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Working Paper

Bargaining Power and Supply Base Diversification

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Ross School of Business Working Paper
Working Paper No. 1118
December 2009

Bargaining power and supply base diversification

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Abstract

We examine a supply base diversification problem faced by a buyer who periodically holds auctions to award short term supply contracts among a cohort of suppliers (i.e., the supply base). To mitigate significant cost shocks to procurement, the buyer can diversify her supply base by selecting suppliers from different regions. We find that the optimal degree of supply base diversification depends on the buyer's bargaining power, i.e., the buyer's ability to choose the auction mechanism. At one extreme, when the buyer has full bargaining power and thus can dictatorially implement the optimal mechanism, she prefers to fully diversify. At the other extreme, when the buyer uses a reverse English auction with no reserve price due to her lack of bargaining power, she may consider protecting herself against potential price escalation from cost-advantaged suppliers by using a less diversified supply base. We find that in general the more bargaining power the buyer has to control price escalation from cost-advantaged suppliers the more she prefers a diversified supply base. This insight is shown to be robust to correlation between regional costs, asymmetry across regions, and intermediate levels of bargaining power.

November 2009

1. Introduction

It is common for buyers (procurement managers) responsible for procuring an item to identify a *supply base*, a group of qualified suppliers that are capable of producing the item. A supply base is a well-known tool for managing risks. For specialized items where availability is the main objective, buyers can place orders with multiple suppliers to manage non-delivery risks (e.g., Anupindi and Akella 1993). But, as is our focus in this paper, a supply base can also be a crucial strategic tool for purchasing commodity-type items where cost, not availability, is the central issue.

Buyers typically do not know the true costs of suppliers, who possess private information about their cost drivers (inventory level, capacity utilization, financial status, etc.). To find a low price, buyers increasingly employ procurement auctions aimed at price discovery (Jap 2003). As the practitioner survey Beall et al. (2003) page 49 points out, "If a qualified supply base is identified, and the market for a particular commodity/purchase family group changes rapidly, [procurement auctions] are an excellent tool to award business for short duration and re-auction regularly. For example, one company interviewed purchases highly engineered printed circuit boards quarterly through [procurement auctions]." In a procurement auction, competition between suppliers can come down to cents or fractions of a cent, yet these small differences can translate into millions of dollars of savings to the buyer given large volumes — a high tech firm we interacted with runs quarterly auctions in which commodity (cables, connectors, etc.) suppliers compete on unit prices in increments of one tenth of a cent.

When margins are razor-thin, factors such as transportation costs, commissions, and logistics costs become non-negligible (Pederson 2004). Buyers are increasingly aware of the need to make sourcing decisions based on *total cost*, which from the buyer's perspective measures the total cost of procuring from the supplier. In addition to the supplier's price, total cost includes non-price costs such as logistics and transportation costs, shipping insurance and commissions (Ariba 2005). In this paper we introduce the idea of strategic supply base design to mitigate total procurement cost shocks, and examine how the buyer's optimal supply base design is affected by the buyer's bargaining clout. We now motivate and introduce both these concepts.

Supply base design to mitigate cost shocks. The "non-price costs" associated with a supplier can be closely related to the supplier's geographic region, and thus subject to *cost shocks* affecting that region. For example, shipping costs associated with procuring from a supplier are largely affected by local logistics markets and regulations within the supplier's region, and can be dramatically increased by labor strikes or regulation changes. In February 2007, the CN Railway strike disabled almost three quarters of Canada's rail capacity, forcing companies such as Ford to look for much more expensive alternatives like truck freight for shipments from its Canadian suppliers. Seeking heightened security for the Olympics in the summer of 2008, the Chinese government forbade a wide range of hazardous materials at six major ports; affected buyers incurred significant rerouting costs. Other examples of regional cost shocks include ocean shipping insurance rates (which are based on geopolitical and geosecurity elements along shipping routes[1]).

Ideally, a buyer could respond to regional cost shocks by instantly augmenting her supply base with new suppliers from unaffected regions. However, for some buyers this can be impractical (for all but the most catastrophic scenarios), because finding and qualifying a new supplier is usually time-consuming and costly. The process of vetting suppliers, called supplier qualification screening (Wan and Beil 2009), typically involves reference checks, financial audits, site visits to supplier facilities abroad, approval and buy-in from the buyers' internal customers, etc. At a Fortune 100 manufacturer we interacted with it takes an average of 8 to 26 weeks to find and qualify a new supplier — even for commodity parts.

Instead of frequently finding and qualifying totally new suppliers, buyers, including the large manufacturer we interacted with, build their supply base as a long-term strategic decision, and then frequently auction off short-term supply contracts among them to find the current lowest-total-cost supplier. For such buyers, therefore, an important strategic decision arises when forming their supply base: Facing potential regional cost shocks, should the buyer's supply base include *similar* suppliers (selected from the same region) or *diversified* suppliers (selected from different regions)?

Intuitively, geographically diversifying the supply base, i.e., selecting suppliers from different regions, can mitigate regional cost shocks. For example, once a prolonged labor strike at the ports in region A drives up the cost of transporting goods from the supplier in region A, a buyer who sources a large and expensive-to-transport component can avoid a high transportation cost if she has a supplier in an unaffected region B. However, a buyer seeking to minimize total procurement cost needs to take into account the impact of diversifying on her contract payment: Will the supplier in region B strategically mark up his price to make a windfall profit based on his cost advantage over the supplier in region A? If so, how should the buyer design her supply base in the first place to manage both regional-costs risks and supplier-windfall-profit-taking risks?

[1]A recent example is the thousand-percent increase in shipping insurance premiums for Asia to Europe ocean transport, as freighters funneling through the Suez canal face a gauntlet of pirates and kidnappers based in an increasingly destabilized Somalia (Costello 2008).

Bargaining power and supply base design decision. In our study the buyer's contract payment is determined through a competitive bidding process (i.e., auction). Thus, it is crucial to understand how the buyer's ability to design auctions (i.e., choose auction format and rules) should be taken into account when she designs her supply base. We term such ability the buyer's *bargaining power*. For forward auctions, Bulow and Klemperer (1996) point out that an auctioneer with no bargaining power can only run an English auction with no reserve price while an auctioneer with full bargaining power can utilize an optimal auction mechanism.

Similarly, in this paper, at one extreme we model a buyer with no bargaining power — such a buyer cannot make credible take-it-or-leave-it offers and must solely rely on supplier competition for price concessions, utilizing a simple reverse English auction with no reserve price. In such an auction, the lowest-total-cost supplier charges the buyer a price that is set according to second-lowest supplier's total-cost, creating the risk of severe windfall-profit taking. Returning to our example two paragraphs above, the supplier in region B could take windfall profits and consequently the buyer's total cost could be the total cost of the supplier in region A, which includes A's regional cost shock! Thus, the imperative to diversify the supply base (i.e., choose suppliers from different regions) is mitigated by the need for cost parity among suppliers. We find that the optimal amount of diversification depends on the total number of suppliers and the likelihood of regional cost shocks.

At the other extreme, we model a buyer having full bargaining power, who thus can design an optimal procurement mechanism within which suppliers compete for the buyer's business (e.g., could promise to bias against the supplier in B who has regional cost advantage). Between the two extremes there can be intermediate cases, where for example the buyer is unable to use an optimal mechanism but can commit to using a reserve price in a reverse English auction. We find that supplier cost parity is less crucial for buyers with more bargaining power — such buyers are better served by a diversified supply base — and the optimal supply-base-design strategy can depend on the distributions of supplier costs and regional cost shocks.

The next section reviews related literature, and §3 introduces the model and assumptions. Section 4 analyzes the buyer's optimal supply-base-design problem and compares two cases: one in which the buyer has full bargaining power and uses the optimal mechanism, and the other in which the buyer has no bargaining power and uses a reverse English auction without a reserve price. In §5.1–5.3 we analyze, respectively, cases where regional costs are codependent, regions are ex ante asymmetric, and a buyer with intermediate bargaining power uses a reserve price in conjunction with a reverse English auction. We provide numerical illustrations of our results in §6 and conclude in §7. All proofs are provided in the electronic companion.

2. Literature Review

Our paper analytically studies how buyers should select suppliers to mitigate regional cost risks, and is thus related to the supply risk management literature. However, our paper differs from the majority of the literature in two main aspects. First, we focus on supply risks that can be modeled as "cost shocks," while the existing literature mainly focuses on catastrophic "supply shocks" that cause supply shortages. Such "supply shocks," more commonly referred to as supply disruptions, include natural disasters (fire, hurricane, earthquake, etc.), supplier bankruptcy, etc. Researchers have studied various mitigation and contingency strategies to manage supply disruption risks; readers are referred to Tomlin (2006), which categorizes these strategies as stockpiling, multi-sourcing, using backup options, managing demand, and others. Among these categories, multi-sourcing and using backup options are related to supply base design. Studies on multi-sourcing to mitigate supply disruptions typically focus on buyers' inventory management decisions (e.g., determining the optimal ordering quantity and split of quantities among suppliers) and model the impact of disruptions by various random yield models. Recent examples include Dada et al. (2007), Federgruen and Yang (2007, 2008), etc.; readers are referred to Tomlin (2006), which provides a detailed survey of early work of this stream. For work including backup options in the supply base, see, for example, Yang et al. (2009) and references therein.

Second, this paper studies price escalation risks (e.g., windfall-profit taking by suppliers), while the majority of supply risk management literature presumes exogenous contract prices (or unit procurement costs) and ignores suppliers' strategic pricing behavior. One exception is Babich et al. (2007), which endogenizes suppliers' pricing decisions in a multi-sourcing problem where a buyer allocates ordering quantities among suppliers with correlated default risks. They assume that suppliers have full information of competitors' costs, and show how suppliers' pricing decisions can be affected by their default risk correlations. In particular, they find that the buyer prefers suppliers with positively correlated default risks despite the loss of diversification benefits, because default risk correlation increases supplier competition. In our paper, which studies the supply base design problem in the presence of suppliers' regional cost risks, we model supplier competition via procurement auctions in which suppliers possess private cost information, and we show how supplier competition can be affected by correlations across suppliers' cost shocks. We find that the buyer's bargaining power dictates her preference for the supply base design, namely, a buyer with stronger bargaining power prefers a more diversified supply base, which effects less correlation across suppliers' cost shocks.

The term "bargaining power" is probably one of the most widely used but vaguely defined concepts in the literature of bargaining models. In the literature of bargaining games with complete information, the asymmetric Nash bargaining model (Roth 1979) "captures some imprecisely defined 'bargaining power' " (Binmore et al. 1986) by including weighting scalars in the calculation of utility products. However, the literature on bargaining games with incomplete information focuses on analyzing bargaining outcomes given different bargaining mechanisms (see Ausubel et al. (2002) for a detailed survey), without explicitly defining players' "bargaining power." In the present paper, we interpret the term "bargaining power" as the buyer's ability to impose an auction mechanism that she favors, an interpretation that can be traced to the prominent work of Bulow and Klemeperer (1996). In other words, we use the term "bargaining power" as a way to rank the auction mechanisms that we study in this paper.

Extensive work has examined procurement cost reduction via supply base competition. Elmaghraby (2007) surveys industry practices in designing and running auctions for e-sourcing events, while Elmaghraby (2000) provides a comprehensive survey of operations research and economics work on competitive sourcing strategies, including auctions. Grey et al. (2005) discuss the role of e-marketplaces within long-term buyer-supplier relationships. Our paper considers a buyer who finds the lowest-price provider by periodically auctioning off short-term supply contracts among a stable supply base. Recent work on the use of auctions in supply chains include Chen (2007), which studies a buyer auctioning supply contracts, and Chen and Vulcano (2008), which studies a supplier's auction to sell capacity and compares first- and second-price auction formats. We study various auction formats, but focus on understanding how they affect the buyer's supply base design decision. Methodologically, our paper is related to the auction and mechanism design literature; readers are referred to the books by Krishna (2002) and Milgrom (2004), which provide excellent treatments and detailed references on auction theory.

3. Model and Preliminaries

3.1 Model setup

We study a stylized model in which a risk-neutral buyer (e.g., an OEM) selects a cohort of N qualified suppliers to form a supply base for a needed input component. We allow N to be any integer greater than or equal to two. In period $t = 0$, the buyer designs the supply base. For simplicity, we assume that designing the supply base amounts to a one-time decision and no suppliers are removed from or added to the supply base after it is established. This models settings where frequently finding and qualifying new suppliers is impractical due to costly and time-consuming supplier qualification screening processes.

To focus on the supply base diversification decision, we assume that N is exogenously given. Suppliers can be selected from different geographic *regions*. The buyer's decision variables are the number of regions to select suppliers from, R, and the number of suppliers to select from each region, denoted by $n_1, n_2, \ldots, n_R$ for region 1, region 2 ..., and region R, respectively, where $\sum_{r=1}^{R} n_r = N$. We assume that there are at least N ex ante symmetric regions available and within each region up to N suppliers can be found. (We extend our results to ex ante asymmetric regions in §5.2. The analysis also changes in a straightforward way if a limited number of regions are available; see our discussion in §7.) Thus, the number of regions R can be any integer from 1 to N; in particular, $R = 1$ means selecting all suppliers from only one region, which we call the *pooling strategy*, and $R = N$ means selecting each supplier from a different region, which we call the *fully diversifying strategy*.

After establishing her supply base (finding and pre-qualifying the suppliers) in period zero, in each of the following periods (indexed by $t \geq 1$) the buyer runs an auction to award an indivisible short-term contract to one of the suppliers in the supply base. This setup is most appropriate when the buyer procures commodity parts from suppliers, who do not fully rely on the buyer's contract to keep afloat. To keep the analysis focused and tractable, we assume that the buyer does not store inventory and does not have in-house production, hence she must contract with one supplier in every period. This setup could model, for example, a buyer who produces high tech, short life-cycle products, relies on suppliers for key components, and holds quarterly supply auctions. When analyzing auction outcomes we assume that the suppliers are risk-neutral and fully rational players following a Bayesian Nash bidding equilibrium, as is standard in the auction literature.

