\{x, \sum_i y_i\right\} + v\left(\sum_i y_i - x\right)^+ - p\left(x - \sum_i y_i\right)^+, \tag{1}$$

where x is the realized demand and y_i is supplier i's realized delivery quantity; that is, $y_i = \min\{q_i, (K_i - \xi_i)^+\}$. We can rewrite (1) in a more compact form by defining $\psi_k \equiv -\eta_k c_k/(r+p-v)$ and $\phi_k \equiv (r+p-(1-\eta_k)c_k)/(r+p-v)$. Then,

$$\pi(\mathbf{q}) = (r+p-v)\left(\sum_i \psi_i q_i + \sum_i \phi_i y_i - \left(\sum_i y_i - x\right)^+\right) - px. \tag{2}$$

Letting $\Pi_2(\mathbf{q}; \mathbf{a}^r)$ denote the second-stage expected profit—that is, $\mathsf{E}_{\xi(\mathbf{a}^r), \mathbf{X}}[\pi(\mathbf{q})]$—and taking expectations over the capacity losses $\xi = (\xi_1, \xi_2)$ and demand X, we have

$$\Pi_2(\mathbf{q}; \mathbf{a}^r) = (r+p-v)\left\{\sum_i \psi_i q_i + \mathsf{E}_{\xi(\mathbf{a}^r)}\left[\sum_i \phi_i y_i\right] - \mathsf{E}_{\xi(\mathbf{a}^r), X}\left[\left(\sum_i y_i - X\right)^+\right]\right\} - p\mathsf{E}_X[X]. \tag{3}$$

Let $\Pi_2^*(\mathbf{a}^r)$ denote the optimal second-stage expected profit as a function of the realized reliability indices; that is, $\Pi_2^*(\mathbf{a}^r) = \max_{\mathbf{q}\geq 0}\{\Pi_2(\mathbf{q}; \mathbf{a}^r)\}$. Then, the firm's first-stage expected profit (as a function of improvement effort), is given by

$$\Pi_1(\mathbf{z}) = \sum_{i=1}^{2} -m_i z_i + \theta_1\theta_2\Pi_2^*(a_1(z_1), a_2(z_2)) + \theta_1(1-\theta_2) \cdot \Pi_2^*(a_1(z_1), a_2^0) + (1-\theta_1)\theta_2\Pi_2^*(a_1^0, a_2(z_2)) + (1-\theta_1)(1-\theta_2)\Pi_2^*(a_1^0, a_2^0), \tag{4}$$

and the firm's first-stage problem can be written as $\max_{\mathbf{z}\geq 0}\{\Pi_1(\mathbf{z})\}$. Instead of framing the first-stage problem in terms of the effort vector $\mathbf{z}$, it is analytically more convenient to frame it in terms of the reliability indices $\mathbf{a}(\mathbf{z}) = (a_1(z_1), a_2(z_2))$. We therefore rewrite (4) as

$$\Pi_1(\mathbf{a}) = \sum_{i=1}^{2} -m_i z_i(a_i) + \theta_1\theta_2\Pi_2^*(a_1, a_2) + \theta_1(1-\theta_2) \cdot \Pi_2^*(a_1, a_2^0) + (1-\theta_1)\theta_2\Pi_2^*(a_1^0, a_2) + (1-\theta_1)(1-\theta_2)\Pi_2^*(a_1^0, a_2^0), \tag{5}$$

where $z_i(a_i)$ is the effort level associated with the reliability index a_i. Note that $z_i(a_i)$ is a convex increasing function of a_i because $a_i(z_i)$ is a concave increasing function of z_i.

4. Pure Strategies

As discussed in §1, some firms (e.g., Honda and Toyota) engage in both dual sourcing and process improvement, whereas other firms engage in either dual sourcing or process improvement but not both. In this section and the next, we focus on the two pure strategies: (a) dual sourcing without improvement and (b) single sourcing with improvement. We first characterize and investigate each strategy in isolation (§4) and, then, in §5 compare and contrast the strategies to develop insights as to when a particular strategy is preferred. (Because we ignore the supplier-competition benefits of dual sourcing, there is additional value to dual sourcing that we do not capture; see Babich 2006, and Babich et al. 2007.) In §6 we will return to our general model formulation in which the firm can engage in both process improvement and dual sourcing.

4.1. Dual Sourcing

The firm makes no process improvements in the pure dual sourcing strategy; therefore, we are left with the second-stage problem in which the firm determines the order quantities $\mathbf{q} = (q_1, q_2)$ to maximize $\Pi_2(\mathbf{q}; \mathbf{a}^r)$, which is given by (3), and where $\mathbf{a}^r = (a_1^0, a_2^0)$. Before characterizing the optimal solution, we present a technical property that will be useful in establishing several important directional results in subsequent sections.

Lemma 1. $\Pi_2(\mathbf{q}; \mathbf{a}^r)$ *is submodular in* $\mathbf{q}$.

Lemma 1 tells us that, everything else being equal, an increase in q_i results in a decrease in the optimal q_j^*, where j denotes the complement of i; that is, $j = 2(1)$ if $i = 1(2)$. Despite the fact that we are maximizing a submodular function that is not in general jointly concave, we can establish the necessary and sufficient condition for the optimal procurement quantity vector $\mathbf{q}^*$.

Theorem 1. *There exists an optimal procurement vector* $\mathbf{q}^*$ *that maximizes* $\Pi_2(\mathbf{q}; \mathbf{a}^r)$ *such that* $q_i^* = 0$, $q_i^* = K$, *or* $\nabla_{q_i}\Pi_2(\mathbf{q}^*; \mathbf{a}^r) = 0$, $i = 1, 2$.

Theorem 1 uses the unimodal concept (see, e.g., Aydin and Porteus 2008) to establish the necessary and sufficient condition for $\mathbf{q}^*$. See the proof of Theorem 1 in the online appendix for details. To the best of our knowledge, this work is the first to establish the necessary and sufficient conditions for the optimal dual sourcing quantities for a random capacity model.[3] Although it follows from Theorem 1 and (3) that the optimal (interior) procurement quantity $\mathbf{q}^*$ satisfies

$$\psi_i + G_i(K_i - q_i^*, a_i^0)\big(\phi_i - \mathsf{E}_{\xi(a_j^0)}[F(q_i^* + y_j)]\big) = 0, \quad i = 1, 2, \quad (6)$$

closed-form solutions will not typically exist in general. Using (6), we can establish the following relationship between the optimal procurement quantity/expected profit and the reliability index.

Lemma 2. (a) *The firm's optimal procurement quantity from supplier* i, q_i^*, *is increasing in the supplier's reliability index* a_i^0. (b) *The firm's optimal expected second-stage profit,* $\Pi_2^*(a_i^0)$, *is increasing in the supplier's reliability index* a_i^0.

The firm pays ηc per unit ordered but not received. As the reliability increases, the expected quantity of undelivered units (for a given order size q) decreases, so the firm is willing to order more units.

To further explore the firm's dual sourcing strategy, for the rest of this section we assume that demand is deterministic and $\eta = \mathbf{0}$; that is, the firm pays only for what is delivered. Without loss of generality, we assume $\phi_1 G_1(K_1, a_1^0) \geq \phi_2 G_2(K_2, a_2^0)$ (if not, reverse the label). The following theorem characterizes the firm's optimal procurement quantity $\mathbf{q}^*$ as a function of demand.

Theorem 2. *Assume demand* x *is deterministic,* $\eta = \mathbf{0}$, *and* $\phi_1 G_1(K_1, a_1^0) \geq \phi_2 G_2(K_2, a_2^0)$. *The firm's optimal procurement vector* $\mathbf{q}^*$ *is given by*

$$x \in \Omega_1 \quad \Rightarrow \quad q_1^* = x, \quad q_2^* = 0$$

[3] Dada et al. (2007) analyze a related supply uncertainty problem with N suppliers but do not establish necessary and sufficient conditions for the optimal procurement quantities. On page 21 of their paper, they write, "Proposition 5 also has technical implications. Basically, in contrast to (10) and (11)—which establish necessary, but not sufficient, conditions for optimality—Proposition 5 helps establish a sufficient (but not necessary) condition for optimality." We note that our Equation (6) can be viewed as a generalization of the two-supplier case of Equation (A5) in Dada et al. (2007) to allow for the committed cost. We also note that the focus of Dada et al. (2007) is quite different from ours. They mainly focus on the supplier selection problem (and do not consider improvement), whereas we focus on contrasting the dual sourcing and improvement strategies.

$$x \in \Omega_2 \;\Rightarrow\; q_1^* = x - q_2^*,\quad q_2^* \text{ satisfies } \phi_1 G_1(K_1 - (x - q_2^*)) = \phi_2 G_2(K_2 - q_2^*)$$

$$x \in \Omega_3 \;\Rightarrow\; q_1^* = x - (K_2 - G_2^{-1}(\phi_1)),\quad q_2^* = x - (K_1 - G_1^{-1}(\phi_2))$$

$$x \in \Omega_4 \;\Rightarrow\; \begin{cases} q_1^* = x - (K_2 - G_2^{-1}(\phi_1)), \quad q_2^* = K_2, \\ \quad \text{if } G_1^{-1}(\phi_2) \geq G_2^{-1}(\phi_1) \\ q_1^* = K_1, \quad q_2^* = x - (K_1 - G_1^{-1}(\phi_2)), \\ \quad \text{if } G_1^{-1}(\phi_2) < G_2^{-1}(\phi_1) \end{cases}$$

$$x \in \Omega_5 \cup \Omega_6 \;\Rightarrow\; q_1^* = K_1, \quad q_2^* = K_2,$$

where Ω_i, $i = 1, \ldots, 6$, *partition the demand space and are given by*

$$\Omega_1\colon\quad 0 \leq x \leq K_1 - G_1^{-1}\left(\frac{\phi_2}{\phi_1} G_2(K_2)\right)$$

$$\Omega_2\colon\quad K_1 - G_1^{-1}\left(\frac{\phi_2}{\phi_1} G_2(K_2)\right) < x \leq K_1 + K_2 - (G_1^{-1}(\phi_2) + G_2^{-1}(\phi_1))$$

$$\Omega_3\colon\quad K_1 + K_2 - (G_1^{-1}(\phi_2) + G_2^{-1}(\phi_1)) < x \leq K_1 + K_2 - \min(G_1^{-1}(\phi_2), G_2^{-1}(\phi_1))$$

