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Supply diversification with isoelastic demand

Tao Li [a], Suresh P. Sethi [b,*], Jun Zhang [c]

[a] Leavey School of Business, Santa Clara University, Santa Clara, CA 95053, United States
[b] Naveen Jindal School of Management, The University of Texas at Dallas, Richardson, TX 75080, United States
[c] School of Management, Fudan University, Shanghai 200433, China

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ABSTRACT

We study a firm's sourcing strategy when facing two unreliable suppliers and a price-dependent isoelastic demand. At optimality, the firm always orders at least from the low-cost supplier. The firm also orders from the high-cost supplier if and only if the effective purchase cost from the low-cost supplier is greater than the actual purchase cost from the high-cost supplier. We also find that when the firm orders from both suppliers, the total order quantity decreases as the correlation between the suppliers' capacities increases.

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1. Introduction

We study a firm's optimal sourcing strategy with two suppliers for a product. The suppliers may be unreliable due to their random capacities. The demand for the product is deterministic and price dependent with constant elasticity. We show that the cost-first-reliability-second (CFRS) decision rule continues to be optimal when deciding which supplier to source from, as in Hill (2000), Anupindi and Akella (1993), Dada et al. (2007), Federgruen and Yang (2009, 2011), and Li et al. (2013). Moreover, whether the firm should diversify (order from both suppliers) depends on how low the cost of high-cost supplier is in comparison to the cost of the low-cost supplier, but not on the correlation structure between the suppliers' capacities. The capacity correlation only affects the order quantities when the optimal sourcing strategy is to diversify. As the suppliers' capacities become more correlated in the sense of the supermodular order, the firm's optimal total order quantity decreases. These results corroborate those obtained with deterministic linear demand (Li et al., 2013) as well as price-independent stochastic demand (Dada et al., 2007). Therefore, our paper provides evidence toward the robustness of the results with respect to demand specifications.

A firm's optimal sourcing strategy with unreliable suppliers has been widely studied; see, for example, Gerchak and Parlar (1990), Ramasesh et al. (1991), and Parlar and Wang (1993). Recently, the firm's pricing decision has been taken into consideration in exploring the optimal sourcing strategy with supply uncertainty. Tang and Yin (2007) study the benefit of responsive pricing with supply uncertainty. Interestingly, when the firm can price its product based on the supplier's capacity realization, the CFRS sourcing rule may not yield the optimal supplier set. For example, Feng and Shi (2012) demonstrate that the CFRS rule is no longer optimal when the firm can adjust prices dynamically. Li et al. (2013) show that the CFRS sourcing rule is not optimal when there are more than two suppliers and their capacities are correlated.

Whereas Li et al. (2013) assume a demand linear in price primarily for tractability, we consider a more realistic isoelastic demand having a great deal of empirical support. Indeed, the extant literature is replete with empirical estimation of demand functions for a wide variety of products including food items (such as soft drinks or juices) and nonfood items (such as detergents or paper towels), where we find that the functions estimated are often isoelastic, and seldom linear, in price. See, e.g., Tellis (1988), Mulhern and Leone (1991), and Hoch et al. (1995). According to Mulhern and Leone (1991), linear demand models have the undesirable property of having lower elasticities for deeply discounted prices, and modeling price/quantity relationships using them is erroneous. Not surprisingly, we see a wide use of isoelastic demands in the production economics literature as can be seen in the papers of Petruzzi and Dada (1999), Tramontana (2010), Wang et al. (2012), and Nilsen (2013).

Our use of an isoelastic demand also finds its justification in observations made by Lau and Lau (2003) that different demand-curve functions can lead to very different results in a multi-echelon system and that, in some situations, a very small change in the demand-curve appearance can lead to large changes in the optimal solutions for the system. Shi et al. (2013) argue that the form of the demand function may affect firm's operational strategies significantly. Since Li et al. (2013) derive firm's sourcing strategy under a linear demand, it is important to show if the

* Corresponding author.
E-mail addresses: tli1@scu.edu (T. Li), sethi@utdallas.edu (S.P. Sethi), jzhang4@gmail.com (J. Zhang).