Two types of costs are associated with each supplier $i = 1, \ldots, N$ in each period t. The first type of cost is an idiosyncratic production cost, $x_i^t \in [0, 1]$, which as typical in auction models is assumed to be independently and identically distributed across suppliers and periods according to a commonly known distribution F. Cost x_i^t represents supplier i's firm-specific and privately-known cost of fulfilling the contract offered in period t, per supplier i's inventory level, capacity utilization, working capital position, debt status, etc. For simplicity we assume F has a positive and continuous density f and is stationary over time (this assumption can also be relaxed; see our discussion in

§7). As is standard in the auction theoretic literature, we also assume that $x + \frac{F(x)}{f(x)}$ is increasing in x. This technical assumption ensures a pure-strategy implementation of the optimal mechanism (described in §3.2), and is satisfied, for example, by all logconcave f, including uniform, normal, logistic, and exponential distributions (Bagnoli and Bergstrom 2005).

The second type of cost is a region-specific cost, y_r^t, which represents (from the buyer's perspective) common costs affecting all suppliers in region r in period t. We let a_i^t denote the regional cost of supplier i in period t, that is, $a_i^t = y_r^t$ if supplier i is located in region r. In our analysis, we assume such regional costs are not related to suppliers' production costs but are the additional, additive procurement expenses the buyer incurs when doing business with a supplier in the region, for instance, transportation and logistics costs. (Our results easily extend to cases where regional factors also influence suppliers' production costs; see our discussion in §7.) We assume that, at the outset of each period t, the buyer can observe all regional costs, and each supplier i can observe his own regional cost a_i^t but may or may not observe other suppliers' regional costs. We assume that y_r^t's are independently and identically distributed across regions and periods according to a commonly known distribution G with finite mean (i.e., $E[y_r^t] < \infty$). In §5.1, we discuss how our results extend when regional costs are possibly codependent, and in §5.2 study cases where regions can be asymmetric in terms of their regional and production cost distributions. For simplicity we assume G is stationary over time, although this too can be relaxed (see §7).

The buyer seeks to minimize her expected long-term total procurement cost. Let $\boldsymbol{x}^t \stackrel{def}{=} (x_1^t, x_2^t ..., x_N^t)$ denote the vector of realized supplier production costs in period t; let $\boldsymbol{y}^t \stackrel{def}{=} (y_1^t, y_2^t, ..., y_N^t)$ denote the vector of realized regional costs in period t; and let $\boldsymbol{a}^t \stackrel{def}{=} (a_1^t, a_2^t, ..., a_N^t)$ denote the vector of realized regional costs of suppliers in period t. The supply base design problem can be formulated as:

$$\min_{n_1,...,n_R} \underset{(\boldsymbol{x}^t,\boldsymbol{y}^t)}{E} \left[\sum_{t \geq 1} \beta^t \pi^{Mech}(\boldsymbol{x}^t; \boldsymbol{a}^t) \right] = \frac{\beta}{1-\beta} \underset{(\boldsymbol{x}^1,\boldsymbol{y}^1)}{E} \left[\pi^{Mech}(\boldsymbol{x}^1; \boldsymbol{a}^1) \right]$$
$$s.t. \quad R \in \{1, ..., N\}, \quad n_i \in \mathbb{N} \ \forall i \in \{1, ..., R\}, \text{ and } \ n_1 + ... + n_R = N,$$

where β is a discount factor and $\pi^{Mech}(\boldsymbol{x}^t, \boldsymbol{a}^t)$ is the buyer's period-t total procurement cost given the auction mechanism $Mech$. Since x_i^t's and a_i^t's are assumed to be identically distributed from period to period, the buyer's objective is simplified to minimizing the expected one-period total procurement cost. Therefore, we omit the superscript t for notational convenience in the rest of this paper. In §4, we focus on two auction mechanisms — the optimal mechanism (denoted by $Mech = OPT$) and the reverse English auction without reserve price (denoted by $Mech = RE$), representing the cases in which the buyer has full bargaining power and zero bargaining power, respectively (Bulow and Klemperer 1996). In §5.3, we study the case in which the buyer has intermediate bargaining power and can impose a reserve price in a reverse English auction (denoted by $Mech = RER$). We describe these three auction mechanisms in §3.2.

The buyer's supply base design strategy affects her expected total procurement cost because different strategies yield different $\boldsymbol{a}^t$ given a realized $\boldsymbol{y}^t$. For example, in a four-supplier case ($N = 4$), if the buyer selects all four suppliers from region 1, (i.e., pooling), the suppliers' regional costs are $\boldsymbol{a} = (y_1, y_1, y_1, y_1)$, while if the buyer selects two suppliers from regions 1 and 2 each, the suppliers' regional costs are $\boldsymbol{a} = (y_1, y_1, y_2, y_2)$. The pooling strategy enables the buyer to "win big" (i.e., secure a low regional cost no matter which supplier wins the contract) if region 1 happens to have a low regional cost, but it is clearly a very risky strategy — the buyer would "lose big" (i.e., suffer a high regional cost no matter which supplier wins the contract) if a large cost shock hits region 1. In contrast, a diversification strategy — say, the two-region strategy — engenders regional cost disparities among suppliers and hence increases the likelihood for the buyer to access at least some suppliers from low-cost regions. But is this more temperate, diversified approach better than potentially winning big with a pooling strategy? As yet the buyer's preference for or against diversification is unclear, mainly because the buyer's contract price is determined through supplier competition (an auction), which would obviously be affected by the cost disparities introduced by diversification strategies. Thus, one might imagine that the buyer's optimal supply base design strategy will depend on the number of suppliers N, the cost distributions F and G, and the auction mechanism. In this paper, we characterize the buyer's optimal supply base design strategy and describe when and if her optimal strategy depends on her ability to choose an auction mechanism (i.e., her bargaining power). To this end, we next formally describe the auction mechanisms we will examine.

3.2 Auction mechanisms

Optimal mechanism (OPT). When the buyer has full bargaining power, she can offer suppliers a join-or-leave-it mechanism such that all suppliers will participate and the buyer's expected total procurement cost is minimized. We refer to such a mechanism as the *optimal mechanism* (OPT). Let $\psi(x_i) \stackrel{def}{=} x_i + \frac{F(x_i)}{f(x_i)}$, which is commonly referred to as supplier i's *virtual cost* in the mechanism design literature, and let $\psi(x_i) + a_i$ denote supplier i's *adjusted virtual cost*, that is, supplier i's virtual cost adjusted by the additive regional cost a_i. In equilibrium, the optimal mechanism awards the contract to supplier j having the lowest adjusted virtual cost, i.e., $j = \underset{i=1...N}{\arg\min}\{\psi(x_i) + a_i\}$, breaking ties evenly, and pays the contract winner $\min\{\psi^{-1}[\psi(x_{j_1}) + a_{j_1} - a_j], 1\}$, where $j_1 = \underset{i=1\ldots N,\ i\neq j}{\arg\min} \{\psi(x_i) + a_i\}$ is the losing supplier with the lowest adjusted virtual cost. The payment is truncated from above by an optimal reserve price of 1. Because the buyer must contract with a supplier, if the buyer uses a reserve price, it is always optimal to set it at the worst possible supplier cost type, i.e., at 1. The optimality of these award and payment rules can be proved by straightforward adaptation of Myerson (1981).[2] To implement this optimal mechanism, we now propose a modified reverse clock auction, in which bidding proceeds as follows. The auction begins at calling price $\psi(1) + \max_{i=1\ldots N}\{a_i\}$, and continuously drops. Each bidder signals their willingness to stay in the auction or drop out, and the auction ends when at most one bidder remains in the auction. Let p be the calling price when the auction ends. The last bidder remaining in the auction, say bidder j, wins and is paid $\min\{\psi^{-1}(p - a_j), 1\}$; ties are broken randomly.

Proposition 1 *The optimal mechanism can be implemented by the modified reverse clock auction described above. Furthermore, in such an auction, bidders have a dominant strategy of staying in the auction until the calling price reaches their true adjusted virtual cost.*

Reverse English auction without/with reserve (RE/RER). In the case where the buyer does not have any bargaining power, she can only demand price concessions on the basis of competing offers from suppliers and cannot credibly impose a reserve price. Thus, the contract award and payment decisions can be modeled as outcomes of a reverse English total-cost auction without a reserve price (RE). The auction begins with a high initial total-cost bid (again referred to as the "calling price") which drops continuously. Each bidder signals their willingness to stay in the auction or drop out, and the auction ends when at most one bidder remains in the auction. Let p be the calling price when the auction ends. The last bidder remaining in the auction, say bidder j, wins and is paid the calling price at which the auction ended minus his regional cost, i.e., $p - a_j$; ties are broken randomly. In such an auction, it is a weakly dominant strategy for a supplier to stay in the auction until the calling price reaches his true total cost $x_i + a_i$ before dropping out (although he may not have to); see, for example, Maskin and Riley (2000). Thus, the auction ends when the second-lowest total-cost supplier drops out of the auction, and the lowest total-cost supplier is

[2] Myerson (1981) assumes the principal (i.e., the buyer in our case) does not possess non-public information. In our case, however, the buyer can possess non-public information about the regional costs when the suppliers cannot observe their competitors' regional costs. However, following the approach of Mylovanov and Tröger (2008), one can show that in our case the buyer finds it optimal to truthfully announce all regional costs and then implement the mechanism as if the costs were publicly known. The intuition is that regional costs only affect suppliers' payoffs indirectly (through the buyer's allocation and payment rules).

the winner and winds up being paid the difference between his regional cost and the second-lowest total cost. We also study cases where the buyer has some bargaining power and can impose the optimal reserve price of 1 in a reverse English auction (RER); the auction proceeds as before, but the winner's payment is capped at 1, i.e. $\min\{p - a_j, 1\}$. In such a case, it remains optimal for bidders to bid down to their true total costs before dropping out.

Under the three mechanisms, the buyer's expected total procurement cost can be written as expectations of order statistics as follows:

$$\underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\pi^{OPT}(\boldsymbol{x},\boldsymbol{a})\right] = \underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\min_{i=1,\ldots,N}\{\psi(x_i)+a_i\}\right]; \tag{1a}$$

$$\underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\pi^{RE}(\boldsymbol{x},\boldsymbol{a})\right] = \underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\text{second}\min_{i=1,\ldots,N}\{x_i+a_i\}\right]; \tag{1b}$$

$$\underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\pi^{RER}(\boldsymbol{x},\boldsymbol{a})\right] = \underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\text{second}\min_{i=1,\ldots,N}\{x_i+a_i, 1+a_i\}\right], \tag{1c}$$

where "second $\min\{\cdot\}$" denotes the second-lowest value in the set. Throughout the paper, $X_{k:N}$ and $Y_{k:N}$ denote the k^{th}-lowest order statistic out of N independent random draws from distributions F and G, respectively, and $\overline{X}_{k:N}$ and $\overline{Y}_{k:N}$ denote their respective expectations; $\mathbb{I}_{\{A\}}$ denotes the indicator function of event A; and $\vee$ and $\wedge$ denote the componentwise maximum and minimum operators, respectively.

4. Analysis and Results

To evaluate the buyer's expected total procurement cost under different diversification strategies, we need to compute expected order statistics of asymmetrically distributed random variables as shown by equations (1a)–(1c). However, this is generally intractable because closed-form expressions for expected order statistics are generally restricted to identically and independently distributed random variables following a handful of distributions (such as power-function or exponential distributions). Our problem is even more challenging because the expected total procurement cost (i) takes an ex ante expectation over $\boldsymbol{x}$ given a realized $\boldsymbol{a}$, involving order statistics of random variables from asymmetric distributions; then (ii) takes an ex ante expectation over $\boldsymbol{a}$, which involves elements that can exhibit various correlations depending on the supply base design strategy.

Thus, to have a hope of tackling the challenging problem of optimal supply base design, we need to exploit the problem's structure. We accomplish this by undertaking an iterative analysis of the buyer's diversification tradeoff, introduced next.