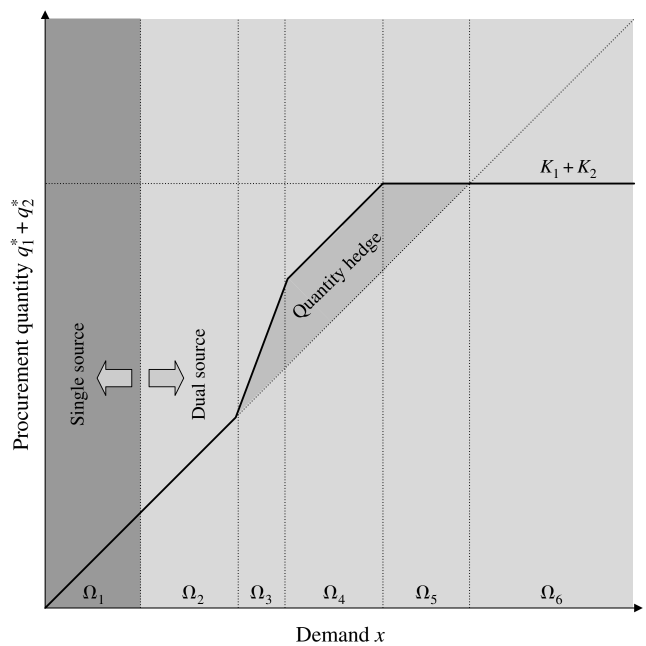
$$\Omega_4\colon\quad K_1 + K_2 - \min(G_1^{-1}(\phi_2), G_2^{-1}(\phi_1)) < x \leq K_1 + K_2 - \max(G_1^{-1}(\phi_2), G_2^{-1}(\phi_1))$$

$$\Omega_5\colon\quad K_1 + K_2 - \max(G_1^{-1}(\phi_2), G_2^{-1}(\phi_1)) < x \leq K_1 + K_2$$

$$\Omega_6\colon\quad x > K_1 + K_2.$$

This theorem indicates that the firm's procurement strategy is driven largely by the relative magnitudes of demand and supplier capacities (see Figure 1). When the suppliers' effective capacities are high relative to demand (i.e., region Ω_1), it is optimal to order a quantity equal to the demand, but only from the most attractive supplier—the lower-cost one if both suppliers have identical reliabilities. As demand increases, dual sourcing becomes optimal.[4] At first, in region Ω_2, it is optimal to order a total quantity equal to demand. As demand increases further, (i.e., region Ω_3) the firm continues to dual source but, for additional protection, orders a total quantity larger than demand. In other words, it hedges against capacity losses through diversification (dual sourcing) and "over ordering." We note that such quantity hedging, that is, over ordering, never occurs in a single-supplier random capacity model (Ciarallo et al. 1994). Quantity hedging protects the firm against capacity shortfall in the event that the *other* supplier experiences a capacity shortage, and hence quantity hedging is valuable only when there are multiple suppliers. As demand increases even further (i.e., regions Ω_4 and Ω_5), the quantity hedge is constrained by one or more of the supplier capacities, until eventually (in region Ω_6) demand is so high that it exceeds the suppliers' maximum (i.e., design) capacity. At this point, a quantity hedge is no longer feasible. Our numerical studies indicate that in the case of stochastic demand a qualitatively similar progression holds.

Figure 1 **Optimal Procurement Quantity as a Function of Demand**



The firm uses dual sourcing and possibly a quantity hedge to mitigate the impact of unreliable (and/or

[4] In this paper, we typically use the term dual sourcing to refer to a strategy in which the firm has two suppliers available to it, even if the firm only sources from one of the two suppliers. At times, however, we also use the term dual sourcing to refer to the situation in which the firm simultaneously sources from both suppliers. The particular meaning of the term dual sourcing will be clear from the context.

limited) capacity. As reliability increases, one might therefore anticipate that a firm would be less likely to engage in these tactics. The following corollary confirms this intuition, but with a slight caveat for dual sourcing.

Corollary 1. (a) *The quantity hedge region, that is,* $\Omega_3 \cup \Omega_4 \cup \Omega_5$, *contracts and the quantity hedge size, that is,* $[q_1^* + q_2^* - x]^+$, *decreases as either* a_1^0 *or* a_2^0 *increases, that is, as supplier* 1*'s or* 2*'s reliability increases*. (b) *The single sourcing region* (Ω_1), *expands as* a_1^0 *increases and contracts as* a_2^0 *increases*.

Whereas the quantity hedge becomes less attractive as either supplier's reliability increases,[5] dual sourcing may become more attractive if the (initially) nonpreferred supplier's reliability increases sufficiently to compensate for its cost and/or reliability disadvantage. If both suppliers are initially identical, then dual sourcing becomes less attractive as either supplier's reliability increases.

4.2. Single Sourcing with Improvement

In the pure improvement strategy the firm can source from only one supplier. Because improvement efforts are not guaranteed to succeed, the firm may wish to delay commitment to a supplier until after observing the success or failure of its improvement efforts. We call this late commitment. Alternatively, the firm may commit to a supplier before observing the improvement outcome. We call this early commitment. Both early and late commitment are observed in practice. "Interviews with purchasing managers…indicated that supplier development is not always successful. If the effort fails the supplier may be dropped despite the fact that the buying firm has invested in the supplier" Krause (1999, p. 219). However, "performance improvement sought by buying firms [is] often only possible when they commit to long-term relationships with key suppliers" (Krause et al. 2007, p. 531), and so some firms prefer to commit to the supplier in advance (Handfield et al. 2000).[6] In what follows, we first consider early commitment and then late commitment.

4.2.1. Early Commitment. The firm selects one supplier and (after making improvement efforts) single sources from that supplier. Let i denote the chosen supplier. After characterizing the optimal improvement effort, we will discuss supplier selection.

Adapting (3) and (5) to the single-sourcing case, the firm's second-stage and first-stage expected profit functions are given by

$$\Pi_2(q_i; a_i^r) = (r+p-v) \cdot \big(\psi_i q_i + \phi_i \mathsf{E}_{\xi_i(a_i^r)}[y_i] - \mathsf{E}_{\xi_i(a_i^r),X}[(y_i - X)^+]\big) - p\mathsf{E}_X[X]$$

and

$$\Pi_1(a_i) = -m_i z_i(a_i) + \theta_i \Pi_2^*(a_i) + (1-\theta_i)\Pi_2^*(a_i^0), \quad (7)$$

respectively, where $\Pi_2^*(a_i) = \max_{q_i \geq 0}\{\Pi_2(q_i; a_i)\}$. The second-stage single-sourcing problem, that is, $\max_{q_i \geq 0}\{\Pi_2(q_i; a_i)\}$, can be viewed as a special case of the dual sourcing problem characterized in §4.1, but with the other (not selected) supplier having an infinite procurement cost. All results of §4.1 therefore apply to this second-stage problem. Now we are in a position to characterize the firm's optimal investment effort.

Theorem 3. *Let* $\partial^2 G_i(\cdot, a_i)/\partial a_i^2 \leq 0$; *that is, the supplier's marginal reliability improvement is decreasing in the reliability index*. *If* $\eta_i = 0$, *then the firm's expected profit—*$\Pi_1(a_i)$*—is a concave function of the reliability index* a_i. *Furthermore, the optimal index* a_i^* *satisfies*

$$\frac{m_i}{\theta_i}\frac{\partial z_i(a_i)}{\partial a_i} = \int_{K_i - q_i^*}^{K_i} \left((\phi_i - F(K_i - \xi_i)) \frac{\partial G_i(\xi_i, a_i)}{\partial a_i} \right) d\xi_i. \quad (8)$$

[5] The fact that $[q_1^* + q_2^* - x]^+$ decreases as reliability increases should not be confused with Lemma 2(a) which states that q_i^* increases in supplier i's reliability. Recall that Lemma 1 implies that an increase in q_1 results in a decrease in q_2 (and vice versa), so the total order quantity $q_1^* + q_2^*$ can decrease in the reliability.

[6] "Perkins recently spent 8 months trying to convince a key supplier to consider a kaizen; the supplier's managers were reluctant because another company's recent kaizen failed to yield significant improvements. The lack of trust was compounded by Perkins' reputation for 'arm's length' relationships with suppliers, which manifested in Perkins frequently switching suppliers on the basis of price. Perkins is now aggressively trying to reverse this perception through its new purchasing philosophy, which emphasizes cooperative relationships with key suppliers and well-defined purchasing objectives beyond purchase price" (Handfield et al. 2000, p. 46). We also note that Krause et al. (2007) found empirical support for the hypothesis that "there is a positive relationship between buying firms' commitments to long-term relationships with key suppliers and buying firms' performance improvements" (p. 531).