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insights obtained there hold for the more realistic but less tractable isoelastic demand. By showing that they do, this paper testifies for the robustness of the results obtained in Li et al. (2013).

2. Model

Consider a firm that may order a product from two suppliers to sell to customers in a single selling season. Supplier i $(i=1,2)$ has a random capacity R_i. On an order of quantity Q_i by the firm from supplier i, the supplier's deliver quantity is $\min\{Q_i, R_i\}$. We assume that R_i has the distribution function $G_i(r)$ and the corresponding density function $g_i(r) \geq 0$ for $r>0$. Denote $\overline{G}_i(r) \equiv 1-G_i(r)$ and $g(r_1,r_2)$ as the joint probability density function of (R_1,R_2).

The selling season consists of two stages. In the first stage, the firm orders Q_i from supplier i and receives $S_i(Q_i)=\min\{Q_i,R_i\}$ at the end of the first stage. Denote $\mathbf{Q} \equiv (Q_1,Q_2)$ as the vector of the order quantities. Let $S(\mathbf{Q})=S_1(Q_1)+S_2(Q_2)$ denote the total delivered quantity. The firm pays a supplier only for the quantity delivered at the unit purchase cost c_i. In the second stage, based on the total delivered quantity $S(\mathbf{Q})$, the firm decides the unit retail price p for the product. We assume the demand to be price-dependent and isoelastic, that is, $D(p)=ap^{-b}$ with $a>0$ and $b>1$. Unsold products are salvaged at a unit price $\gamma < c_i$ and the cost of lost goodwill is δ for each unit of unsatisfied demand. We assume that the firm has pricing power and is therefore able to adjust the retail price depending on the amount delivered from the suppliers. On the other hand, the wholesale prices are specified in purchase contracts signed with the suppliers before the supply uncertainty is resolved. Possible examples are those of a big food processor/retailer purchasing product from small farmers whose yields depend on weather and a multinational corporation purchasing from fringe overseas suppliers subject to disruptions in shipping their products. In a year when the delivered amount is low, the food processor can adjust the retail price while the farmers cannot as they have contractually agreed to supply at the wholesale prices determined before the yields are realized. In the second example, it is relatively easier for the multinational to adjust its retail price than it is for the overseas suppliers to adjust their wholesale prices.

The firm's objective is to choose the order quantities $\mathbf{Q}$ in the first stage and the retail price p in the second stage to maximize its expected profit $\Pi(\mathbf{Q})$, which is equal to its expected second-stage profit $E[\Pi_2(\mathbf{Q})]$ less its expected purchase cost in the first stage. Consequently, the firm's problem can be formulated as follows:

$$\max_{\mathbf{Q}\geq 0}\left\{\Pi(\mathbf{Q})=E\left[\Pi_2(\mathbf{Q})-\sum_{i=1}^{2}c_iS_i(Q_i)\right]\right\}, \tag{1}$$

where

$$\Pi_2(\mathbf{Q})=\max_{p\geq 0}\pi(p)=p\cdot\min\{D(p),S(\mathbf{Q})\}+\gamma\cdot(S(\mathbf{Q})-D(p))^+ -\delta\cdot(D(p)-S(\mathbf{Q}))^+. \tag{2}$$

In this formulation, the firm's second-stage profit is equal to the sum of its sales and salvage revenues from any leftover products, or equal to its sales revenue less the shortage cost.

3. Analysis

We first solve the firm's second-stage problem to obtain the optimal retail price for a given total delivered quantity S. From (2), we see that $\pi(p)$ is strictly concave and the optimal retail price for a given S is

$$p^*=\begin{cases}\dfrac{b\gamma}{b-1} & \text{if } S\geq a\left(\dfrac{b\gamma}{b-1}\right)^{-b},\\ \left(\dfrac{S}{a}\right)^{-1/b} & \text{otherwise.}\end{cases} \tag{3}$$