4.1 Diversification tradeoff

Suppose the buyer compares an R-region diversification strategy $(\hat{n}_1, \hat{n}_2, \ldots, \hat{n}_R)$ with the $(R+1)$-region strategy $(\hat{n}_1, \hat{n}_2, \ldots, \hat{n}_{R-1}, \tilde{n}_R, \tilde{n}_{R+1})$ such that $\hat{n}_R = \tilde{n}_R + \tilde{n}_{R+1}$. Let $\hat{\boldsymbol{a}}$ be the vector of suppliers' regional costs under the R-region strategy and let $\tilde{\boldsymbol{a}}$ denote the vector of suppliers' regional costs under the $(R+1)$-region strategy. Given that all suppliers have independent and identical production cost distributions, the difference between the two strategies comes entirely from the suppliers' regional costs $\hat{\boldsymbol{a}}$ and $\tilde{\boldsymbol{a}}$. We use a sample-path analysis as follows. On a sample path with given regional costs $\boldsymbol{y}$, the suppliers' regional costs $\hat{\boldsymbol{a}}$ and $\tilde{\boldsymbol{a}}$ can only differ from each other in the last $\tilde{n}_{R+1}$ elements. In particular, when region R experiences a larger cost shock than region $(R+1)$ does, i.e., $y_R > y_{R+1}$, switching to the $(R+1)$-region strategy would have saved the buyer money, resulting in a *diversifying upside*. Conversely, when region R experiences a smaller cost shock than region $(R+1)$ does, i.e., $y_R < y_{R+1}$, switching to the $(R+1)$-region strategy would have resulted in a disbenefit for the buyer, the *diversifying downside*. To facilitate expressing suppliers' regional costs under these two strategies, we let

$$
\begin{aligned}
\boldsymbol{a^{hh}} &\stackrel{def}{=} (a_1, \ldots, a_{N-n_R}, \underbrace{y_R \vee y_{R+1}, \ldots, y_R \vee y_{R+1}}_{\tilde{n}_R \text{ elements}}, \underbrace{y_R \vee y_{R+1}, \ldots, y_R \vee y_{R+1}}_{\tilde{n}_{R+1} \text{ elements}}),\\
\boldsymbol{a^{hl}} &\stackrel{def}{=} (a_1, \ldots, a_{N-n_R}, \underbrace{y_R \vee y_{R+1}, \ldots, y_R \vee y_{R+1}}_{\tilde{n}_R \text{ elements}}, \underbrace{y_R \wedge y_{R+1}, \ldots, y_R \wedge y_{R+1}}_{\tilde{n}_{R+1} \text{ elements}}),\\
\boldsymbol{a^{lh}} &\stackrel{def}{=} (a_1, \ldots, a_{N-n_R}, \underbrace{y_R \wedge y_{R+1}, \ldots, y_R \wedge y_{R+1}}_{\tilde{n}_R \text{ elements}}, \underbrace{y_R \vee y_{R+1}, \ldots, y_R \vee y_{R+1}}_{\tilde{n}_{R+1} \text{ elements}}), \text{ and}\\
\boldsymbol{a^{ll}} &\stackrel{def}{=} (a_1, \ldots, a_{N-n_R}, \underbrace{y_R \wedge y_{R+1}, \ldots, y_R \wedge y_{R+1}}_{\tilde{n}_R \text{ elements}}, \underbrace{y_R \wedge y_{R+1}, \ldots, y_R \wedge y_{R+1}}_{\tilde{n}_{R+1} \text{ elements}}).
\end{aligned}
$$

In other words, $\boldsymbol{a^{hh}}$ denotes the vector $\hat{\boldsymbol{a}}$ when $y_R \geq y_{R+1}$, $\boldsymbol{a^{hl}}$ denotes the vector $\tilde{\boldsymbol{a}}$ when $y_R \geq y_{R+1}$, $\boldsymbol{a^{ll}}$ denotes the vector $\hat{\boldsymbol{a}}$ when $y_R < y_{R+1}$, and $\boldsymbol{a^{lh}}$ denotes the vector $\tilde{\boldsymbol{a}}$ when $y_R < y_{R+1}$. Thus, for a given $Mech$ and realized $(\boldsymbol{x}, \boldsymbol{y})$ we can write

$$
\begin{aligned}
\text{diversifying upside} &\stackrel{def}{=} \left[\pi^{Mech}(\boldsymbol{x}, \hat{\boldsymbol{a}}) - \pi^{Mech}(\boldsymbol{x}, \tilde{\boldsymbol{a}})\right] \mathbb{I}(y_R \geq y_{R+1})\\
&= \left[\pi^{Mech}(\boldsymbol{x}, \boldsymbol{a^{hh}}) - \pi^{Mech}(\boldsymbol{x}, \boldsymbol{a^{hl}})\right] \mathbb{I}(y_R \geq y_{R+1}), \quad \text{and}\\
\text{diversifying downside} &\stackrel{def}{=} \left[\pi^{Mech}(\boldsymbol{x}, \tilde{\boldsymbol{a}}) - \pi^{Mech}(\boldsymbol{x}, \hat{\boldsymbol{a}})\right] \mathbb{I}(y_R < y_{R+1})\\
&= \left[\pi^{Mech}(\boldsymbol{x}, \boldsymbol{a^{lh}}) - \pi^{Mech}(\boldsymbol{x}, \boldsymbol{a^{ll}})\right] \mathbb{I}(y_R < y_{R+1}).
\end{aligned}
$$

By symmetry between y_R and y_{R+1}, we have

$$\begin{aligned}\text{expected diversification upside} &= \frac{1}{2}\underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{hh}}) - \pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{hl}})\right], \text{ and} \\ \text{expected diversification downside} &= \frac{1}{2}\underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{lh}}) - \pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{ll}})\right].\end{aligned}$$

Definition 1 *In comparing the R-region strategy with the $(R+1)$-region strategy, given the auction mechanism $Mech$ and the realized costs $(\boldsymbol{x},\boldsymbol{y})$, we call*

$$\pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{hh}}) - \pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{hl}}) - \pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{lh}}) + \pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{ll}})$$

the diversification tradeoff of a buyer considering switching from the R-region strategy to the $(R+1)$-region strategy.

Clearly, the buyer prefers the $(R+1)$-region strategy if the expected diversification tradeoff is positive; otherwise she prefers the R-region strategy. In general, however, the buyer's preference is not trivial because the diversification tradeoff on a sample path can be positive or negative, depending on $(\boldsymbol{x},\boldsymbol{y})$, and hence the buyer's preference between a more and a less diversified supply base depends on the supplier production cost distribution F, the regional cost distribution G, and the auction mechanism.

However, noticing that $\boldsymbol{a}^{\boldsymbol{hh}} = \boldsymbol{a}^{\boldsymbol{hl}} \vee \boldsymbol{a}^{\boldsymbol{lh}}$ and $\boldsymbol{a}^{\boldsymbol{ll}} = \boldsymbol{a}^{\boldsymbol{hl}} \wedge \boldsymbol{a}^{\boldsymbol{lh}}$, we can prove that the diversification tradeoff is always (i.e., regardless of the realized costs $\boldsymbol{x}$ or $\boldsymbol{y}$) non-positive/non-negative when the buyer's per-period cost function $\pi^{Mech}(\boldsymbol{x},\boldsymbol{a})$ is submodular/supermodular in $\boldsymbol{a}$ for all $\boldsymbol{x}$, per the definitions of submodular and supermodular functions (see, e.g., p.43 of Topkis 1998). Formally, we have the following lemma.

Lemma 1 *If $\pi^{Mech}(\boldsymbol{x},\boldsymbol{a})$ is supermodular in $\boldsymbol{a}$ for all $\boldsymbol{x}$, then the buyer always prefers the $(R+1)$-region strategy to the R-region strategy, which in turn implies that the fully diversifying strategy is optimal. If $\pi^{Mech}(\boldsymbol{x},\boldsymbol{a})$ is submodular in $\boldsymbol{a}$ for all $\boldsymbol{x}$, the converse is true, which in turn implies that the pooling strategy is optimal.*

In other words, Lemma 1 provides a tractable shortcut to the buyer's optimal supply base design problem: Instead of comparing diversification strategies after computing the buyer's expected total procurement cost under each possible supply base design strategy — which in general is technically intractable as we mentioned — we can potentially find the optimal strategy by examining the super- or submodularity of the per-period total cost function $\pi^{Mech}(\cdot)$. Using this approach, we will explore the optimal supply base design strategy and the effect of the buyer's bargaining power.

4.2 Optimal supply base design strategy for a buyer with full bargaining power

Per (1a), we have $\pi^{OPT}(\boldsymbol{x}, \boldsymbol{a}) = \min_{i=1,\ldots,N}\{\psi(x_i) + a_i\}$, which implies that, for any vector of suppliers' production cost $\boldsymbol{x}$, and any two vectors of suppliers' regional costs $\boldsymbol{a}$ and $\boldsymbol{a'}$, it must be true that

$$\pi^{OPT}(\boldsymbol{x}, \boldsymbol{a} \wedge \boldsymbol{a'}) = \pi^{OPT}(\boldsymbol{x}, \boldsymbol{a}) \wedge \pi^{OPT}(\boldsymbol{x}, \boldsymbol{a'}) \text{ and } \pi^{OPT}(\boldsymbol{x}, \boldsymbol{a} \vee \boldsymbol{a'}) \geq \pi^{OPT}(\boldsymbol{x}, \boldsymbol{a}) \vee \pi^{OPT}(\boldsymbol{x}, \boldsymbol{a'}).$$

This in turn implies that $\pi^{OPT}(\boldsymbol{x}, \boldsymbol{a})$ is supermodular in $\boldsymbol{a}$ for any $\boldsymbol{x}$. Therefore, from Lemma 1, we obtain the optimal supply base design strategy under mechanism OPT, as stated in the following proposition.

Proposition 2 *For any F, G, or N, it is always optimal to fully diversify if mechanism OPT is used.*

Proposition 2 highlights a remarkably general result: Whenever the buyer has the power to use the optimal mechanism, it is optimal to fully diversify the supply base, *regardless* of the number of suppliers N, or the cost distributions F and G. This is because, although the buyer's expected total procurement cost under any supply base design strategy in general depends on N, F, and G, the diversification tradeoff (per Definition 1) for a buyer using OPT is non-negative for *all* $\boldsymbol{x}$, $\boldsymbol{y}$, and $R < N$.

To provide intuition for Proposition 2, we will use an example to illustrate why mechanism OPT allows the buyer to enjoy the benefits of diversification, and how OPT functions. Later, we will use this example as a point of contrast to what happens when the buyer has zero bargaining power and uses mechanism RE. For simplicity, our example will assume that regional costs follow a two-point distribution, and are either high, y_H, or low, y_L, where $y_H > y_L$. The optimal mechanism involves the virtual cost function $\psi(\cdot)$, and for convenience we assume suppliers' production costs are uniformly distributed, making the virtual cost function linear (namely, $\psi(x) = 2x$).

With this setup, we examine a two-supplier case for which the pooling strategy has two suppliers in region 1 and the diversifying strategy has suppliers 1 and 2 in regions 1 and 2, respectively. Figure 1(a) pictorially illustrates the diversification upside and diversification downside for a particular pair of supplier production cost realizations x_1 and x_2. Because the function of a reserve price is straightforward, the figure depicts cost realizations for which a supplier with a regional cost advantage will win and receive a payment set by his competitor's dropout bid rather than via the reserve price.[3] In this discussion we assume OPT is implemented with the auction format described in Proposition 1.

[3]In particular, Figure 1(a) assumes $x_1 > x_2$, $\psi(x_1) + y_L < \psi(x_2) + y_H$, and $1 > x_2 + \frac{1}{2}(y_H - y_L)$.

Example 1:

- The top panel of Figure 1(a) depicts the diversification upside, which occurs when $(y_1, y_2) = (y_H, y_L)$. Had the pooling strategy been used, both suppliers would have the high regional cost, supplier 1 would drop out when the calling price reached his true adjusted virtual cost $\psi(x_1) + y_H$ and supplier 2 would win the auction and be paid $\psi^{-1}(\psi(x_1) + y_H - y_H) = x_1$, yielding a total procurement cost $x_1 + y_H$ to the buyer. In contrast, had the diversifying strategy been used, the buyer's supply base would have one supplier (supplier 2) with the low regional cost. In such a case, mechanism OPT would capture the cost reduction opportunity by awarding the contract to supplier 2 (so the buyer incurs a low regional cost) and paying him $\psi^{-1}(\psi(x_1) + y_H - y_L) = x_1 + \frac{y_H - y_L}{2}$. Consequently, the buyer pockets a diversification upside equal to $(x_1 + y_H) - [(x_1 + \frac{y_H - y_L}{2}) + y_L] = \frac{y_H - y_L}{2}$.

- The lower panel of Figure 1(a) depicts the diversification downside, which occurs when $(y_1, y_2) = (y_L, y_H)$. Had the pooling strategy been used, both suppliers would have low regional costs, and supplier 2 would win the auction and be paid $\psi^{-1}(\psi(x_1) + y_L - y_L) = x_1$, yielding a total procurement cost of $x_1 + y_L$ to the buyer. However, had the diversifying strategy been used, supplier 1 would be the only supplier with a low regional cost. Mechanism OPT would award the contract to the low-regional-cost supplier 1 and pay him $\psi^{-1}(\psi(x_2) + y_H - y_L) = x_2 + \frac{y_H - y_L}{2}$. Thus the diversification downside equals $[(x_2 + \frac{y_H - y_L}{2}) + y_L] - (x_1 + y_L) = \frac{y_H - y_L}{2} - (x_1 - x_2)$.

Note that in this example, the diversification upside exceeds the diversification downside. Because symmetry implies that the upside and downside occur with equal probability, this example confirms that for these realizations of x_1 and x_2 the buyer always benefits from diversifying.