The assumption of $\partial^2 G_i(\cdot, a_i)/\partial a_i^2 \leq 0$ in Theorem 3 is mild, as it simply requires a (weakly) decreasing marginal return on improvement efforts, and it is satisfied by, for example, the exponential, Weibull (for $\alpha \leq 1$), and uniform distributions. If $\eta_i > 0$, then concavity of the profit function can be established if the capacity loss is uniformly distributed or for more general distributions if the improvement cost is sufficiently convex in effort. Recall that for expositional ease we assume linear effort cost in the paper. Closed form solutions for the optimal target reliability a_i^*, or equivalently the improvement effort z_i^*, will not typically exist, but sensitivity results can be established.

Corollary 2. *The firm's optimal improvement effort* z_i^* *is* (a) *decreasing in the improvement cost* m_i, (b) *increasing in the improvement success probability* θ_i, (c) *decreasing in the unit procurement cost* c_i, (d) *increasing in the committed cost* η_i, *and* (e) *increasing in the unit revenue* r.

To this point, we have characterized the optimal improvement effort if the firm selects supplier $i = 1, 2$ as its single source. The question remains as to which supplier the firm should select. Numerically, this is readily solved by comparing the optimal expected profit associated with each supplier. Analytically, we can establish some properties of the optimal selection. In what follows, we first establish that the potential for reliability improvement can influence supplier selection but only if the two suppliers differ in more than one dimension. We then investigate supplier selection when suppliers differ in both cost and reliability.

Let i^* denote the firm's preferred supplier if reliability improvement is possible, and let j^* denote the firm's preferred supplier if reliability improvement is not possible.

Theorem 4. (a) *If suppliers* 1 *and* 2 *differ in at most one attribute, then* $i^* = j^*$. (b) *If suppliers* 1 *and* 2 *differ in more than one attribute, then* i^* *may not equal* j^*.

The second result is important from a supplier's perspective: willingness to collaborate on improvement can be an order winner even if the supplier is less competitive on other dimensions.

Now let us consider the case where the suppliers differ in their unit costs and reliabilities but have the same committed costs and design capacities. Without loss of generality, we assume that $c_1 \leq c_2$; that is, supplier 1 is cheaper than supplier 2. Define $\delta_c = c_2 - c_1 \geq 0$ and $\delta_a = a_2^0 - a_1^0$. Also, define $\bar{\delta}_a$ as the threshold value of δ_a such that supplier 2 is preferred if and only if $\delta_a \geq \bar{\delta}_a$.

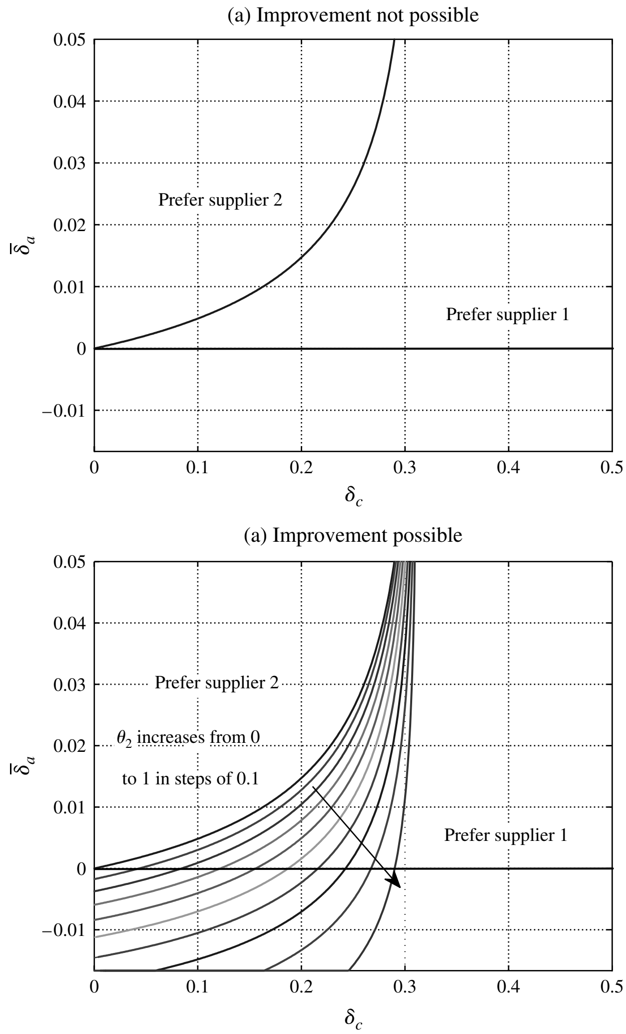
Lemma 3. *All else being equal*, $\bar{\delta}_a$ *is increasing in* δ_c.

In other words, as supplier 2 becomes more expensive relative to supplier 1, the required reliability difference for supplier 2 to be preferred also increases. In Figure 2 we present $\bar{\delta}_a$ as a function of δ_c when reliability improvement is not possible and reliability improvement at supplier 2 *is* possible. (Figure 2 was obtained by setting $c_1 = 0.1$, $\theta_1 = 0$, $a_1^0 = 2/K$, $x = 100$, $K = 120$, $G(\cdot, a_i) \sim \exp(\cdot, a_i)$, $m_2 = 1$, and $a_2(z_2) = a_2^0 + \log(1 + z_2)$.)

Focusing first on Figure 2(a), in which reliability improvement is not possible, we observe a convex increasing switching curve, that is, supplier 2 needs to have an increasingly large reliability advantage ($\bar{\delta}_a > 0$) to compensate for a cost disadvantage. In Figure 2(b), for which reliability improvement is possible, we present the switching curve as a function of supplier 2's improvement probability. Two observations are worth noting. First, and different from (a), the switching threshold $\bar{\delta}_a$ can be negative. This means that a higher-cost and lower-reliability supplier may be selected if its reliability can be improved. Second, the switching threshold $\bar{\delta}_a$ decreases as the probability of improvement increases. These and other related findings can be formally established. In particular, (a) $\bar{\delta}_a > 0$ if reliability cannot be improved but $\bar{\delta}_a$ can be negative if reliability can be improved; and (b) $\partial\bar{\delta}_a/\partial m_2 \geq 0$, $\partial\bar{\delta}_a/\partial\theta_2 \leq 0$, $\partial\bar{\delta}_a/\partial m_1 \leq 0$, and $\partial\bar{\delta}_a/\partial\theta_1 \geq 0$ (proofs omitted). In other words, a supplier can improve its attractiveness to the buying firm by reducing the firm's cost of improvement or by increasing its chances of success. A supplier can even overcome an initial cost and reliability disadvantage if its improvement potential is sufficiently attractive.

4.2.2. Late Commitment. In late commitment the firm exerts improvement effort at one or both suppliers and, after observing improvement outcomes, procures from a single supplier. By postponing supplier selection, late commitment hedges against uncertain improvement outcomes and, therefore, (weakly) dominates early commitment. If improvement efforts

Figure 2 Supplier Switching Curve



are guaranteed to succeed, that is, $\theta = \mathbf{1}$, then late commitment offers no value over early commitment. In this subsection we compare late and early commitment and investigate the value of late commitment; that is, under what circumstances does it outperform early commitment, and how much value does it provide?

In late commitment, the optimal second-stage expected profit $\Pi_2^*(a_1^r, a_2^r) = \max\{\Pi_2^*(a_1^r), \Pi_2^*(a_2^r)\}$, where $\Pi_2^*(a_i^r)$ is the optimal second-stage profit if the firm single sources from supplier i, given a realized reliability index of a_i^r. Substituting this into (5), we obtain the firm's first-stage profit function as

$$\begin{aligned}\Pi_1^L(\mathbf{a}) = \sum_{i=1}^{2} -m_i z_i(a_i) &+ \theta_1\theta_2 \max\{\Pi_2^*(a_1), \Pi_2^*(a_2)\} \\ &+ \theta_1(1-\theta_2)\max\{\Pi_2^*(a_1), \Pi_2^*(a_2^0)\} \\ &+ (1-\theta_1)\theta_2 \max\{\Pi_2^*(a_1^0), \Pi_2^*(a_2)\} \\ &+ (1-\theta_1)(1-\theta_2)\max\{\Pi_2^*(a_1^0), \Pi_2^*(a_2^0)\}, \end{aligned} \quad (9)$$

where we use the superscript L to denote that it is the late commitment profit function. Because of the max operation in (9), $\Pi_1^L(\mathbf{a})$ is neither concave nor unimodal in $\mathbf{a}$.

Let a_i^{*L} denote the optimal reliability index for supplier $i = 1, 2$ in late commitment and let a_i^{*E} denote the optimal reliability index if supplier $i = 1, 2$ is selected in early commitment.

Lemma 4. *$a_i^{*L} \le a_i^{*E}$ for $i = 1, 2$.*

Late commitment targets a (weakly) lower reliability index for a supplier than early commitment does, assuming that supplier is selected in early commitment. Equivalently, the firm exerts (weakly) less effort on improving a supplier. The reason is that in late commitment a particular supplier, say i, is used if and only if it is preferred in the second stage, whereas in early commitment that supplier (if selected) is guaranteed to be used in the second stage. The uncertainty as to whether a supplier will be used dampens the firm's improvement effort.

We now turn our attention to the value provided by late commitment. We use Π_1^{*L} (Π_1^{*E}) to denote the optimal late (early) commitment expected profit. Letting j denote the complement of i—that is, $j = 2(1)$ if $i = 1(2)$–it follows (almost immediately) from Lemma 4 and (9) that $\Pi_1^{*L} = \Pi_1^{*E}$ if $\Pi_2^*(a_i^{*E}) < \Pi_2^*(a_j^0)$ for $i = 1$ or $i = 2$. That is, late commitment offers no value if one supplier dominates the other in the sense that the supplier (at its current reliability) is preferred over the other supplier at that supplier's optimum (early commitment) reliability. If such a dominance exists, there is no value to postponing supplier selection, as the optimal selection does not depend on improvement outcomes. In absence of this dominance, late commitment can provide value.