That is, when the total delivery is less than $a(b\gamma/(b-1))^{-b}$, the firm sets the price to sell all. Otherwise, the firm sets the price at $b\gamma/(b-1)$ and salvages the leftover products. In our analysis, the quantity $a(b\gamma/(b-1))^{-b}$ plays a significant role; let $A\equiv a(b\gamma/(b-1))^{-b}$. Let $f_{\mathbf{Q}}(s)$ be the conditional density of the random variable S given $\mathbf{Q}$. By (1) and (3), the firm's first-stage problem can be reformulated as follows:

$$\max_{\mathbf{Q}\geq 0}\Pi(\mathbf{Q})=\int_0^A s\left(\frac{s}{a}\right)^{-1/b}f_{\mathbf{Q}}(s)\,ds+\int_A^\infty\frac{\gamma(A-s+bs)}{b-1}f_{\mathbf{Q}}(s)\,ds-\sum_{i=1}^{2}c_iE[S_i(Q_i)]. \tag{4}$$

Note that the firm never sells more than A units of the product in total. Consequently, the optimal order quantity must satisfy $Q_1\leq A$ and $Q_2\leq A$. As can be seen from Eq. (4), $\Pi(\mathbf{Q})$ has different expressions for $Q_1+Q_2\leq A$ and $Q_1+Q_2>A$. So the optimal order quantities are obtained by first finding the best order quantities under either of these two conditions and then selecting the better ones.

Denote $(\overline{Q}_1,\overline{Q}_2)$ as the solutions to the first-order condition for $Q_1+Q_2\leq A$:

$$\overline{G}_i(Q_i)\left[(Q_i+Q_{3-i})^{-1/b}-\frac{bc_i}{b-1}a^{-1/b}\right]+\int_0^{Q_{3-i}}\int_{Q_i}^\infty\left[(Q_i+r_{3-i})^{-1/b}-(Q_i+Q_{3-i})^{-1/b}\right]g(r_1,r_2)\,dr_i\,dr_{3-i}=0\quad\text{for } i=1,2. \tag{5}$$

Similarly, denote $\widehat{Q}_i$ $(i=1,2)$ as the solution to the first-order condition for $Q_1+Q_2>A$:

$$\frac{b-1}{b}a^{1/b}\int_0^{A-Q_i}\int_{Q_i}^\infty\left[(Q_i+r_{3-i})^{-1/b}-A^{-1/b}\right]g(r_1,r_2)\,dr_i\,dr_{3-i}-(c_i-\gamma)\overline{G}_i(Q_i)=0\quad\text{for } i=1,2. \tag{6}$$

Define $h_i(\cdot)=g_i(\cdot)/(1-G_i(\cdot))$ as the hazard rate function of R_i. To ensure that the profit function is unimodal, we make some assumptions specified in the following lemma. All proofs are relegated to the appendix.

Lemma 1 (*Unimodality conditions*). *Assume that*

$$\int_0^{\overline{Q}_{3-i}}\int_{\overline{Q}_i}^\infty(\overline{Q}_i+r_{3-i})^{-1/b-1}g(r_1,r_2)\,dr_i\,dr_{3-i}+b\int_0^{\overline{Q}_{3-i}}\left[(\overline{Q}_i+r_{3-i})^{-1/b}-(\overline{Q}_i+\overline{Q}_{3-i})^{-1/b}\right]g(\mathbf{x}^i)\,dr_{3-i}-bh_i(\overline{Q}_i)\int_0^{\overline{Q}_{3-i}}\int_{\overline{Q}_i}^\infty\left[(\overline{Q}_i+r_{3-i})^{-1/b}-(\overline{Q}_i+\overline{Q}_{3-i})^{-1/b}\right]g(r_1,r_2)\,dr_i\,dr_{3-i}\geq 0, \tag{7}$$

$$a\int_0^{A-\widehat{Q}_i}\int_{\widehat{Q}_i}^\infty(\widehat{Q}_i+r_{3-i})^{-1/b-1}g(r_1,r_2)\,dr_i\,dr_{3-i}+b\int_0^{A-\widehat{Q}_i}\left[(\widehat{Q}_i+r_{3-i})^{-1/b}-A^{-1/b}\right]g(\mathbf{x}^i)\,dr_{3-i}-bh_i(\widehat{Q}_i)\int_0^{A-\widehat{Q}_i}\int_{\widehat{Q}_i}^\infty\left[(\widehat{Q}_i+r_{3-i})^{-1/b}\right.$$

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