While this example applied to a particular set of assumptions on F, G, N, and realizations of x_1 and x_2, the important takeaway is that mechanism OPT helps the buyer capture surplus from a supplier enjoying a regional cost advantage because OPT's rules bias against such a supplier. For example, consider the outcome for the upper-right part of Figure 1(a): Supplier 2 is paid $x_1 + \frac{y_H - y_L}{2}$, which is actually $\frac{y_H - y_L}{2}$ dollars less than the lowest total cost the buyer could possibly incur if she transacted with supplier 1. The buyer gets away with this by promising ex ante to compare suppliers' virtual costs, not actual costs, when determining the auction winner and

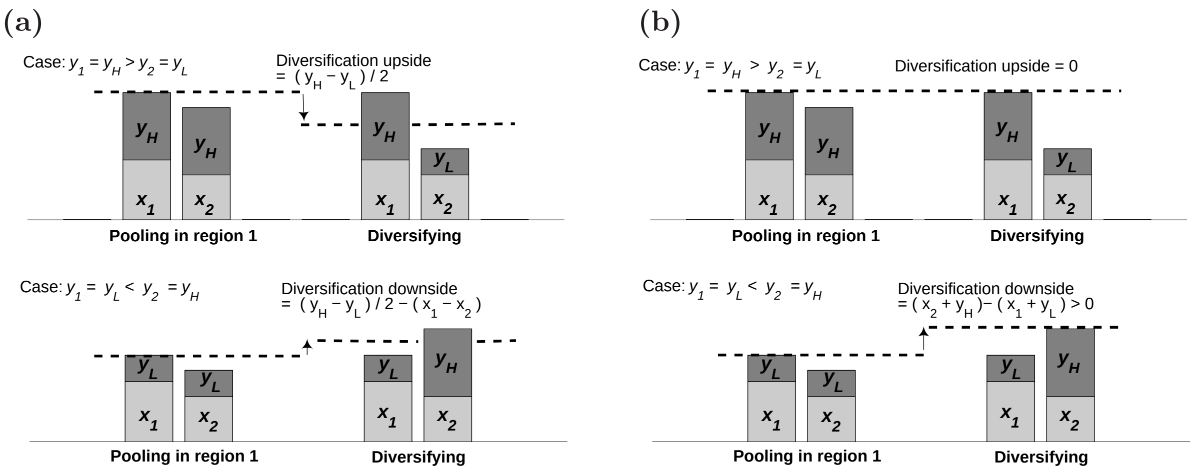

Figure 1: The diversification upside and downside. Panel (a) plots for mechanism OPT with $N = 2$ suppliers, assuming $F \sim U[0, 1]$; Panel (b) plots for mechanism RE with $N = 2$ suppliers.

payment. This biases against the advantaged supplier. In particular, when supplier 2 enjoys a regional cost advantage, he only wins the auction if

$$x_2 \in \{x_2 | \psi(x_2) + y_L \leq \psi(x_1) + y_H\} \subset \{x_2 | x_2 + y_L \leq x_1 + y_H\}. \tag{2}$$

In summary, mechanism OPT biases against advantaged suppliers in order to reduce their payment, and in doing so might impose an inefficient allocation (evidenced by the proper subset relation in (2); see also MacAfee and McMillan 1989, Rezende 2009). The upshot is that, because diversifying engenders cost realizations in which suppliers can enjoy a regional cost advantage and mechanism OPT allows the buyer to capitalize on the resulting cost-saving opportunities, the buyer finds it optimal to fully diversify her supply base.

Despite being theoretically optimal, mechanism OPT may be difficult to implement in practice. First, it requires the buyer to impose rather complex take-it-or-leave-it allocation and payment rules that bias against suppliers with a cost advantage. The buyer may have a difficult time convincing suppliers to go along with such a scheme, who might not understand why they should be put at a disadvantage even though they have a low regional cost that is attractive for the buyer. In such a case, the optimal mechanism may be off the table and the buyer might have to employ another mechanism which does not require her to exert bargaining power over the suppliers. This motivates our analysis using mechanism RE in the next subsection.

4.3 Optimal supply base design strategy for a buyer with zero bargaining power

We now examine the setting where the buyer uses a reverse English auction with no reserve price (zero bargaining power). We first study the case in which the buyer designs a supply base with two suppliers, and then examine the case in which the supply base consists of $N \geq 3$ suppliers.

4.3.1 Two suppliers

Per (1b), we have $\pi^{RE}(\boldsymbol{x}, \boldsymbol{a}) = \max\{x_1 + a_1, x_2 + a_2\}$ when $N = 2$, which implies that, for any vector of suppliers' production costs $\boldsymbol{x}$, and any two vectors of suppliers' regional costs $\boldsymbol{a}$ and $\boldsymbol{a'}$, it must be true that

$$\pi^{RE}(\boldsymbol{x}, \boldsymbol{a} \vee \boldsymbol{a'}) = \pi^{RE}(\boldsymbol{x}, \boldsymbol{a}) \vee \pi^{RE}(\boldsymbol{x}, \boldsymbol{a'}) \text{ and } \pi^{RE}(\boldsymbol{x}, \boldsymbol{a} \wedge \boldsymbol{a'}) \leq \pi^{RE}(\boldsymbol{x}, \boldsymbol{a}) \wedge \pi^{RE}(\boldsymbol{x}, \boldsymbol{a'}).$$

This in turn implies that $\pi^{RE}(\boldsymbol{x}, \boldsymbol{a})$ is submodular in $\boldsymbol{a}$ for all $\boldsymbol{x}$. Therefore, from Lemma 1, we obtain the optimal supply base design strategy under mechanism RE when $N = 2$:

Proposition 3 *With two suppliers, for any F or G, it is always optimal to pool if mechanism RE is used.*

Surprisingly, with two suppliers, Proposition 3 shows that, rather than diversifying the supply base, the buyer prefers to select the two suppliers from the same region if she has no bargaining power (i.e., uses reverse English auctions without reserve price). Perhaps more surprising, this preference persists for any supplier cost distribution and any regional cost distribution. Why is it never optimal to spread out the regional cost risk by diversification when the buyer uses mechanism RE, even if large supply shocks are very likely? This is because without a reserve price mechanism RE fully exposes the buyer to windfall profit-taking by the advantaged supplier with lower regional cost, who largely absorbs what would have been the buyer's upside benefit of diversifying. Such windfall profit-taking by the advantaged supplier is so severe that the buyer always has no diversification upside. We illustrate this with an example. As a point of contrast to mechanism OPT, we use the same setup as for Example 1, but apply mechanism RE instead of mechanism OPT. The diversification upside and downside are illustrated in Figure 1(b)'s top and bottom panels, respectively. [4]

Example 2:

[4]Figure 1(b) assumes $x_1 > x_2$ and $x_1 + y_L < x_2 + y_H$.

- The top panel of Figure 1(b) illustrates the diversification upside, which occurs when $(y_1, y_2) = (y_H, y_L)$. Had the pooling strategy been used, both suppliers would have high regional cost, and the lowest total-cost supplier (supplier 2) would win the auction and be paid supplier 1's total cost minus supplier 2's regional cost, i.e., $x_1 + y_H - y_H = x_1$. Thus, the buyer's total procurement cost would be the largest total cost, i.e., $x_1 + y_H$. In contrast, had the diversifying strategy been used, supplier 2 would have low regional cost. However, this does not mean the buyer will get any benefit from having such a low-regional-cost supplier. On the contrary, supplier 2, with lower total cost, would win the auction but charge price $x_1+y_H-y_L$, matching supplier 1's total cost and yielding a total procurement cost $x_1 + y_H$ to the buyer. In other words, mechanism RE would allow the advantaged supplier 2 to fully absorb the diversification benefit, leaving zero diversification upside to the buyer.

- The lower panel of Figure 1(b) illustrates the diversification downside, which occurs when $(y_1, y_2) = (y_L, y_H)$. Had the pooling strategy been used, both suppliers would have low regional costs, and supplier 2, with lower total cost, would win the auction and be paid supplier 1's total cost minus supplier 2's regional cost, i.e., $x_1 + y_L - y_L = x_1$. Thus, the buyer's total procurement cost would be the largest total cost, i.e., $x_1 + y_L$. In contrast, had the diversifying strategy been used, only supplier 1 would have low regional cost. Supplier 1 would charge price $x_2 + y_H - y_L$, matching supplier 2's total cost and yielding a total procurement cost of $x_2 + y_H$ to the buyer. In other words, mechanism RE would allow the advantaged supplier 1 to fully absorb the benefit of its regional cost advantage, saddling the buyer with a large diversification downside.

In this example, mechanism RE allowed the supplier with lower regional cost to take so much windfall profit that diversifying yielded no diversification benefit but exposed the buyer to the diversification downside. That is, diversifying caused a "heads you win, tails I lose" scenario for the buyer. The key takeaway is that severe windfall profit-taking makes the buyer worse off by diversifying, and consequently she is better off pooling her two suppliers in the same region.

As Propositions 2-3 reveal, the optimal supply base designs under OPT and RE are polar opposites. This encapsulates our fundamental message in this paper: Bargaining power is a key driver of supply base diversification decisions. The buyer's bargaining power (i.e., the auction mechanism she is able to deploy) determines how much diversification benefit she can pocket, which then informs her decision to diversify the supply base or not. A weak buyer who foresees not being able to pocket the benefits of diversification should take this into account and design her supply base with less diversification than she would if she held full bargaining power over suppliers. This key finding is confirmed in our following analysis of the case in which the buyer uses mechanism RE with $N \geq 3$ suppliers.

4.3.2 More than two suppliers

The goal of this subsubsection is to show that a buyer with zero bargaining power (RE) and three or more suppliers finds that, in many cases, it is suboptimal to fully diversify. This is in stark contrast to the strategy of always fully diversifying, which is optimal for a buyer with full bargaining power (OPT). Thus, this subsubsection reinforces the main message of the paper: The buyer's bargaining power can drastically affect her optimal supply base design.

With three or more suppliers, the optimal diversification strategy under mechanism RE turns out to be much more complicated than that with two suppliers, for two reasons. First, as discussed earlier, the buyer's total procurement cost $\pi^{RE}(\boldsymbol{x}, \boldsymbol{a})$ is the second-lowest order statistic of the possibly correlated total costs of N suppliers. Second, this total procurement cost can easily be shown to be neither submodular nor supermodular in $\boldsymbol{a}$ for all $\boldsymbol{x}$ — hence, the buyer's preference between the R-region strategy and the $(R+1)$-region strategy in general depends on N, R, and the cost distributions F and G.

To gain insight into the buyer's supply base design preference, we will characterize how the buyer's preference is affected by the shape and scale of the regional cost distribution G, given N and supplier production cost distribution F. For any distribution G, we accomplish this by examining a family of models $\{(F, G^{(s)}),\ s \in \mathbb{R}^+\}$, where $G^{(s)}(y) \stackrel{def}{=} G(\frac{y}{s})$. Regional cost distribution $G^{(s)}$ has the same "shape" as G, but a different scale. We call s the scale parameter. Since we have normalized the range of F to the unit interval, this sequence of models captures an increasing variation of the regional cost distribution relative to that of the supplier production cost distribution.

Large regional costs drive preference away from pooling. Section 4.3.1 shows that with two suppliers a buyer using mechanism RE always finds it optimal to pool. Following that intuition, does the buyer always prefer to pool even with three or more suppliers? Here we show that the answer is "no," and in fact the buyer prefers not to pool when the regional cost variation dominates suppliers' production cost variation, i.e., when s is large. This can happen, for example, in cases where suppliers use standard production technology and the variability of production costs is negligible in comparison to that of regional costs — which could be driven by a variety of sources ranging from incremental transportation rate changes to catastrophic port strikes. When the regional cost variation is relatively large, pooling and "losing big" (as described on page 8) could be catastrophic for the buyer. (For example, if a strike hit the originating port in a region containing all N of her suppliers.) Intuitively the buyer might want to diversify her supply base, but then again we recall the $N = 2$ case for which we know that pooling is optimal due to supplier windfall-profit taking. How can the buyer benefit from diversifying when using mechanism RE? The key is that, with $N \geq 3$ suppliers, the buyer can *partially diversify* by grouping suppliers together into different regions. This curbs unilateral regional cost advantages and forestalls windfall-profit taking. Suppliers in a low-cost region will — in the course of competing for the buyer's business in the auction — transfer the surplus of their regional cost advantage to the buyer. This result is formalized in Proposition 4 below, which shows that, in fact, the buyer would always prefer to have at least $R = \lfloor \frac{N}{2} \rfloor$ regions (with at least two suppliers per region) to any less diversified strategy with $R < \lfloor \frac{N}{2} \rfloor$ regions. Therefore, we see that the number of suppliers can affect the supply base design strategy under mechanism RE, and the pooling strategy can be dominated by the partially diversifying strategy.

Preference between full and partial diversification driven by regional cost distribution's shape. We now turn to the main goal of this subsubsection, which is to show that a buyer using mechanism RE with three or more suppliers need not find fully diversifying optimal. In particular, we show that the buyer prefers the partially diversifying strategy to the fully diversifying strategy when the scale parameter s is large and G has a left (low-cost) "tail" (this will be made more precise shortly). These conditions make windfall-profit taking a serious concern for the buyer. When s is big, regional costs largely determine the auction winner. Furthermore, when G has a left tail there is more chance for low "outlier" regional costs. Hence, fully diversifying under these conditions is apt to backfire by yielding a winning supplier with a sizeable, unilateral regional cost advantage that he absorbs through windfall-profit taking: Even though the buyer has suppliers in N regions, she incurs costs as if she contracts with a supplier in the second-cheapest of N regions. On the other hand, if the buyer chose to forestall windfall profit-taking by partially diversifying, then she would have two suppliers in each of $\lfloor \frac{N}{2} \rfloor$ regions, and incur costs associated with the cheapest of $\lfloor \frac{N}{2} \rfloor$ regions. After netting out the production costs (whose variation is small relative to regional costs), the buyer's preference between partial and full diversification depends on the relative sizes of $\overline{Y}_{2:N}$ and $\overline{Y}_{1:\lfloor \frac{N}{2} \rfloor}$. The following proposition summarizes the results so far in this section.