Theorem 5. *Let suppliers 1 and 2 be identical except for their unit costs, and let $c_1 \le c_2$. Then $\Pi_1^{*L} > \Pi_1^{*E}$ if $[\Pi_2^*(a_2^{*E}) - \Pi_2^*(a_1^0)]^+ > mz(a_2^{*E})/(\theta(1-\theta))$.*

Corollary 3. (a) *If* $\Pi_1^{*L} > \Pi_1^{*E}$ *for some* $c_1 = \hat{c}_1 \le c_2$, *then* $\Pi_1^{*L} > \Pi_1^{*E}$ *for all* $\hat{c}_1 \le c_1 \le c_2$. (b) *There exist* θ_a *and* θ_b *with* $0 < \theta_a < \theta_b < 1$ *such that* $\Pi_1^{*L} = \Pi_1^{*E}$ *if* $\theta < \theta_a$ *or* $\theta > \theta_b$.

Theorem 5 and its corollary tell us that cost difference, improvement success probability, and improvement cost all play a role in determining whether late commitment outperforms early commitment. Let us take each in turn. As the difference in unit costs $c_2 - c_1$ decreases, the more expensive supplier requires a smaller reliability advantage to be selected in the second stage (this follows from Lemma 3). Therefore, the firm is less certain (in the first stage) which supplier will be preferred, so there is more value in postponing its selection. A similar argument holds for any supplier parameter: the more similar the suppliers are, the more value there is to postponing selection. Late commitment is less likely to offer value when the improvement success probability θ is very low or very high. By allowing for improvement effort at both suppliers, late commitment hedges against an improvement failure at one supplier. This hedging benefit is more pronounced if the probability of one success and one failure is high, as that is the event in which the hedge is useful. Thus, the hedging benefit is low if θ is very low (very high) because the probability of both efforts failing (succeeding) is high. As the unit improvement cost m increases, the cost of experimentation (i.e., improve one or both suppliers before choosing which is best) increases, so one might reasonably conjecture that the value of late commitment should decrease in the improvement cost. We did observe this in our numerical study.

We carried out an extensive study to investigate the value of late commitment. We adopted a uniform distribution $U(0, b)$ for the capacity loss. Drawing from the process improvement literature, e.g., Porteus (1986), we used a log function for reliability improvement; that is, $a(z) = a^0 + \log(1 + z)$. Demand was uniformly distributed with a mean of 100 and standard deviation of 30. We set the unit revenue $r = 1$, the salvage value $v = 0$, and the penalty cost $p = 0$. Suppliers were identical except in their unit cost c. The design capacity was fixed at $K = 120$. Initial reliability was parameterized by the expected relative capacity loss $\mathsf{E}[\xi]/K$. Table 1 summarizes the values of parameters in the study. There were a total of 121,500 problem instances.

The value of late commitment (relative to early commitment), $V_L = (\Pi_1^{*L} - \Pi_1^{*E})/\Pi_1^{*E}$, was 4.7% on average, with a maximum of 90.0% and a minimum of 0.0%. In Figure 3, we show the value of late commitment as a function of the cost difference $\Delta_c = c_2 - c_1$, success probability θ, improvement cost m, and initial reliability $\mathsf{E}[\xi]/K$. For example, in Figure 3(a), we plot V_L for different values of the committed cost, and V_L represents the average value across all instances with that committed cost and that cost difference. Other subfigures are similarly constructed. We see that the value of late commitment is highest when (a) the cost difference is low, (b) the success probability is not too high or too low, (c) the improvement cost is low, (d) the reliability is low, and (e) the committed cost is high. Observations (a)–(c) are consistent with our earlier discussion. That is, late commitment is valuable when suppliers are similar, hedging benefits are high, and experimentation cost is low. In addition, late commitment is more valuable when suppliers are less unreliable and the committed cost is high. At higher committed costs η, the firm is more sensitive to low reliability because it incurs a higher cost for undelivered units. Therefore, late commitment is more valuable as η increases because late commitment gives a higher probability of at least one supplier having increased reliability.

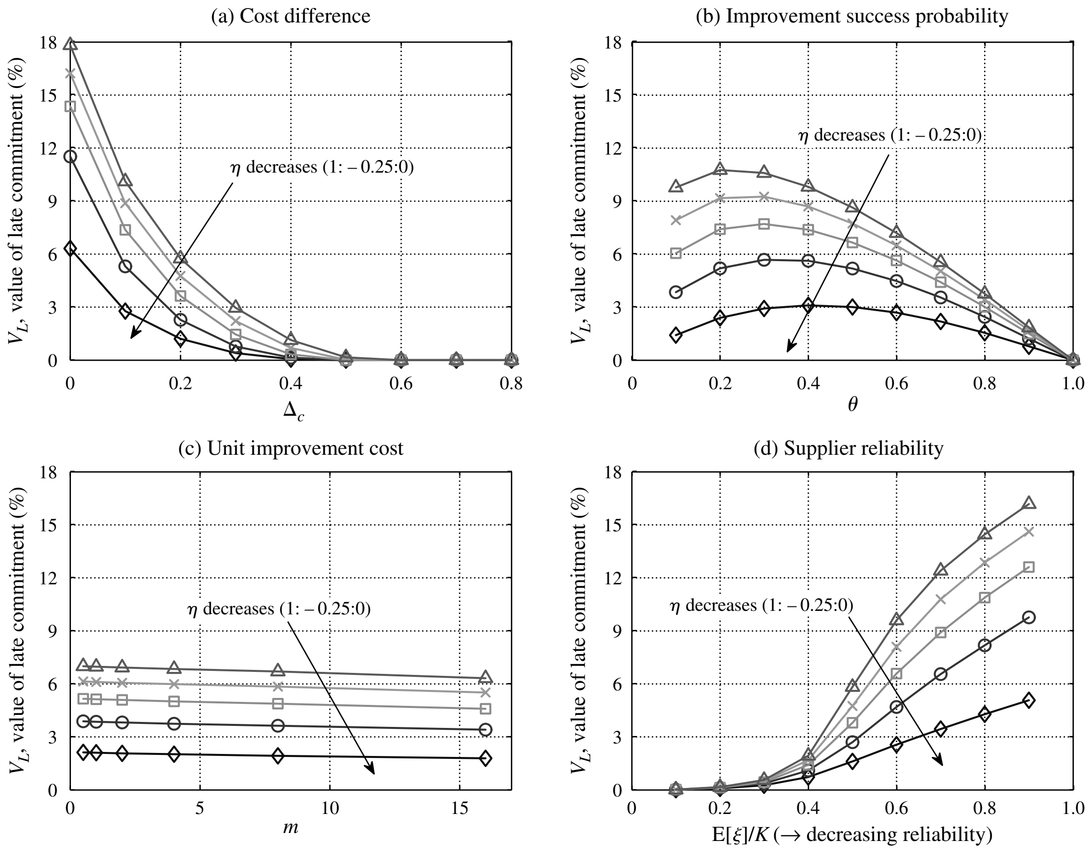
Table 1 Study Design for Late Commitment Value

Parameter	Values
Supplier 2 unit cost c_2	0.1 to 0.9 in increments of 0.1
Supplier 1 unit cost c_1	0.1 to c_2 in increments of 0.1
Improvement success probability θ	0.1 to 1.0 in increments of 0.1
Expected relative capacity loss $\mathsf{E}[\xi]/K$	0.1 to 0.9 in increments of 0.1
Fraction of committed cost η	0.0 to 1.0 in increments of 0.25
Unit improvement cost m	0.5, 1, 2, 4, 8, 16

5. Dual Sourcing or Single Sourcing with Improvement?

Having investigated the dual sourcing and single sourcing with improvement strategies, we now explore how attributes of the suppliers—for example, cost and reliability—influence the firm's strategy preference. For brevity, in this section (and §7) we use

Figure 3 The Value of Late Commitment



DS to denote dual sourcing and SSI to denote single sourcing with improvement. Define Π^*_{SSI} and Π^*_{DS} as the optimal expected profit for the SSI (with early commitment) and DS strategies, respectively. (We do not consider any fixed costs associated with a given strategy, as the directional effects of such fixed costs are obvious.) Before comparing the strategies, we take a brief detour that will be helpful for interpreting some later findings.

The fundamental challenge in a random supply setting is that the delivered quantity can differ from the ordered quantity. For the purposes of this discussion, consider any general supply process that transforms an order q into a delivery $y(q)$. Let us define $\rho(q) = y(q)/q$ as the "yield" for a given order quantity q. The buying firm faces two challenges: a mean effect and a variability effect. The mean effect refers to the fact that $\mathsf{E}[\rho(q)] \le 1$.[7] Absent variability, that is, when $\rho(q)$ is a deterministic function of q, then the firm can scale its order quantity to ensure it receives exactly the quantity it desires. However, if the firm faces a positive committed cost, then this scaling can be expensive, as the firm pays for units not received. The variability effect refers to the fact that the firm is uncertain about the quantity it will receive. This uncertainty results in the firm having to deal with overage or underage costs even if demand is deterministic. For a deterministic demand, random yield model with no committed cost, Agrawal and Nahmias (1997) prove that the buying firm is better off when the mean yield is higher and the yield variance is lower. Although it may not be generally true that variance fully captures

[7] In theory a random supply process may result in $\mathsf{E}[\rho(q)] > 1$, but it is natural to consider $\mathsf{E}[\rho(q)] \le 1$. The logic presented can be adapted to the case in which $\mathsf{E}[\rho(q)] > 1$.

the variability effect, it is helpful to frame our discussion of DS and SSI in terms of how each strategy influences the mean and variance of $\rho(q)$, denoted as $\mu_\rho(q)$ and $\sigma^2_\rho(q)$, respectively. In a random capacity setting, both DS and SSI increase $\mu_\rho(q)$ (proof omitted) and reduce $\sigma^2_\rho(q)$ (numerically observed) relative to the "original" single supplier system and, therefore, improve the firm's performance by mitigating the mean/variability effects of random capacity.[8] DS achieves this by splitting the order between suppliers, whereas SSI does it by reducing (in a stochastic sense) the supplier's capacity loss. For later use, we note that if the two suppliers have identically distributed effective capacities, then the more the order split departs from an equal division, the less mitigation benefit DS achieves.