Proposition 4 *When the scale parameter s of the regional cost distribution is sufficiently large:*

- *The partially diversifying strategy that has $\lfloor \frac{N}{2} \rfloor$ regions with at least two suppliers each dominates any strategy with fewer regions;*

- *The buyer prefers the partially diversifying strategy to the fully diversifying strategy if $\overline{Y}_{2:N} > \overline{Y}_{1:\lfloor \frac{N}{2} \rfloor}$; vice versa.*

We now lend analytical support to our earlier statement that the buyer prefers partial diversification when G has a left "tail." More precisely, we analytically show how a left tail causes $\overline{Y}_{2:N}$ to exceed $\overline{Y}_{1:\lfloor \frac{N}{2} \rfloor}$. Setting $\bar{G}(y) \overset{def}{=} 1 - G(y)$ and letting $\bar{G}^{-1}$ denote the inverse function of $\bar{G}$, one can show (see the e-companion, §EC.6) that

$$\begin{aligned} \overline{Y}_{2:N} - \overline{Y}_{1:\lfloor \frac{N}{2} \rfloor} &= \int_{-\infty}^{\infty} \left[N\bar{G}^{N-1}(y) - (N-1)\bar{G}^{N}(y) \right] dy - \int_{-\infty}^{\infty} \bar{G}^{\lfloor \frac{N}{2} \rfloor}(y) dy \\ &= \int_{0}^{1} \left[Nz^{N-1} - (N-1)z^{N} - z^{\lfloor \frac{N}{2} \rfloor} \right] \frac{1}{g[\bar{G}^{-1}(z)]} dz. \end{aligned} \tag{3}$$

Note that for $z \in (0,1)$, there exists a $\underline{z} \in (0,1)$ such that $nz^{n-1} - (n-1)z^{n} - z^{\lfloor \frac{N}{2} \rfloor}$ is negative to the left of $\underline{z}$ and positive to the right of $\underline{z}$. Therefore, if G has a left tail such that most of its density is piled close to the right end-point of the support, then $g(\bar{G}^{-1}(z))$ is large for z close to zero but is small for z close to one, and thus $\overline{Y}_{1:\lfloor \frac{N}{2} \rfloor} - \overline{Y}_{2:N}$ must be negative, which implies that partially diversifying is preferred. Likewise, if regional costs tend to be packed closely towards the low-cost end, G's density is piled near the left endpoint and the opposite argument implies that pooling is preferred.

The above paragraph discussed how the shape of a general cost distribution G drives the buyer's preference between partial and full pooling. To illustrate this point in a more specific way, we consider a parameterized power-function family of regional costs, $G^{(s)}(y) = (\frac{y}{s})^{v}$, where $y \in [0, s]$. This distribution's density function takes various shapes according to the shape parameter $v > 0$: As illustrated in Figure 3(a), the density distribution is very concentrated near the left endpoint when v is small; in contrast, the density distribution flattens out as v increases. Consistent to the above discussion on the shape of distribution G, we find that the buyer prefers fully diversifying when v is small but prefers the partially diversifying strategy otherwise.

Corollary 1 *Suppose $G^{(s)}(y) = (\frac{y}{s})^{v}$. When scale parameter s is sufficiently large, there exists a threshold $\underline{v}$ such that the buyer prefers fully diversifying if $v < \underline{v}$, and partially diversifying if $v > \underline{v}$.*

In summary, we have shown that, even with more than two suppliers, a buyer using mechanism RE will often not wish to fully diversify her supply base. This reenforces our main message that bargaining power can have a profound impact on the buyer's supply base design.

4.4 General takeaways

Sections 4.2–4.3 suggest that the buyer should carefully evaluate her bargaining clout before deciding to diversify her supply base. Buyers with strong bargaining power always find it optimal to have just one supplier per region (fully diversifying); this is because diversifying mitigates the exposure to regional cost shocks, while such buyers can use reserve prices and biasing rules to prevent suppliers from absorbing the benefits of diversification and hence capture significant benefits from having a supplier in a low-cost region. In contrast, for buyers who have extremely little channel power and cannot prevent advantaged suppliers from making significant windfall profits, there is little benefit to diversifying and they should only add more regions to their portfolio if doing so is unlikely to forfeit the benefits of diversification to an advantaged supplier. Because a supplier with a sizeable regional cost advantage can largely absorb the resulting benefits if he is the only supplier in his region, the buyer can avoid the emergence of such an advantaged supplier by keeping two suppliers in each region (partially diversifying). In particular, for a buyer who uses a two-supplier supply base, there is little benefit to diversifying and she should always instead simply pool her risk by choosing both suppliers in a single region. While such a buyer is inevitably more vulnerable to cost shocks, by pooling she ensures greater cost parity between suppliers, which she needs to drive down suppliers' price bids. A buyer with weak bargaining power who uses more than two suppliers will diversify a two-supplier region into two single-supplier regions only if neither region is likely to contain an advantaged supplier that can absorb the benefits of the diversification. Because the benefit of this diversification accrues precisely when just one of the two regions experiences a large regional cost, this pushes the buyer to prefer diversifying only if, in such a case, she has supplier(s) in a third region which is unlikely to experience a large regional cost. Consequently, buyers with weak bargaining power prefer to fully diversify only if there are at least three suppliers in the supply base and the regional cost distribution does not have a left (low-cost) tail.

5. Extensions

5.1 Codependent regional costs

Our analyses in §4 assumed independent regional costs. However, one can easily imagine situations where regions exhibit vulnerability to common shock factors, such as the price of oil or global shipping volumes. This subsection examines the results of Propositions 2-4 for a setting with ex ante symmetric and codependent regions. We first discuss how the result extend, and then conclude this subsection with a proposition formalizing this discussion.

Regional codependence does not affect buyer's preference for diversifying with OPT. Proposition 2 revealed that the buyer prefers to fully diversify no matter what the production cost and regional cost distributions are. The intuition is that the buyer diversifies in order to enjoy the upside benefit of finding suppliers with attractive regional costs. Surprisingly, this general result extends even when the regional costs can be codependent (technically, this follows from the fact that Lemma 1 holds even when regional costs are codependent). Thus, even if regions' costs are correlated, the buyer still places exactly one supplier in each region in order to diversify her regional cost risk as much as possible.

Regional codependence affects the buyer's preference under RE only when she has three or more suppliers. Because Lemma 1 remains valid in the presence of regional codependence, Proposition 3 extends to codependent regions and consequently a buyer using mechanism RE always prefers to forestall windfall-profit taking by pooling when she has just two suppliers. Diversifying leaves the buyer with downside risk but no upside benefit, and this remains true no matter how small the windfall-profit taking risk is: Regardless of how highly positively correlated the regional costs are, the buyer's preference for pooling is unchanged. On the other hand, when the buyer has three or more suppliers and uses mechanism RE, regional codependence can affect her supply base design preference. To see why, consider correlated, random regional costs $(y_1, y_2, \ldots, y_R)$ for which there exists a random state variable ξ having distribution $P(\cdot)$ such that the y_r's are independently distributed according to some distribution function $G(\cdot|\xi)$. (In the terminology of Shaked (1977), these random variables are "positive dependent by mixture.") Using §4.3.2's results for the case with identically and independently distributed regional costs (Proposition 4), we can see that the effect of regional codependence on the diversification strategy thus depends on both $P(\cdot)$ and the family of distributions $G(\cdot|\xi)$. (Unless of course the family $G(\cdot|\xi)$ is such that $\overline{Y}_{1:\lfloor \frac{N}{2} \rfloor}$ never exceeds $\overline{Y}_{2:N}$ [or vice-versa] — in such cases the codependence does not affect the buyer's preference between fully and partially diversifying.) For example, consider $G(y|\xi) = s^{-\xi} y^{\xi}$ with a given $s > 0$. In such a case, a small value of state variable ξ can model the case in which regional costs are mainly driven by global factors and exhibit small variance; in contrast, a large ξ can model the case in which regional costs are mainly driven by local factors and exhibit large variance. According to Corollary 1, it is clear that the buyer prefers partially diversifying if the state variable distribution $P(\xi)$ has enough of its density concentrated at large values of ξ, but would instead prefer fully diversifying were the density concentrated primarily at small values of ξ.

The following proposition formalizes this subsection's discussion.

Proposition 5 *With codependent, ex ante symmetric regions,*

- *Under mechanism OPT, the buyer's preference is robust to regional codependence and she always finds it optimal to fully diversify her supply base.*
- *Under mechanism RE,*
  - *with two suppliers the buyer's preference is robust to regional codependence and she always finds it optimal to pool her supply base;*
  - *with three or more suppliers, regional codependence can affect the buyer's preference between fully diversifying and partially diversifying.*

5.2 Asymmetric regions

In this subsection, we extend our analysis of the supply base design decision and the effect of bargaining power to cases in which regions may be ex ante asymmetric. For example, this could model settings where "offshore" regions are characterized by low production costs and high regional costs, while "onshore" regions have higher production costs but lower regional costs. To formalize the existence of different types of regions (such as onshore versus offshore), we will introduce $k = 1, 2, \ldots$ as an index over region types. For a type-k region, let F_k denote the production cost distribution and let G_k denote the regional cost distribution. Furthermore, we denote the total cost distribution for a region-k supplier as $H_k \stackrel{def}{=} F_k \oplus G_k$, where the convolution operator $\oplus$ is such that $H_k(z) = \int_{-\infty}^{\infty} G_k(z-x)dF_k(x)$. Similarly, let $\hat{H}_k \stackrel{def}{=} \hat{F}_k \oplus G_k$, where $\hat{F}_k(z) \stackrel{def}{=} F_k(\psi_k^{-1}(z))$ and $\psi_k^{-1}(\cdot)$ is the inverse function of $\psi_k(x) \stackrel{def}{=} x + \frac{F_k(x)}{f_k(x)}$. In words, $\hat{F}_k(z)$ and $\hat{H}_k(z)$ denote the distributions of a region-k supplier's virtual cost and adjusted virtual cost, respectively. We will assume independence of production costs and regional costs. The optimal mechanism is as discussed in §3.2, with ψ replaced by ψ_k for each type-k supplier i.

Weak buyer still prefers to pool. For simplicity we will focus our RE analysis on the two-supplier case. With asymmetric regions, we can prove that Proposition 3 still holds. In other words, a buyer using mechanism RE will never want to choose two suppliers each from different, asymmetric regions. For a buyer facing offshore and onshore regions, the buyer should always choose between onshore and offshore, and never mix by choosing one supplier from each. An important follow-up question is which region the buyer should locate her two suppliers in: Is it better to choose both suppliers onshore or offshore? Intuitively, one might expect that the buyer needs to compare the regions' total cost distributions. In fact, however, the answer boils down to comparing $\tilde{H}_k \overset{def}{=} F_k^2 \oplus G_k$, the distribution of the highest total cost in region k. Because competitive pricing in the auction will influence the buyer's total costs, when all else is equal the buyer favors regions with suppliers who tend to be evenly matched. Thus, the variability of production costs within the region is important to the buyer, and she may even favor a region with a higher average production costs if these costs are less variable. The following proposition formalizes this discussion.

Proposition 6 *With two suppliers, it is always optimal to pool if mechanism RE is used, even when regions are ex ante asymmetric. In particular, it is optimal to choose a type-k region such that the expected highest total cost,* $\int_{-\infty}^{\infty} z d\tilde{H}_k$*, is minimized.*

Strong buyer prefers diversification unless access to attractive regions is limited. Even if the buyer has access to N regions, some regions may be so comparatively bad that she would never choose to locate suppliers there.[5] Thus, asymmetry may break the buyer's preference for diversification, even if she has full bargaining power. However, this stems from limited availability of regions. For the remainder of our discussion we focus on what happens in settings where the buyer has access to up to N copies of each region type. In this case, we can prove that our earlier insights remain valid: With full bargaining power it is optimal to fully diversify the supply base. However, the way in which the buyer chooses to fully diversify the supply base may be more nuanced than in the case with ex ante symmetric regions. In particular, even with N copies of each region type available, the buyer might choose to use multiple types of regions when fully diversifying her supply base. For example, consider a two-supplier case with two types of regions. Suppose that $\hat{H}_1$ is the two-point distribution with probability mass q at zero and probability mass $1-q$ at one, and that $\hat{H}_2$ is the uniform distribution $U[0,1]$. When $q > \frac{1}{3}$, it is easy to confirm the optimality of the "mixed diversification strategy" which puts one supplier in each type of region. Comparing the region types, we see that type-1's costs are bimodal and in this sense are "riskier" than type 2's costs which are uniform. Choosing a supplier from a type-2 region helps the buyer decrease her risk. However, with one supplier already positioned to manage risks, there is diminished need to use the second in the same way. As a result, the buyer can be better off using one type-2 region as a "safety" and then gambling on a "bet" by having one type-1 region.

[5]For example, suppose $N = 2$ and there are two regions with the same production cost distribution $U[0,1]$ but different regional cost distributions G_1 and G_2. Suppose that G_k has probability mass p_k at 1 and probability mass $1-p_k$ at 0. It is easy to check that it is optimal to select both suppliers from region 1 if and only if $p_2 > \frac{p_1}{5-4p_1}$.

Proposition 7 *If mechanism OPT is used, it is always optimal to fully diversify even when regions are ex ante asymmetric. However, the optimal diversification strategy may involve different region types.*

In summary, we again see that buyers with more bargaining power prefer more diversification. This is the key takeaway of this section. We also observed that the ability to mix-and-match ex ante asymmetric regions naturally adds additional considerations about how best to tactically execute a fully diversifying strategy. However, as this latter point is beyond the main "bargaining power" message of this paper, we defer a fuller analysis of this point to future work.

5.3 Optimal supply base design for a buyer with moderate bargaining power

Mechanisms OPT and RE represent the full and zero bargaining power cases, respectively. Using these two mechanisms, comparing the buyer's diversification preferences reveals that buyers with more bargaining power favor more diversification. In this subsection we examine whether this insight extends to a third auction mechanism, the reverse English auction with a reserve price (RER). Compared to the zero-bargaining power mechanism, RER adds the power to set a credible reserve price. Thus, our goal in this section is to see whether adding the reserve price to the reverse English auction format will encourage, or discourage, diversification. To make our results comparable with Propositions 2-4, and for simplicity, we will assume that suppliers' production costs and regional costs are all independent and that regions are ex ante symmetric.