5.1. Nonidentical Suppliers

Firms within a given industry may exhibit heterogeneity in their capabilities and performance because of (among other things) "their history or initial firm endowment" Barney (2001, p. 647) or their geographic location (Hazra and Mahadevan 2006). Arguing that the Internet has facilitated global sourcing, Hazra and Mahadevan (2006) suggest that supply base heterogeneity has increased in recent years and that supplier capacity and cost structures are two primary dimensions of heterogeneity. We say that two suppliers are more heterogeneous if they differ more on a particular attribute. For example, define $c_1 = c - \Delta_c$ and $c_2 = c + \Delta_c$, then the suppliers become more heterogeneous as Δ_c increases ($0 \le \Delta_c < c$). We refer to Δ_c as the cost heterogeneity parameter. Analogously to Δ_c, define Δ_η, Δ_a, and Δ_K as the committed cost, reliability, and capacity heterogeneity parameters, respectively.

Theorem 6. *Assuming both suppliers are identical except in the pertinent heterogeneity parameter, then* (a) Π^*_{SSI} *is increasing in* Δ_c, Δ_K, Δ_η, *and* Δ_a. (b) Π^*_{DS} *is increasing in* Δ_c *and* Δ_η. *Also,* Π^*_{DS} *is increasing in* Δ_a *if* $G(\cdot, a)$ *is uniformly distributed.*[9]

[8] In comparing DS to the original single-supplier system, which is limited to $q \le K$, it is appropriate to compare the mean and variability for $q \le K$. In this case, DS increases the mean and reduces the variability. For $q > K$, DS increases the mean but may increase the variability because the single source supply system can provide at most K.

[9] Recall that for a uniform $(0, b)$ distribution, the reliability index a is given by $1/b$. Numerically, we observed that Π^*_{DS} was increasing in Δ_a even if $G(\cdot, a)$ follows some other types of distributions, e.g., the Weibull distribution. Numerically we observed that Π^*_{DS} was also increasing in Δ_K.

Table 2 **Study Design for Heterogeneous and Homogeneous Suppliers**

Parameters	Values
Fraction of committed cost η	0, 0.25, 0.5, 0.75, 1.0
Improvement success probability θ	0.1, 0.3, 0.5, 0.7, 0.9
Unit cost c	0.1, 0.3, 0.5, 0.7, 0.9
Unit improvement cost m	0.5, 1, 2, 4, 8
Design capacity K	20, 50, 80, 120, 160, 200
Expected relative capacity loss $\mathrm{E}[\xi]/K$	0.1, 0.3, 0.5, 0.7, 0.9

One supplier becomes more attractive and one becomes less so as the heterogeneity parameter increases. Being a single-sourcing strategy, SSI benefits as heterogeneity increases because its preferred supplier becomes more attractive. That DS should benefit from heterogeneity is less obvious, as there is a tension between the increasing attractiveness of one supplier and the decreasing attractiveness of the other. Focusing on the unit cost, the firm can reduce its average unit cost by directing more of its order to the lower-cost supplier, but doing so reduces the mean/variabilility mitigation benefit associated with DS. However, the average cost benefit outweighs the mitigation disadvantage. A similar argument holds for the committed cost.[10]

More interesting, perhaps, than the effect of supplier heterogeneity on strategy performance is its effect on strategy preference. We examine this question both numerically and analytically. We constructed 18,750 base case instances for the study. The underlying study was the same as that described in §4.2.2 but with the base case parameter values in this study shown in Table 2. For each base case, we studied the impact of heterogeneity on cost, reliability, design capacity, and committed cost. For each heterogeneity type, we did the following for all 18,750 base case instances: we created 11 different heterogeneity values (e.g., varying the ratio of Δ_c/c from 0% to maximum possible values min(99%, $r/c - 1$)) and solved for the optimal dual and improvement strategies at

[10] If supplier 1 and supplier 2 differ in more than one parameter, then increasing heterogeneity can hurt DS even if increasing heterogeneity makes supplier 1 unambiguously more attractive and supplier 2 unambiguously less attractive. Examples are available from the authors.

each heterogeneity value.[11] For any given heterogeneity value, let %SSI denote the percentage of base cases in which SSI was strictly preferred; that is, $\Pi^*_{SSI} > \Pi^*_{DS}$. Define %DS similarly and define %Ind as the % of cases in which the firm was indifferent; that is, $\Pi^*_{SSI} = \Pi^*_{DS}$. For each heterogeneity type, Figure 4 presents %SSI, %DS, and %Ind as a function of the pertinent heterogeneity value. We discuss each heterogeneity type in turn.

We see from Figure 4(a) that SSI is increasingly preferred as cost heterogeneity increases. This is confirmed analytically by the following theorem.

Theorem 7. *If both suppliers are identical except in c_i, then $\Pi^*_{SSI} - \Pi^*_{DS}$ is increasing in Δ_c.*

A partial explanation for this result is that although both strategies benefit from the cheaper supplier, the benefit for DS is offset somewhat by the more expensive supplier. To fully understand this result, let us consider the mean/variability mitigation benefit of each strategy. As cost heterogeneity increases, (a) DS directs a higher fraction of its total order to the lower cost supplier, and this reduces its mitigation benefit, and (b) SSI exerts more improvement effort (see Corollary 2), and this increases its mitigation benefit. The net effect is that SSI is increasingly preferred as heterogeneity increases.

As reliability heterogeneity increases, the mitigation benefit of DS decreases (numerically observed) and SSI exerts less improvement effort (numerically observed), and this decreases its mitigation benefit. Thus, the net effect of increasing reliability heterogeneity does not unambiguously favor DS or SSI. Under certain conditions, we can establish that increasing reliability heterogeneity favors DS:

Theorem 8. *Assume $G(\cdot, a)$ is uniformly distributed, demand equals x with probability 1, and $\theta = 1$. If both suppliers are identical except in reliability a_i, then $\Pi^*_{SSI} - \Pi^*_{DS}$ is locally decreasing in Δ_a (i.e., $\partial\Pi^*_{SSI}/\partial\Delta_a < \partial\Pi^*_{DS}/\partial\Delta_a$) if $-m(\partial z(a_1^*)/\partial\Delta_a) < (\phi\Delta_a/(2a))(2K - x)^2$.*

However, $\Pi^*_{SSI} - \Pi^*_{DS}$ is not in general decreasing in Δ_a. We see from Figure 4(b) that %SSI is not monotonic decreasing in reliability heterogeneity. Observe that DS is more likely to be preferred than SSI at a high reliability heterogeneity. At a high heterogeneity, SSI exerts little effort in improving the already highly reliable supplier, and DS procures only a small quantity from the highly unreliable supplier. Whereas SSI incurs the improvement cost, DS confronts supply risk from the highly unreliable supplier. However, in a random capacity setting, a highly unreliable supplier does not necessarily translate to a high supply risk because supply risk depends on the order size: an unreliable supplier can deliver a very small quantity with a high probability because the realized capacity loss has to be very high to impact a small order. Thus, the improvement cost disadvantage of SSI is more significant than the supply risk of DS, so DS is more likely to be preferred (albeit not by a very large amount) when reliability heterogeneity is high. In the extreme case of reliability heterogeneity, that is, when one supplier is perfectly reliable, DS weakly dominates SSI.

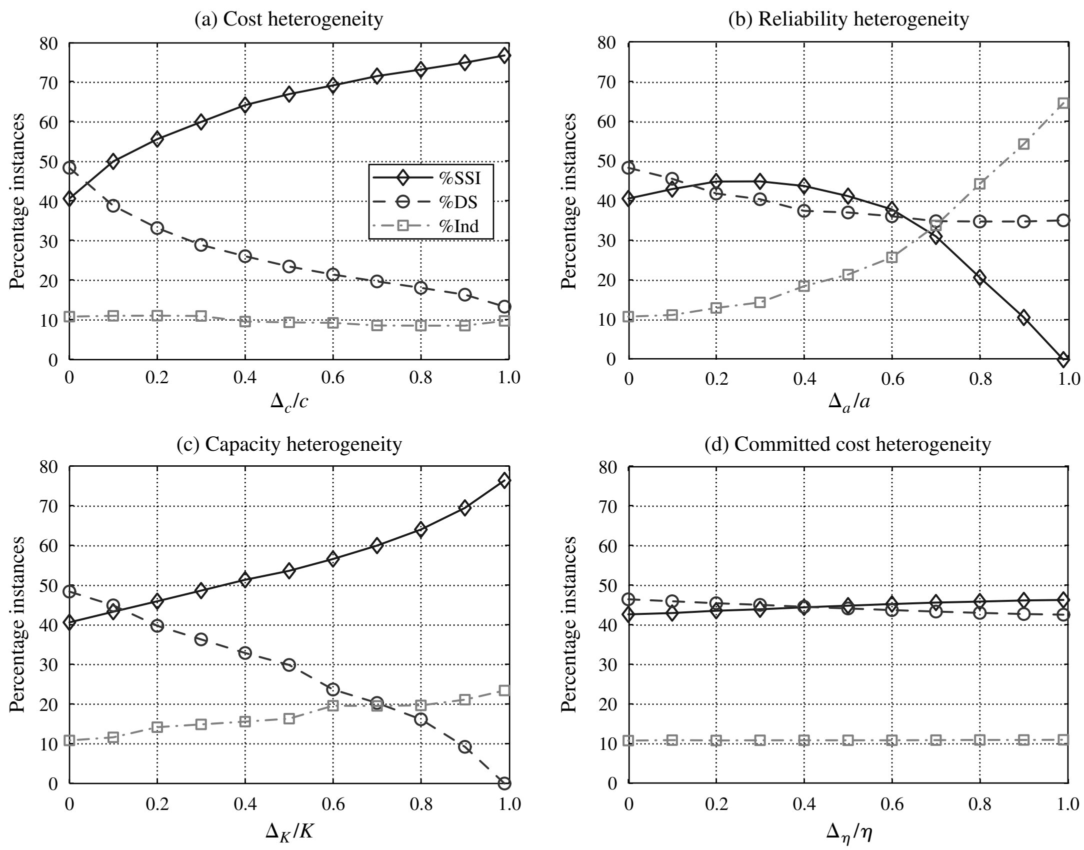
We see from Figure 4(c) that capacity heterogeneity favors SSI. Increasing capacity heterogeneity reduces the mean/variability mitigation benefits for both DS and SSI. However, the reduction in the mitigation benefit is more rapid for DS than for SSI and, therefore, SSI is increasingly preferred. (These statements can be analytically established for the mean effect and were numerically observed for the variability effect.) In the extreme case of capacity heterogeneity (i.e., when one supplier has zero capacity), DS adds no value on top of SSI and hence is never preferred.

As committed cost heterogeneity increases, (a) DS directs a higher fraction of its total order to the lower committed-cost supplier, which reduces its mitigation benefit; and (b) SSI exerts less improvement effort (see Corollary 2), and this reduces its mitigation benefit. The net effect is therefore unclear. We see from Figure 4(d) that committed cost heterogeneity has only a weak effect but that SSI seems to be increasingly preferred as heterogeneity increases.

To this point we have assumed that suppliers differed only on a single dimension, so increasing heterogeneity made one supplier unambiguously better. When suppliers differ on multiple dimensions, increasing heterogeneity may not favor one supplier. For example, cost and reliability may be negatively correlated: as the cost difference increases, so does

[11] When exploring committed cost heterogeneity, we excluded the $\eta = 0$ and $\eta = 1$ cases, as we cannot have heterogeneity with these extreme values.

Figure 4 Heterogeneous Supplier Results (Random Capacity)



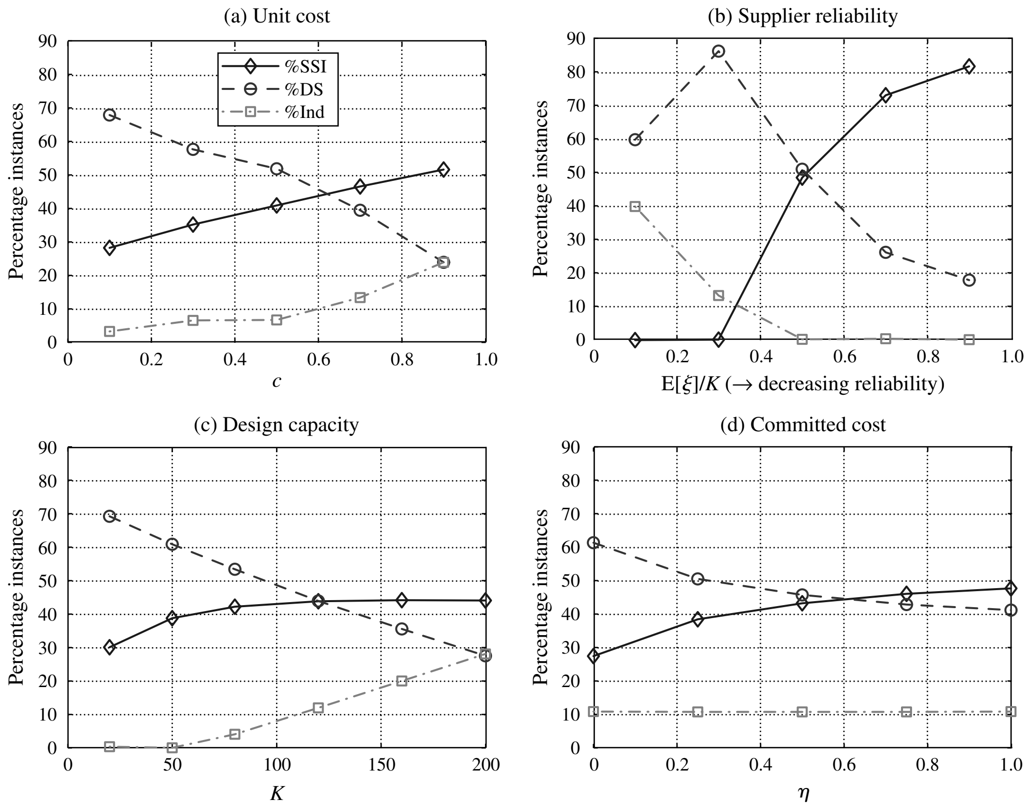
the reliability difference, with the lower-cost supplier becoming less reliable. In our numerical studies, we observed that cost heterogeneity (which favors SSI) had a stronger effect than reliability heterogeneity (which favors DS at high heterogeneity).

5.2. Identical Suppliers

We now explore how supplier attributes influence the firm's strategy preference (DS or SSI) assuming a homogenous (i.e., identical) supply base. That is, we investigate if and how the firm's preference changes as a particular attribute such as, supplier cost, is changed simultaneously for both suppliers. For example, both suppliers might be impacted by increases in energy prices and pass this price increase on to the firm. We assume suppliers are identical in this subsection, so we suppress the supplier subscript $i = 1, 2$ on parameters. Π^*_{SSI} increases in the success probability θ and decreases in the improvement cost m. Therefore, all else being equal, SSI is favored as θ increases or m decreases. Both Π^*_{SSI} and Π^*_{DS} decrease in the cost c and committed cost η but increase in the design capacity K and reliability index a. We conducted a numerical study to explore the impact on strategy preference. The underlying study was the same as used in the heterogeneous study (see Table 2), so there were 18,750 problem instances. Analogous to the heterogeneous study, Figure 5 presents %SSI, %DS, and %Ind as a function of the unit cost c, reliability (as measured by $\mathsf{E}[\xi]/K$), design capacity K, and committed cost η.

We see from Figure 5(a) that DS becomes less preferred as the unit cost c increases. The firm's order quantity decreases as c increases. We observed numerically that SSI was better at mitigating the mean/variability effect at lower order quantities and DS was better at higher order quantities. This is consistent with the finding that higher unit costs tend to favor SSI. At very high unit costs, the total order quantity is very low and supply risk is negligible in a

Figure 5 Homogenous Supplier Results (Random Capacity)



random capacity model (assuming the upper bound on the capacity loss is less than the design capacity), and the firm will be indifferent between SSI and DS. We did observe this in the numerical study.

We see from Figure 5(b) that SSI is preferred at low reliabilities (as measured by $\mathsf{E}[\xi]/K$), but DS is preferred at high reliabilities. This is consistent with our numerical observation that SSI was better at mitigating the mean/variability effect at lower reliabilities and DS was better at higher reliabilities.

We see from Figure 5(c) that the preference for DS decreases as the design capacity increases. If $\mathsf{E}[\xi]/K < 0.5$, supply risk decreases as K increases, as there is an increasingly large guaranteed minimum capacity. The firm is then indifferent between DS and SSI for sufficiently high K. If $\mathsf{E}[\xi]/K \geq 0.5$, supply risk does not disappear even at very high capacities, and SSI is weakly preferred to DS.

We see from Figure 5(d) that SSI is increasingly preferred as the committed cost η increases. SSI exerts more improvement effort as η increases (see Corollary 2), which increases its mitigation benefit. One mechanism dual sourcing uses to manage supply risk is the quantity hedge, but this is more expensive as the committed cost increases. The combined effect is to make SSI increasingly preferred as η increases.

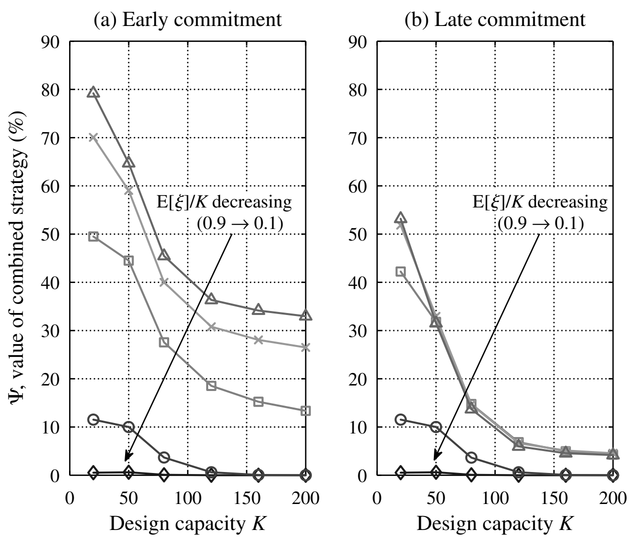
6. Combined Strategy

As discussed in §1, some firms (e.g., Honda and Toyota) engage in both dual sourcing and process improvement, and we now turn our attention to the general problem in which the firm can combine improvement (of one or both suppliers) with DS. The following lemma partially characterizes the firm's expected profit function, $\Pi_1(\mathbf{a})$, which was given earlier by (5).