In the remainder of this section we will show that greater bargaining power does indeed encourage the buyer to diversify more. We demonstrate this by finding the buyer's supply base design preference under RER and then comparing it to her preferences under RE. We first show that, with two suppliers, the buyer can find it optimal to diversify if using mechanism RER, in contrast her universal preference for pooling with mechanism RE. We then show that for three or more suppliers, when the scale parameter of the regional cost distribution is large, the buyer always prefers to fully diversify with mechanism RER, in contrast to her preference under RE which was to partially diversify depending on the region cost distribution's shape.

Diversification can be optimal with two suppliers. With two suppliers, the sign of the buyer's diversification tradeoff (per Definition 1) under mechanism RER can be positive or negative, depending on the realized values of the regional cost difference $|y_1 - y_2|$ and the larger production cost $X_{2:2}$, as stated in the following lemma. This contrasts sharply with the always non-positive diversification tradeoff under mechanism RE.

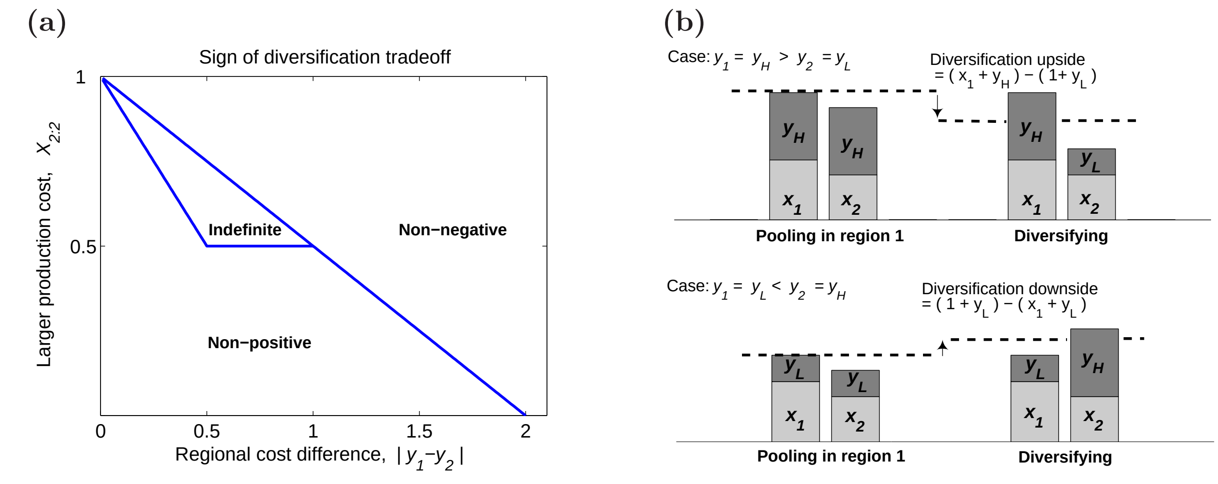

Figure 2: Effect of reserve price when $N = 2$. Panel (a) illustrates Lemma 2; panel (b) illustrates how the reserve price affects the diversification tradeoff.

Lemma 2 *If $|y_1 - y_2| \geq 2(1 - X_{2:2})$, the buyer's diversification tradeoff (per Definition 1) is non-negative. If $|y_1 - y_2| \leq 1 - X_{2:2}$, or if $|y_1 - y_2| \leq 2(1 - X_{2:2})$ and $X_{2:2} \leq \frac{1}{2}$, the diversification tradeoff is non-positive.*

Figure 2(a) illustrates Lemma 2, and Figure 2(b) demonstrates the intuition behind it: When the regional cost difference is large (e.g., $|y_1 - y_2| \geq 2 - 2X_{2:2}$), a reserve price effectively limits windfall profit-taking and allows the buyer to capture significant cost savings when sourcing from a low-regional-cost supplier. Consequently, diversifying makes the buyer better off under mechanism RER. As a direct comparison against mechanism RE, Figure 2(b) shows the diversification upside and downside under mechanism RER for the same setting as in Figure 1(b).

Example 3:

- When $(y_1, y_2) = (y_H, y_L)$, had the buyer diversified, although the advantaged supplier 2 would still win the auction (as in Figure 1(b)), the reserve price would cap its payment at 1, yielding a total procurement cost $1 + y_L$ to the buyer. Namely, the reserve price would increase the diversification upside to $(x_1 + y_H) - (1 + y_L)$, compared to zero in Figure 1(b).

- When $(y_1, y_2) = (y_L, y_H)$, had the buyer diversified, although the advantaged supplier 1 would still win the auction (as in Figure 1(b)), the reserve price would again cap its payment at 1, yielding a total procurement cost $1 + y_L$ to the buyer. Namely, the reserve price would decrease the diversification downside to $(1+y_L)-(x_1+y_L)$, compared to $(x_2+y_H)-(x_1+y_L)$ in Figure 1(b).

As a result of effectively truncating large windfall profit opportunities, when the regional cost difference is large the buyer who can use a reserve price in a reverse English auction has a positive diversification tradeoff. However, when the regional cost difference is small, the reserve price is inactivated — in such cases the auction payment is (as in RE) set purely by pricing competition. Thus, even with a reserve price, the buyer could have a negative diversification tradeoff.

In general, the preference for or against diversification plays out according to the specific distributions of F and G, in particular their probability masses over the regions depicted in Figure 2(a). However, we can prove that under RER the buyer can indeed find it optimal to diversify, as formalized at the end of this subsection.

With three or more suppliers, fully diversify with large regional costs. We now turn to the case with three or more suppliers, and consider any family of regional cost distributions $G^{(s)}$ as defined in §4.3.2. Note that when the scale parameter s of the regional cost distribution is large enough, mechanism RER is a good "facsimile" of mechanism OPT: In both cases the winner is likely to be determined by regional costs, while the payment is likely to be determined by the reserve price. Using this intuition, we can prove that when s is large it is optimal to fully diversify under mechanism RER. This contrasts with the buyer's preference under RE, which even with a large s favored partially pooling depending on the shape of the regional cost distribution, G.

Proposition 8 *Suppose the buyer uses mechanism RER.*

- *With two suppliers, the buyer finds it optimal to diversify if the expected regional cost difference* $E[|y_1 - y_2|]$ *is large enough.*
- *With more than two suppliers, for any family of regional cost distributions* $G^{(s)}$ *as defined in §4.3.2, the buyer finds it optimal to fully diversify when the scale of the regional cost distribution* s *is sufficiently large.*

6. Numerical Illustrations

This section numerically illustrates our results. For concision we focus on Propositions 2-5. To provide a common metric for comparing the relative performance of different supply base design strategies, we benchmark all supply base design strategies to the pooling strategy and define, for any supply base design strategy "X"

$$\textit{rate of cost improvement} = 1 - \frac{\text{expected total cost under strategy "X"}}{\text{expected total cost under the pooling strategy}}, \tag{4}$$

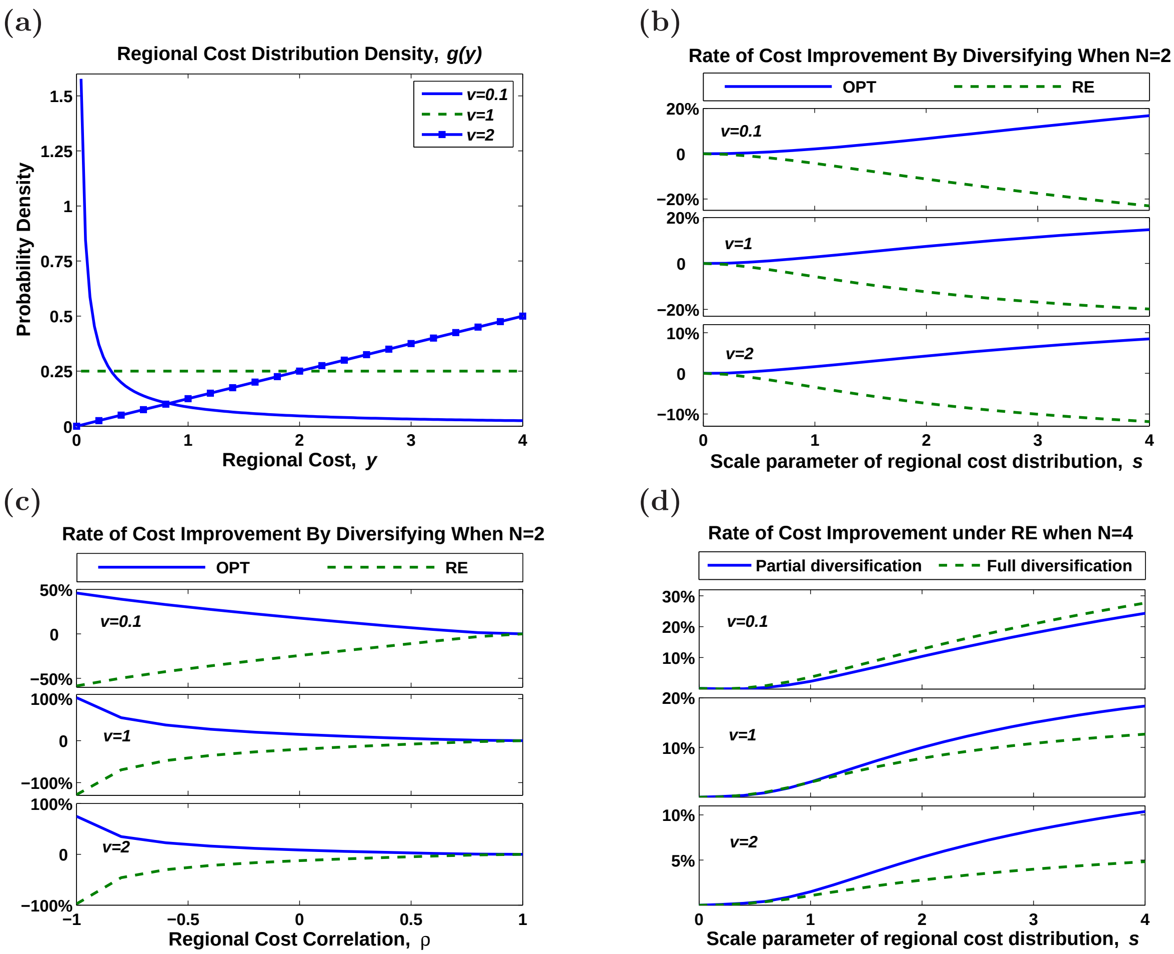

Figure 3: Panel (a) illustrates the power-function distribution's density, $g(y) = vs^{-v}y^{v-1}$, for scale parameter $s = 4$ and shape parameters $v = 0.1,\ 1,\ 2$. Panels (b)-(d) assume that suppliers' production costs follow $F \sim U[0,1]$ and regional costs follow one of the power-function distributions in Panel (a). For two suppliers, rates of cost improvement for diversifying under mechanisms OPT and RE are plotted versus scale parameter s (Panel (b)) and regional cost correlation ρ (Panel (c)). Panel (d) plots, for various scale parameters s, the cost improvement for the partial ($R = 2$) and the full ($R = 4$) diversification strategies when there are four suppliers.

where "X" could be full diversification, partial diversification, etc. All our examples assume the supplier production cost distribution $F \sim U[0,1]$. For the regional cost distribution we use members of the power-function family $G^{(s)}(y) = (\frac{y}{s})^v$, where v and s are the shape and scale parameters, respectively, and the domain of $G^{(s)}$ is $[0, s]$. Figure 3(a) illustrates the density functions of these distributions for a fixed scale parameter $s = 4$ and three shape parameters $v = 0.1, 1, 2$.

Illustration of Propositions 2-3. Figure 3(b) plots the rates of cost improvement for the diversifying strategy under mechanisms OPT and RE, for the two-supplier case. For all three regional cost distributions ($v = 0.1, 1, 2$), the rate is positive under mechanism OPT and negative under mechanism RE, confirming that diversifying is optimal under OPT (Proposition 2) and pooling is optimal under mechanism RE (Proposition 3). In all cases, the magnitude of the rate of cost improvement increases as the scale of the regional cost distribution increases. In summary, the buyer can be significantly better off by optimizing her supply base design, especially when the variation of regional costs is large relative to that of supplier production costs, i.e., when s is large.

Illustration of Proposition 5. Figure 3(c) illustrates the effect of regional cost codependence by studying a two-supplier case, in which two regions (regions 1 and 2) have correlated and identically distributed regional costs. In particular, the figure assumes region 1 has a random cost $y_1^c = \lambda y_1 + \sqrt{1-\lambda^2} y_2$ and region 2 has a random cost $y_2^c = \lambda y_2 + \sqrt{1-\lambda^2} y_1$, $\lambda \in [-\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}]$, where y_1 and y_2 are i.i.d. draws from one of the power-function distributions illustrated in Figure 3(a). Thus, y_1^c and y_2^c are identically distributed and have correlation $\rho = 2\lambda\sqrt{1-\lambda^2} \in [-1, 1]$. Figure 3(c) plots the rate of cost improvement from diversifying for various regional cost correlations ρ. Confirming Proposition 5, we see that diversifying is always optimal under mechanism OPT and pooling is always optimal under mechanism RE, no matter how the regions' costs are correlated. We also see that the magnitude of the buyer's benefit from choosing the optimal strategy decreases with the regional cost correlation. Intuitively, the buyer is indifferent between pooling and diversifying when the regional costs are perfectly positively correlated — in such a case, all regions are equivalent from a cost perspective. Indeed, we see zero cost difference when $\rho = 1$. In contrast, we see that choosing the optimal supply base design strategy is the most critical when the regional costs are perfectly negatively correlated — the case in which regional cost disparity is most significant. A buyer who uses mechanism OPT can take advantage of such regional cost disparity and hence finds it extremely beneficial to diversify her supply base; in contrast, a buyer who uses mechanism RE expects severe windfall profit-taking by advantaged suppliers and consequently finds it extremely beneficial to pool her two suppliers in the same region.

Illustration of Proposition 4. Figure 3(d) plots the rates of cost improvement for partially diversifying ($R = 2$) and fully diversifying ($R = 4$) for a setting in which the buyer uses mechanism RE and has four suppliers. Proposition 4 is verified: When the scale parameter s is large enough: (I) the pooling strategy is dominated by the partially diversifying strategy; and (II) the buyer prefers fully diversifying when the shape parameter is small, i.e., $v = 0.1$, but prefers the partially diversifying strategy when the shape parameter is larger, i.e., $v = 1, 2$. Moreover, the figure indicates that the insights of Proposition 4 can hold even when the scale parameter $s \simeq 1$, i.e., when the variation of the regional cost distribution is comparable to that of the supplier production cost distribution. However, the plots also indicate that the performance difference between the partially and fully diversifying strategies is reasonably small when the scale parameter s is small.

7. Conclusions

A buyers' total procurement cost includes not only the contract payment to a supplier, but also other costs such as transportation/logistics costs that depend on a supplier's region and are subject to regional cost shocks driven by labor strikes, regulation changes, political events, etc. To mitigate regional cost risks, a buyer seeking to minimize her total procurement cost can strategically reduce the cost correlation across suppliers by diversifying her supply base (i.e., choosing suppliers from different regions). However, in settings where the buyer's payment to her supplier is determined by a competitive bidding process (i.e., an auction), the buyer's upside benefit of diversification — having a significantly cost-advantaged supplier — can be undermined by this supplier's windfall profit-taking. This paper models the interaction between the buyer's supply-base-design strategy and the risks of windfall profit-taking by suppliers, and characterizes the optimal supply-base-design strategy under various auction mechanisms. To our knowledge, this paper is the first study of supply base design to mitigate regional cost shocks.

We find that the buyer needs to make a tradeoff between the benefit from diversifying her risk of exposure to cost shocks, and the risk that suppliers will absorb such benefits for themselves by taking windfall profits. The ability of suppliers to take windfall profits depends upon the buyer's bargaining power, that is, the buyer's ability to choose an auction mechanism to suppress supplier profits. In particular, at one extreme, when the buyer has full bargaining power and thus can impose the optimal mechanism (i.e., the optimal reserve price plus the optimal contract allocation rule that biases against cost-advantaged suppliers), windfall profit-taking is curbed and consequently the buyer finds it optimal to fully diversify her supply base (i.e., select each supplier from a different region). However, at the other extreme, when the buyer has no bargaining power and solely relies on supplier competition for price concessions (i.e., uses a reverse English auction with no reserve price), supplier windfall profit-taking can be severe and consequently the buyer diversifies less. With two suppliers she always finds it optimal to pool both suppliers in a single region. With more suppliers she prefers a blended strategy: She diversifies by using multiple regions, but keeps two suppliers per region to hedge her bets and eliminate the risk that any supplier possesses a unilateral regional cost advantage. We also study cases where the buyer has intermediate bargaining power and thus can impose a reserve price when using a reverse English auction. We find that imposing a reserve price allows the buyer to truncate large supplier profits, so when the cost shock size is likely to be large the buyer prefers fully diversifying when she can use a reserve price. Overall, buyers with strong bargaining power prefer to diversify more, while buyers with less bargaining power prefer to diversify less due to concerns about windfall profit-taking.

We find that introducing codependence across regional cost shocks generally leaves the buyer's supply base design decision unchanged, but can affect the buyer's decision when she has three or more suppliers and is susceptible to severe windfall profit-taking by advantaged suppliers (format RE). In these cases, codependence can encourage or discourage diversification, depending on whether or not it reduces the risk of an advantaged supplier emerging — that is, reduces the risk of windfall profit-taking. We also examine ex ante asymmetry across regions. Although asymmetry complicates the tactics of supply base design, it generally leaves the main strategic finding intact — namely, buyers with more bargaining power prefer to diversify more.

Our study was motivated by focusing on shocks to the buyer's "non-price" costs (transportation costs, logistics costs, etc.), but our results can easily be extended to cases where suppliers share regional cost drivers, such as costs associated with a small local labor force, regional energy market, or a common second-tier supply base. More precisely, all analyses in this paper follow if regional cost y_r is re-interpreted as a commonly known cost factor shared by all suppliers within region r.

Although we assume that the distributions capturing production costs and regional costs remain static over time, Propositions 2-3 (and their extensions Propositions 5-6) directly extend to cases where these distributions vary over time, given that these results hold regardless of production cost distribution F or regional cost distribution G. For Proposition 4, which says the optimal strategy depends on the shape of the regional cost distribution G, we suspect that the optimal supply-base design decision depends on the shape of the regional cost distribution G "on average," if G is time-variant.

We examined three auction mechanisms that are theoretically and practically important. Of course, buyers may also use other auction mechanisms or unstructured bargaining processes — for example, the buyer may negotiate with the advantaged supplier. For such cases, we suspect that the key insight of our paper will continue to apply: The more bargaining clout the buyer has to control windfall-profit taking by cost-advantaged suppliers, the more she will prefer building a diversified supply base. Our results can also extend to the cases where the buyer has only a limited number of regions to choose from; suppose there are only $\overline{R} < N$ regions available — then the buyer tends to use all $\overline{R}$ regions if fully diversifying is optimal in the unconstrained case, or tends to use $\min\{\overline{R}, \lfloor \frac{N}{2} \rfloor\}$ regions if the partially diversifying strategy is optimal in the unconstrained case. Some other extensions are possible and would also have straightforward implications, for example, imposing a fixed cost of using additional regions.

Finally, to keep our analysis focused and tractable we ignore the buyer's inventory decisions. To the extent that the buyer can anticipate regional cost shocks, she may choose to speculatively purchase inventory to avoid future cost spikes, e.g., impending logistic cost increases in a certain country. Interestingly, our analysis suggests that the usefulness of such a strategy depends on the buyer's bargaining clout. Speculative inventory might behoove a buyer with little bargaining clout, who might use it to help avoid paying windfall profits to cost advantaged suppliers. On the other hand, speculative inventory would likely be of much less benefit to a buyer with strong bargaining clout, who could contract with cost-advantaged suppliers without paying an undue price premium, thereby reducing the speculative benefits of holding inventory. We leave a detailed analysis of the interplay between inventory decisions, bargaining power and supply base design to our future work.

References

Anupindi, R. and R. Akella. 1993. Diversification under supply uncertainty. *Management Science* **39**, 944-963.

Ariba Global Services Organization. 2005. Supply watch. Quarter **3**.

Ausubel, L. M., P. Cramton, and R. J. Deneckere. 2002. Bargaining with incomplete information. In *Handbook of Game Theory with Economic Applications*, **3**, Aumann, R. J. and S. Hart (eds.), Elsevier Science Publishers.

Babich, V., A. N. Burnetas, P. H. Ritchken. 2007. Competition and diversification effects in supply chains with supplier default risk. *Manufacturing & Service Operations Management* **9**, 123-146.

Bagnoli, M., T. Bergstrom. 2005. Log-concave probability and its applications. *Economic Theory* **26**, 445-469.

Beall, S., C. Carter, P. L. Carter, T. Germer, T. Hendrick, S. D. Jap, L. Kaufmann, D. Maciejewski, R. Monczka, K. Petersen. 2003. The role of reverse auctions in strategic sourcing. Center for Advanced Procurement Studies Research.

Binmore, K., A. Rubinstein, and A. Wolinsky. 1986. The Nash bargaining solution in economic modelling. *Rand Journal of Economics*, **17**, 176-188.

Bulow, J. and P. Klemperer. 1996. Auctions versus negotiations. *The American Economic Review* **86**, 180-194.

Chen, F. 2007. Auctioning supply contracts. *Management Science* **53**, 1562-1576.

Chen, Y. and G. Vulcano. 2008. Effects of information disclosure under first- and second-price auctions in a supply chain setting. *Manufacturing & Service Operations Management* **11**, 299-316.

Costello, M. 2008. Shipping insurance cost soars with piracy surge off Somalia. *The Times*, September 11, 2008.

Dada, M., N. C. Petruzzi, and L. B. Schwarz. 2007. A newsvendor 's problem when suppliers are unreliable. *Manufacturing & Service Operations Management* **9**, 9-32.

Elmaghraby, W. 2000. Supply contract competition and sourcing policies. *Manufacturing & Service Operations Management* **2**, 350-371.

Elmaghraby, W. 2007. Auctions within e-sourcing events. *Production and Operations Management* **16**, 409-422.

Federgruen, A. and N. Yang. 2007. Optimal supply diversification under general supply risks. To appear in *Operations Research*.

Federgruen, A. and N. Yang. 2008. Selecting a portfolio of suppliers under demand and supply risks. *Operations Research* **56**, 916-936.

Grey, W., T. Olavson, and D. Shi. 2005. The role of e-marketplaces in relationship-based supply chains: A survey. *IBM Systems Journal* **44**, 109-123.

Jap, S. D. 2003. An Exploratory study of the introduction of online reverse auctions. *Journal of Marketing* **67**, 96-107.

Krishna, V. 2002. *Auction Theory*. Academic Press.

Maskin, E. and J. Riley. 2000. Asymmetric auctions. *The Review of Economic Studies* **67**, 413-438.

Milgrom, P. 2004. *Putting Auction Theory to Work*. Cambridge University Press.

Myerson, R. B. 1981. Optimal auction design. *Mathematics of Operations Research* **6**, 58-73.

Mylovanov, T., and T. Tröger. 2008. Optimal auction design and irrelevance of private information. *Working Paper.*

Nash, J. F. 1950. The bargaining problem. *Econometrica*, **18**, 155-162.

Pedersen, A. 2004. Putting a price tag on an international procurement office. *Purchasing* Oct. 7.

Rezende, L. 2009. Biased procurement auctions. *Economic Theory* **38**, 169-185.

Roth, A. 1979. *Axiomatic Models of Bargaining*. Berlin: Springer-Verlag.

Shaked, M. 1977. A concept of positive dependence for exchangeable random variables. *The Annals of Statistics.* **5**, 505-515.

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

Topkis, D. M. 1998. *Supermodularity and Complementarity*. MIT Press, Cambridge, Massachusetts.

Wan, Z. and D. R. Beil. 2009. RFQ auctions with supplier qualification screening. *Operations Research* **57**, 934-949.

Yang, Z., G. Aydin, V. Babich, and D. R. Beil. 2009. Supply disruptions, asymmetric information and a backup production option. *Management Science* **55**, 192-209.

Electronic Companion for
Bargaining Power and Supply Base Diversification

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EC.1. Proof of Proposition 1

If a supplier drops out of the auction when the calling price is higher than his true adjusted virtual cost and there is at least one other supplier staying in the auction, the supplier loses the auction and gets zero profit. In contrast, a supplier can possibly win the auction and get a positive profit by staying in the auction until the calling price reaches his true adjusted virtual cost. Thus, dropping out of the auction before the calling price reaches his true adjusted virtual cost is a dominated strategy for the supplier.

If a supplier stays in the auction when the calling price falls below his true adjusted virtual cost, it is possible that he wins the auction. However, in such a case his payment will be below his production cost and he will earn negative profit. Thus, staying in the auction when the calling price falls below the true adjusted virtual cost is a dominated strategy for the supplier.

Therefore, it is a dominant strategy for each supplier to stay in the auction until the calling price reaches his true adjusted virtual cost. Consequently, the optimal mechanism is implemented: The supplier with the lowest adjusted virtual cost will win the auction and will be paid exactly as the optimal mechanism's payment rule specifies.

EC.2. Proof of Lemma 1

The expected difference between the total procurement cost under the R-region strategy and that under the $(R+1)$-region strategy equals

$$\frac{1}{2}\underset{(\boldsymbol{x},\boldsymbol{y})}{E}\left[\pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{hh}})-\pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{hl}})+\pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{ll}})-\pi^{Mech}(\boldsymbol{x},\boldsymbol{a}^{\boldsymbol{lh}})\right]. \tag{EC.1}$$

Note that $\boldsymbol{a}^{\boldsymbol{hh}}=\boldsymbol{a}^{\boldsymbol{hl}}\vee\boldsymbol{a}^{\boldsymbol{lh}}$ and $\boldsymbol{a}^{\boldsymbol{ll}}=\boldsymbol{a}^{\boldsymbol{hl}}\wedge\boldsymbol{a}^{\boldsymbol{lh}}$. Therefore, the lemma follows from the definitions of supermodular and submodular functions.

EC.3. Proof of Proposition 2

The fact that $\pi^{OPT}(\boldsymbol{x}, \boldsymbol{a}) = \min_{i=1,\ldots,N}\{\psi(x_i) + a_i\}$ implies that, for any $\hat{\boldsymbol{a}}$ and $\tilde{\boldsymbol{a}}$, we have that $\pi^{OPT}(\boldsymbol{x}, \hat{\boldsymbol{a}} \wedge \tilde{\boldsymbol{a}}) = \pi^{OPT}(\boldsymbol{x}, \hat{\boldsymbol{a}}) \wedge \pi^{OPT}(\boldsymbol{x}, \tilde{\boldsymbol{a}})$ and $\pi^{OPT}(\boldsymbol{x}, \hat{\boldsymbol{a}} \vee \tilde{\boldsymbol{a}}) \geq \pi^{OPT}(\boldsymbol{x}, \hat{\boldsymbol{a}}) \vee \pi^{OPT}(\boldsymbol{x}, \tilde{\boldsymbol{a}})$. Thus, $\pi^{OPT}(\boldsymbol{x}, \boldsymbol{a})$ is supermodular in $\boldsymbol{a}$ for any $\boldsymbol{x}$. Therefore, the proposition follows from Lemma 1.