LEMMA 5. *$\Pi_1(\mathbf{a})$ is a submodular function in* $\mathbf{a}$.

Although $\Pi_1(\mathbf{a})$ can be component-wise unimodal in its reliability index a, it is not in general jointly concave.

Figure 6 The Value of the Combined Strategy



Our primary objective is to explore the value of deploying a combined strategy. We denote the optimal expected profit for the combined strategy as Π^*_{COM}. Recall that Π^*_{DS} and Π^*_{SSI} denote the optimal expected profits for the pure strategies, dual sourcing and single sourcing with improvement, and so $\Pi^*_{COM} \geq \max\{\Pi^*_{SSI}, \Pi^*_{DS}\}$. We define $\Psi = (\Pi^*_{COM} - \max\{\Pi^*_{SSI}, \Pi^*_{DS}\})/\max\{\Pi^*_{SSI}, \Pi^*_{DS}\}$ as the value of the combined strategy; that is, Ψ is the relative increase in expected profit compared to the best (for the given problem instance) of the pure strategies. Unless otherwise stated, Π^*_{SSI} refers to the early commitment optimal profit. We investigated the value of the combined strategy numerically. Because the experimentation/hedging benefit of the late commitment strategy is embedded in the combined strategy, and this value is highest when suppliers are identical (§4.2.2), we focused on identical suppliers in our study. As suppliers become less similar, the value of the combined strategy will decrease. The underlying study was the same as used in §5 (see Table 2), and so there were 18,750 problem instances.

The value of the combined strategy, Ψ, was 24.3% on average, with a maximum of 100.0%, and a minimum of 0.0%. (Using late commitment rather than early commitment, these numbers were 11.7%, 100.0%, and 0.0%, respectively.) Because Ψ has such a large range, the interesting question is when is the value high and when is it low. The factors that had the most pronounced impact were the design capacity K and the reliability. Using both early and late commitment for Π^*_{SSI}, Figure 6 presents the value of the combined strategy as a function of K and the reliability (as measured by the expected relative capacity loss $\mathsf{E}[\xi]/K$). Focusing on early commitment, we see that if reliability is very high (i.e., $\mathsf{E}[\xi]/K = 0.1$), then the combined strategy offers negligible value.[12] At a moderate reliability (i.e., $\mathsf{E}[\xi]/K = 0.3$) the combined strategy is beneficial when design capacity is low relative to mean demand (which was set to 100 in this study). In this case, the buying firm wants to access as much effective capacity as possible and therefore wants to dual source and improve both suppliers. At lower reliabilities (i.e., $\mathsf{E}[\xi]/K = 0.5, 0.7, 0.9$) the combined strategy retains value even at design capacities that are twice the mean demand. Focusing on late commitment, we see a qualitatively similar finding but with a lower value for combined strategy because late commitment dominates early commitment.

In both the dual sourcing and combined strategies, the firm can, but does not have to, source from both suppliers. When suppliers are identical, Theorem 2 and Corollary 1 imply that the firm will source from both suppliers at one pair of reliabilities if it does so at any pair of higher reliabilities. Therefore, if suppliers are identical, the combined strategy sources from both suppliers only if the dual sourcing strategy does. In our study, dual sourcing used both suppliers in 88.7% of the instances and the combined strategy did so in 71.1% of instances.

7. Random Yield

We now consider random yield type of supply uncertainty and adopt the commonly used model in which the delivered quantity is stochastically proportional to the order quantity, that is, $y_i = \min\{q_i, \xi_i q_i\}$, where ξ_i now represents supplier-i's yield rather than its

[12] If suppliers are perfectly reliable, then the combined strategy cannot outperform dual sourcing and so it has no value. However, because our model does not consider the supplier-competition benefits of dual sourcing nor the unit-cost reduction benefits of improvement efforts, it understates the potential value in practice. Therefore, a combined strategy may be useful in highly reliable supply chains if unit cost is influenced by competition and improvement.

capacity loss.[13] The random yield version of our model is identical to that formulated in §3 but with $y_i = \min\{q_i, \xi_i q_i\}$ replacing $y_i = \min\{q_i, (K_i - \xi_i)^+\}$ and $G_i(\cdot, a_i)$ now referring to the yield distribution (for a given reliability index a_i) rather than the capacity-loss distribution. A natural model of reliability improvement for random yield is one in which the yield is (first-order) stochastically larger after improvement and, therefore, an increase in the reliability index, say from a_i to $\hat{a}_i$, implies $G_i(\cdot, a_i) \geq G_i(\cdot, \hat{a}_i)$. Using this random yield model (hereafter RY), we replicated our earlier analysis of the random capacity model (hereafter RC). We also replicated all our numerical studies.[14] For the sake of brevity, we focus our discussion here on the key results and, in particular, focus on some important differences between RC and RY. Online Appendix B contains full statements and proofs of all theoretical results referred to in this section.

In RC, both DS and SSI mitigate the mean and variability effects of supply risk. However, in RY, (a) DS mitigates the variability effect but has no impact on the mean effect and (b) SSI mitigates the mean effect and (depending on the yield distribution) may mitigate or amplify the variability effect (proofs omitted).[15]

Similar to RC, the RY DS quantity problem is well behaved. In fact, the expected profit is jointly concave in the order quantities if G_i has support over $[0, 1]$ (see Theorem 9, online appendix) and not simply jointly unimodal, as for RC.[16] Similar to RC, Π^*_{DS} is increasing in a supplier's reliability index a_i (Lemma 6, online appendix). Different from RC, however, the quantity procured from a supplier is not necessarily increasing, nor even monotonic, in a_i, and can strictly decrease in a_i (Lemma 7, online appendix).

Similar to RC, the improvement problem is concave subject to certain restrictions (Theorem 10, online appendix). Different from RC, however, improvement effort can decrease as the unit cost decreases (Lemma 8, online appendix). With regard to late versus early commitment, the findings on the directional impact of improvement cost, success probability, reliability, supplier cost difference, and committed cost were similar to those for RC. The value of late commitment was, however, lower in RY, with an average value of 1.4% (compared to 4.7% for RC), a maximum of 87.0%, and a minimum of 0.0%.

We next consider the impact of supplier heterogeneity in RY. As with RC, both Π^*_{DS} and Π^*_{SSI} increase in heterogeneity (Theorem 6). With regard to the impact of heterogeneity on strategy preference, there are some key differences between RC and RY. For RC, increasing cost heterogeneity favors SSI (Theorem 7), but for RY increasing cost heterogeneity can favor DS (Theorem 12, online appendix). The reason for the difference is as follows. In RC the mean/variability mitigation benefit of SSI (DS) increases (decreases) in the cost heterogeneity. In RY the mitigation benefit of SSI can decrease in cost heterogeneity because improvement effort can decrease as cost decreases. Therefore, DS is sometimes favored as cost heterogeneity increases. Across our 18,750 base case instances, $\Pi^*_{SSI} - \Pi^*_{DS}$ decreased in cost heterogeneity in only 0.9% of the instances (these were instances with high θ, high η, and low $\mathsf{E}[\xi]/K$), so the aggregate view presented in Figure 7(a) shows %SSI increasing in cost heterogeneity.

In RC, high reliability heterogeneity favored DS. We observed the opposite in RY; that is, high reliability heterogeneity favored SSI (see Figure 7(b)). However, as noted for RC, in the extreme case of reliability heterogeneity (i.e., when one supplier is perfectly reliable) DS weakly dominates SSI. The fundamental distinction between RC and RY that drives this difference is that the supply risk—that is, the probability that delivered quantity is less than the ordered quantity—decreases as the order quantity decreases in