EC.4. Proof of Proposition 3

When $N = 2$, we have $\pi^{RE}(\boldsymbol{x}, \boldsymbol{a}) = \max\{x_1 + a_1,\, x_2 + a_2\}$. It implies that, for any $\hat{\boldsymbol{a}}$ and $\tilde{\boldsymbol{a}}$, we have $\pi^{RE}(\boldsymbol{x}, \hat{\boldsymbol{a}} \vee \tilde{\boldsymbol{a}}) = \pi^{RE}(\boldsymbol{x}, \hat{\boldsymbol{a}}) \vee \pi^{RE}(\boldsymbol{x}, \tilde{\boldsymbol{a}})$ and $\pi^{RE}(\boldsymbol{x}, \hat{\boldsymbol{a}} \wedge \tilde{\boldsymbol{a}}) \leq \pi^{RE}(\boldsymbol{x}, \hat{\boldsymbol{a}}) \wedge \pi^{RE}(\boldsymbol{x}, \tilde{\boldsymbol{a}})$. Thus, $\pi^{RE}(\boldsymbol{x}, \boldsymbol{a})$ is submodular in $\boldsymbol{a}$ for any $\boldsymbol{x}$. Therefore, the proposition follows from Lemma 1.

EC.5. Proof of Proposition 4

It is equivalent to prove the proposition by considering a family of models $\{(F^{(s)}, G), s \in \mathbb{R}^+\}$, where $F^{(s)}(x) \overset{def}{=} F(sx)$. As s goes to infinity, the probability mass of $F^{(s)}$ collects near zero (i.e., for any small $\epsilon > 0$, $s > \epsilon^{-1}$ implies $F^{(s)}(\epsilon) = 1$). Therefore, as s goes to infinity, production costs become negligible and the buyer's expected total procurement cost approaches $E_{\boldsymbol{y}}[\text{second} \min_{i=1,\ldots,N}\{a_i\}]$. We first characterize the buyer's preference for this limiting case. In this limiting case, the buyer's expected total procurement cost equals $\overline{Y}_{1:R}$ if she uses $R \leq \lfloor \frac{N}{2} \rfloor$ regions with at least two suppliers in each. The partially diversifying strategy that has $\lfloor \frac{N}{2} \rfloor$ regions with at least two suppliers each dominates any strategy with fewer regions, since $\overline{Y}_{1:R}$ decreases in R. Because the buyer's expected total procurement cost equals $\overline{Y}_{2:N}$ if she fully diversifies, she prefers the partially diversifying strategy to the fully diversifying strategy if $\overline{Y}_{2:N} > \overline{Y}_{1:\lfloor \frac{N}{2} \rfloor}$; in the reverse case, full diversification is preferred. Because the expected total-cost function is continuous in s, the preference characterization for this limiting case also holds when s is sufficiently large.

EC.6. Proof of Equation (3)

We have $\overline{Y}_{1:\lfloor \frac{N}{2} \rfloor} = \int_{-\infty}^{\infty} \bar{G}^{\lfloor \frac{N}{2} \rfloor}(y)dy$ because the tail probability $\Pr(Y_{1:R} > z) = \Pr(y_r > z, r = 1, \ldots, R) = \bar{G}^R(z)$. We have $\overline{Y}_{2:N} = \int_{-\infty}^{\infty} \left[N\bar{G}^{N-1}(y) - (N-1)\bar{G}^N(y)\right] dy$ because the tail probability $\Pr(Y_{2:R} > z) = \Pr(y_r > z,$ for all $r \in \{1, \ldots, R\}) + \Pr(y_{\hat{r}} \leq z$ for an $\hat{r} \in \{1, \ldots, R\}, y_r > z,$ for all $r \in \{1, \ldots, R\} \setminus \{\hat{r}\}) = \bar{G}^R(z) + RG(z)\bar{G}^{R-1}(z) = R\bar{G}^{R-1}(z) - (R-1)\bar{G}^R(z)$.

EC.7. Proof of Corollary 1

When the regional costs are independent draws from a power-function distribution $G^{(s)}(y) = s^{-v}y^v$ with scale parameter $s > 0$ and shape parameter $v > 0$, we have $\overline{Y}_{1:R} = \frac{s\Gamma(R+1)\Gamma(1+1/v)}{\Gamma(R+1+1/v)}$ and $\overline{Y}_{2:R} = \frac{s\Gamma(R+1)\Gamma(2+1/v)}{\Gamma(R+1+1/v)}$; see Malik (1967). Thus, for $N \geq 4$ even, we have

$$\frac{\overline{Y}_{1:\frac{N}{2}}}{\overline{Y}_{2:N}} = \frac{(N+1/v)(N-1+1/v)\cdots(N/2+1+1/v)}{(1+1/v)N(N-1)\cdots(N/2+1)}.$$

We now show that there exists a threshold $\underline{v} > 0$ such that the above fraction is greater than 1 when $v < \underline{v}$ and less than 1 when $v > \underline{v}$. To see this, note that the numerator minus the denominator can be written as $-b_1v^{-1} + b_2v^{-2} + \ldots + b_{\frac{N}{2}}v^{-\frac{N}{2}}$ with $b_1, \ldots, b_{\frac{N}{2}} > 0$. Thus, the threshold $\underline{v}$ is the unique positive root of $b_1 = b_2v^{-1} + \ldots + b_{\frac{N}{2}}v^{-\frac{N}{2}+1}$. Note $\underline{v}$ is unique because $b_2v^{-1} + \ldots + b_{\frac{N}{2}}v^{-\frac{N}{2}+1}$ is strictly decreasing, approaches positive infinity as v approaches zero, and approaches zero as v approaches positive infinity. For $N \geq 3$ odd, we can similarly prove that $\overline{Y}_{1:\frac{N-1}{2}}/\overline{Y}_{2:N}$ is greater (less) than 1 if v is greater (less) than a threshold $\underline{v} > 0$. Thus the result holds.

EC.8. Proof of Proposition 5

In the presence of regional codependence, Propositions 2-3 still hold because the proof of Lemma 1 does not assume that regions are independent. To see this, note that the sign of equation (EC.1) is not affected by the distribution of $\boldsymbol{y}$ if $\pi^{Mech}(\boldsymbol{x}, \boldsymbol{a})$ is supermodular or submodular in $\boldsymbol{a}$ for all $\boldsymbol{x}$.

EC.9. Proof of Proposition 6

Note that the buyer's total procurement cost equals $\max\{x_1 + a_1, x_2 + a_2\}$ under mechanism RE. Thus, if the buyer has one supplier in region 1 and one supplier in region 2, the expected total cost equals $\int z dH_1(z)H_2(z)$; if the buyer uses two copies of region k, $k = 1, 2$, the expected total cost equals $\int z dH_k(z)H_k(z)$. The diversification strategy that has one supplier in region 1 and one supplier in region 2 is dominated by either or both of the diversification strategies that use two copies of region k, $k = 1, 2$, because

$$\begin{aligned} & 2\int_{-\infty}^{\infty} z dH_1(z)H_2(z) - \int_{-\infty}^{\infty} z dH_1(z)H_1(z) - \int_{-\infty}^{\infty} z dH_2(z)H_2(z) \\ = & -\int_{-\infty}^{\infty} z d[H_1(z) - H_2(z)]^2 = \int_{-\infty}^{\infty} [H_1(z) - H_2(z)]^2 dz > 0, \end{aligned}$$

where the last equality uses integration by parts and the fact that $H_1(-\infty) = H_2(-\infty) = 0$ and $H_1(\infty) = H_2(\infty) = 1$. The proposition follows because the buyer prefers pooling to diversifying with two symmetric regions (per Proposition 3).

EC.10. Proof of Proposition 7

When the buyer uses mechanism OPT, it is optimal to select all suppliers from different regions even when regions are asymmetric, because any R-region strategy having $n_r \geq 2$ suppliers in some region r is dominated by the $(R+1)$-region strategy having $n_r - 1$ suppliers in region r and one supplier in an $(R+1)^{\text{st}}$ region which is of the same type as region r. This is true because the proof of Lemma 1 is still valid given that the distributions of $\boldsymbol{x}$ and $\boldsymbol{y}$ are the same under both the R-region strategy and the $(R+1)$-region strategy.

EC.11. Proof of Lemma 2

With $N = 2$ suppliers, the buyer's total cost under RER equals

$$\pi^{RER}(\boldsymbol{x}, \boldsymbol{a}) = [(x_1 + a_1) \vee (x_2 + a_2)] \wedge (1 + a_1) \wedge (1 + a_2).$$

$$\begin{aligned}
\text{Thus,} \quad \pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{hh}}) &= x_1 \vee x_2 + y_1 \vee y_2, \\
\pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{ll}}) &= x_1 \vee x_2 + y_1 \wedge y_2, \\
\pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{hl}}) &= 1 \wedge [(x_1 + |y_1 - y_2|) \vee x_2] + y_1 \wedge y_2, \\
\pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{lh}}) &= 1 \wedge [(x_2 + |y_1 - y_2|) \vee x_1] + y_1 \wedge y_2.
\end{aligned}$$

$$\begin{aligned}
&\text{Hence, } \pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{hh}}) - \pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{hl}}) + \pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{ll}}) - \pi^{RER}(\boldsymbol{x}, \boldsymbol{a^{lh}}) \\
&= 2(x_1 \vee x_2) + |y_1 - y_2| - \{1 \wedge [(x_1 + |y_1 - y_2|) \vee x_2]\} - \{1 \wedge [(x_2 + |y_1 - y_2|) \vee x_1]\}. \qquad \text{(EC.2)}
\end{aligned}$$

Assuming without loss of generality that $x_1 \geq x_2$, equation (EC.2) equals

- $0 \cdot \mathbb{I}(|y_1 - y_2| \in [0, x_1 - x_2]) + (x_1 - x_2 - |y_1 - y_2|) \cdot \mathbb{I}(|y_1 - y_2| \in (x_1 - x_2, 1 - x_1]) + (2x_1 - x_2 - 1) \cdot \mathbb{I}(|y_1 - y_2| \in (1 - x_1, 1 - x_2]) + (2x_1 + |y_1 - y_2| - 2) \cdot \mathbb{I}(|y_1 - y_2| \in (1 - x_2, \infty))$, if $2x_1 - x_2 - 1 \leq 0$;

- $0 \cdot \mathbb{I}(|y_1 - y_2| \in [0, 1 - x_1]) + (x_1 + |y_1 - y_2| - 1) \cdot \mathbb{I}(|y_1 - y_2| \in (1 - x_1, x_1 - x_2]) + (2x_1 - x_2 - 1) \cdot \mathbb{I}(|y_1 - y_2| \in (x_1 - x_2, 1 - x_2]) + (2x_1 + |y_1 - y_2| - 2) \cdot \mathbb{I}(|y_1 - y_2| \in (1 - x_2, \infty))$, if $2x_1 - x_2 - 1 > 0$.

This implies that equation (EC.2) is non-positive if $|y_1 - y_2| < (1 - x_1)$, is non-negative if $|y_1 - y_2| \geq 2(1 - x_1)$, and is non-positive if $2x_1 - x_2 - 1 \leq 0$ (this latter condition is always satisfied when $x_1 \leq \frac{1}{2}$) and $|y_1 - y_2| < 2(1 - x_1)$. The lemma thus follows.

EC.12. Proof of Proposition 8

Two-supplier case. Assuming without loss of generality that $x_1 \geq x_2$, equation (EC.2) is greater than $(2x_1 - x_2 - 1) \cdot \mathbb{I}(|y_1 - y_2| \leq 2 - 2x_1) + [|y_1 - y_2| - (2 - 2x_1)] \cdot \mathbb{I}(|y_1 - y_2| > 2 - 2x_1)$ when $2x_1 - x_2 - 1 < 0$, and it is greater than $[|y_1 - y_2| - (2 - 2x_1)] \cdot \mathbb{I}(|y_1 - y_2| > 2 - 2x_1)$ when $2x_1 - x_2 - 1 \geq 0$. Thus, the expectation of equation (EC.2) over the distribution of $|y_1 - y_2|$ is greater than $\min\{2x_1 - x_2 - 1, 0\} \Pr(|y_1 - y_2| \leq 2 - 2x_1) + E[|y_1 - y_2| - (2 - 2x_1)||y_1 - y_2| > (2 - 2x_1)] \Pr(|y_1 - y_2| > 2 - 2x_1)$, which is greater than $E[|y_1 - y_2|] - 1 - (2 - 2x_1) \geq E[|y_1 - y_2|] - 3$. This implies that it is optimal to diversify if $E[|y_1 - y_2|] \geq 3$.

$N \geq 3$ **supplier case.** As in Proposition 4's proof, it is equivalent to consider a family of models $\{(F^{(s)}, G), s \in \mathbb{R}^+\}$, where $F^{(s)}(x) \stackrel{def}{=} F(sx)$. In such a case, the buyer using RER has an expected total procurement cost $E_{\boldsymbol{x},\boldsymbol{y}}[\underset{i=1,\ldots,N}{\text{second min}}\{\frac{x_i}{s} + a_i, \frac{1}{s} + a_i\}]$, which approaches $E_{\boldsymbol{y}}[\min_{i=1,\ldots,N}\{a_i\}]$ as s approaches infinity. In this limiting case the buyer's expected total procurement cost is minimized by the fully diversifying strategy, because (as is easy to show) $\min_{i=1,\ldots,N}\{a_i\}$ is supermodular in $\boldsymbol{a}$. Because the expected total-cost function is continuous in s, the preference characterization for this limiting case also holds when s is sufficiently large.

References

Malik, H. J. 1967. Exact moments of order statistics from a power-function distribution. *Skand. Aktuarietidskr.* **50**, 64 - 69.