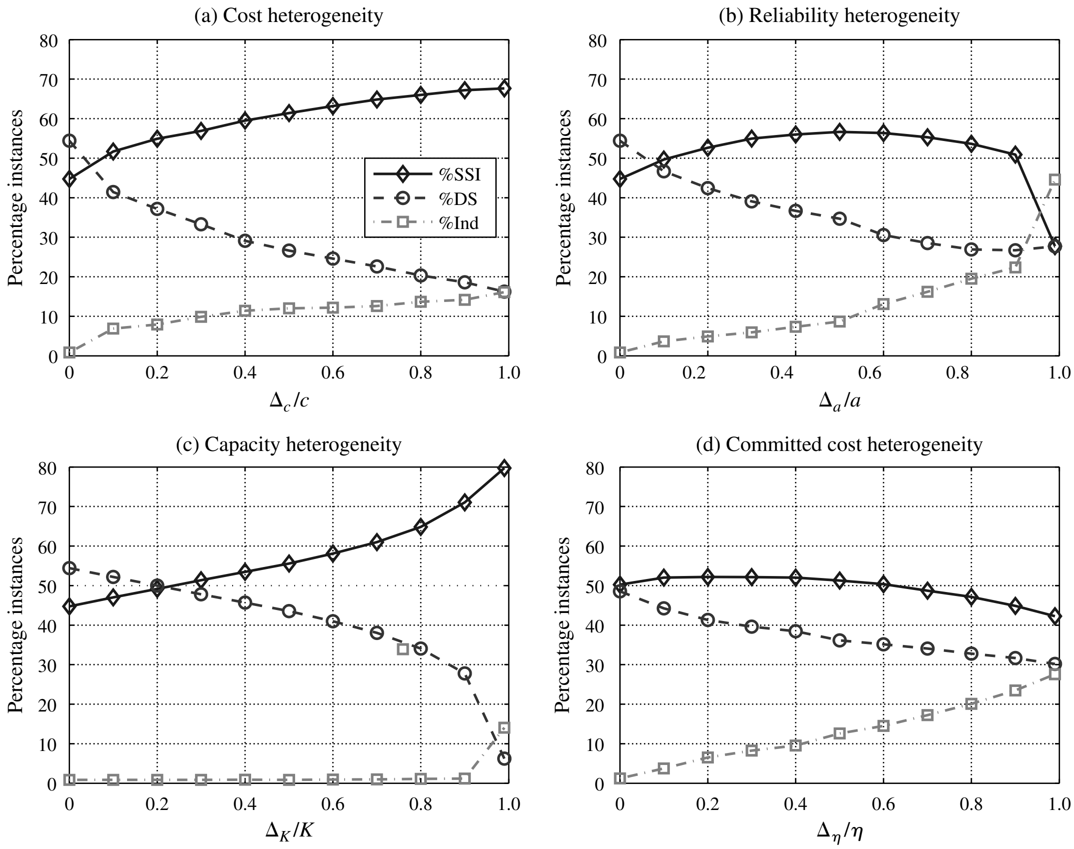
[13] ξ_i has a nonnegative support. If the support has an upper bound of 1, $y_i = \min\{q_i, \xi_i q_i\}$ can be written as $y_i = \xi_i q_i$.

[14] Each study was the same as that described for the random capacity model except that we assumed a uniformly distributed random yield rather than a uniformly distributed a capacity loss. The expected yield loss values, i.e., $1 - \mathsf{E}[\xi]$, were set to the same values as the expected relative capacity loss $\mathsf{E}[\xi]/K$ values in the random capacity studies. As we did not want the design capacity constraint to obscure the comparison of RC and RY, in our numerical studies we adopted RY with a design capacity constraint of K; i.e., $y_i = \min\{q_i, \xi_i q_i\}$ and $q_i \leq K_i$.

[15] SSI mitigates the variability effect if the yield has a uniform $(a, 1)$ distribution but amplifies the variability effect if the yield has a Weibull (α, β) distribution (in which case the reliability index is $a = \beta$).

[16] Parlar and Wang (1993) established joint concavity for a two-supplier, random-yield newsvendor when the firm pays fully for the quantity ordered—i.e., $\eta = 1$. The joint-concavity result extends readily to the case of $\eta \leq 1$.

Figure 7 **Heterogeneous Supplier Results (Random Yield)**



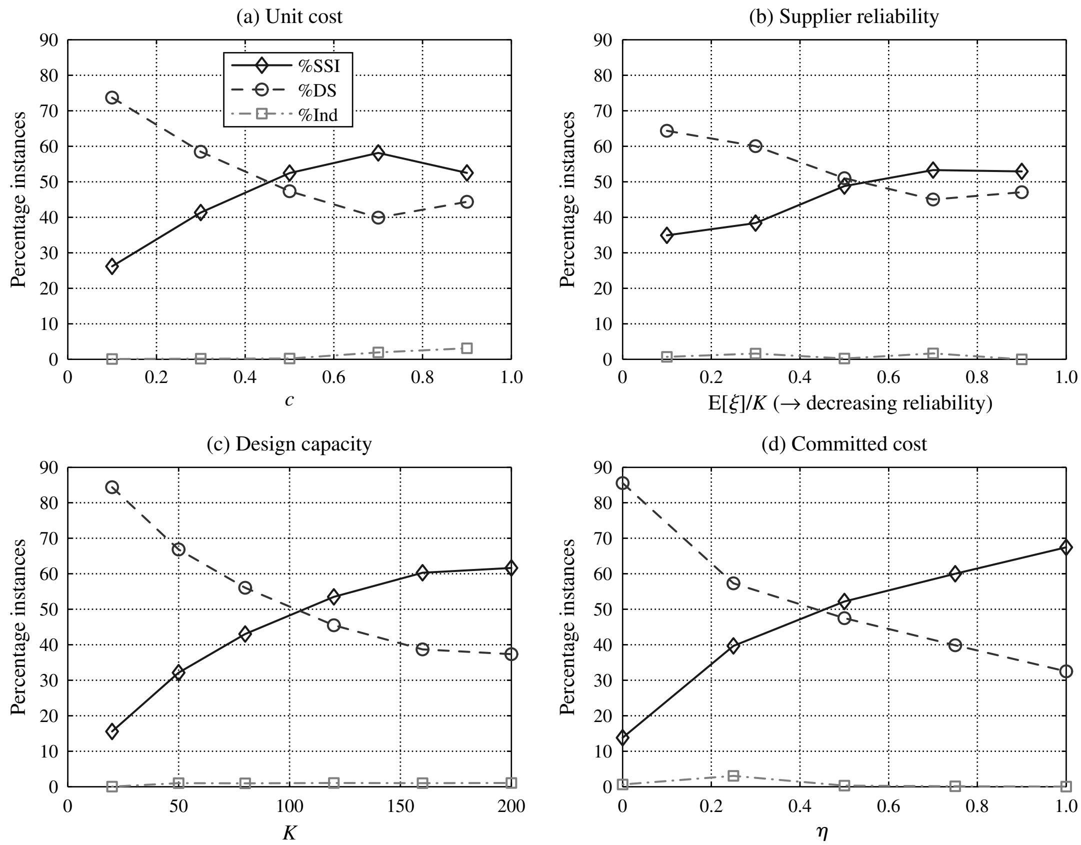
RC but remains constant in RY. Therefore, although a firm can obtain a small quantity with little or no risk of less than full delivery from a low-reliability supplier in RC, even a small quantity has a high risk of less than full delivery in RY. Thus, the low-reliability supplier offers negligible diversification value in RY, and this makes improvement preferable when reliability heterogeneity is high. There is some anecdotal support for this finding in the experience of the semiconductor company Xilinx, which moved from a dual source to a single source strategy because of the large difference in the yield performances of its two chip suppliers:

> Xilinx originally planned to use IBM as the secondary source for its most advanced 90 nm-based FPGA (field programmable gate array)—Spartan 3. However, as UMC continues to widen its production volume and yield advantages over IBM, Xilinx has outsourced all of its orders for 0.13-micron and more advanced processes to UMC, according to a high-ranking executive at Xilinx in Taiwan. (Yu and Lu 2004)

With regard to the impact of parameters when suppliers are identical, we found two key differences between RC and RY. First, the influence of the unit cost c was highly dependent on the value of the committed cost η in RY. (In RC, DS was less preferred as c increased.) At $\eta = 1$ DS was preferred as c increased, but at $\eta = 0$ DS was less preferred as c increased. Second, as can be seen by comparing Figures 5(d) and 8(d), the committed cost η had a much stronger impact in RY. Because DS mitigates the variability effect but not the mean effect in RY, DS is very sensitive to the committed cost, as it makes scaling the order quantity (to account for the mean yield loss) expensive.

With regard to the value of the combined strategy in RY, the average value was 10.2% (compared to 24.3% for RC), with a maximum of 100.0% and a minimum of 0.0%. Using late commitment, these numbers were 6.1%, 100.0%, and 0.0%, respectively. As with RC, the value of combined strategy was highest when capacity and reliability were low. The two

Figure 8 Homogenous Supplier Results (Random Yield)



semiconductor competitors Xilinx and Altera (which both deal with random yield suppliers) offer an interesting contrast in supplier strategies:

> One place where Xilinx takes a distinctively different tack from arch-rival Altera is in their foundry strategy. Xilinx uses multiple foundries—today Toshiba and UMC—claiming that multiple foundries give a hedge against process problems and increase volume production capability. Altera, on the other hand, claims that working with a single fab—TSMC—gives them an edge because they can focus their engineering efforts on the capabilities and characteristics of a single supplier, allowing them to converge faster on a high-yield, high-performance design with each process generation. (Morris 2006)

The Xilinx strategy is consistent with our findings that the combined strategy is valuable if capacity and reliability are a concern. Altera's view suggests that single sourcing might make improvement efforts more efficient (a perspective not captured in our model), which would lower the value of a combined strategy.

8. Conclusions

By relaxing the common assumption in the supply-risk literature that the buying firm does not influence the reliability of its supply base, this research addresses an important strategy observed in practice: the exertion of effort to improve a supplier's reliability performance. We explore a model in which a buying firm can improve a supplier's reliability, dual source, or deploy both strategies.

Our work identifies a number of interesting managerial findings. For random capacity, improvement is preferred over dual sourcing, as supplier cost heterogeneity increases but dual sourcing is favored if reliability heterogeneity is high. For random yield, however, cost heterogeneity can favor dual sourcing and high reliability heterogeneity can favor improvement. If suppliers are homogenous, low reliability favors improvement, whereas low cost or capacity favors dual sourcing. Deploying a combined strategy can add significant value if capacity and reliability are both low.

We hope this work provides a foundation for future research in the area of reliability improvement. For example, future work could explore the supplier competition benefits of dual sourcing. Also, if competing firms share suppliers, then one firm's improvement efforts might spill over and benefit its competitor. Another extension is to consider a general number of suppliers. Although there is anecdotal support for some of our findings, it would be of interest to empirically test some of the observations to develop a richer understanding of supply risk strategies. We note that because "most chip makers don't speak publicly about yield problems" (Weil 2004), it might be difficult to obtain data on supplier reliability performance.

Electronic Companion

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

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