Assuring Available Production Capacity During Supply Channel Selection

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Choosing a supply channel amounts to choosing the limits of a new product's profitability. However, organizations may not have sufficient information to choose upstream supply chain partners optimally. We consider an original equipment manufacturer (OEM) outsourcing production of a new make-to-order product to a pre-qualified contract manufacturer. In addition, the contract manufacturer may select his own supplier for a key component of the OEM's product. We show that competition gives profit maximizing firms an incentive to misreport available production capacity. We then devise request for quotation (RFQ) design strategies that induce firms to credibly relay supply channel capacity information.

INTRODUCTION

As outsourcing activity continues to intensify, high quality vendor selection becomes more critical for the effective and efficient functioning of a supply chain (Murthy et al. 2004, Wang et al. 2010). Furthermore, credibility of vendor information is an important concern during supply channel selection. Jap (2002, 2003) describes uncertainty in whether a vendor will actually dedicate existing capacity to its downstream partner. We demonstrate difficulties in obtaining accurate reports of available production capacity during supply channel selection and find strategies for resolving this issue.

We focus on an original equipment manufacturer (OEM) who conducts a standard sealed bid reverse auction to choose a single contract manufacturer (CM) for a new make-to-order product. The stimulus for the reverse auction is the submission of a request for quotation (RFQ) to several pre-qualified vendors. The RFQ describes how bids translate into a contract between the buying firm and the winning bidder. We assume throughout that the firms in our model are expected profit maximizers, so vendors compete with the objective of offering the largest expected profit for the downstream firm. Then, vendors quote both price and available production capacity to meet a competitive lead time specified in the RFQ. The latter parameter is considered particularly important in just-in-time or make-to-order operations (Weber et al. 1991, Elmaghraby 2000, Dekkers 2002, Murthy et al. 2004).

We explore mechanisms of both shortfall penalties and upside risk sharing in obtaining truthful capacity quotes. While an upstream partner may be taken to court for not delivering on quoted available production capacity, creating incentives for truthful information sharing supersedes going to court for two reasons. First, whether or not inaccurate quoting is intentional may be difficult to prove. Including an appropriate mechanism in an RFQ and, hence, in the final contract between two firms, makes the terms of the relationship explicit and reduces legal expenses. Second, this practice favors ongoing strategic business relationships, particularly ones in which a discrepancy in available production capacity may be unintentional.

We next extend our model to consider a three firm supply chain, where the OEM selects a CM, and each candidate CM also selects an upstream supplier. Procurement outsourcing is a much deliberated topic in industry. The length of an outsourcing supply chain generates increasing uncertainty both in demand for an upstream supplier and in supply for an OEM (Agrell et al. 2004). Fearing loss of competitive advantage or key supplier relationships, large companies like Motorola and HP prefer to keep strategic sourcing and price negotiation with suppliers in-house (Jorgensen 2003, 2004, Smock 2004, Amaral et al. 2006, Kayis et al. 2012). Nevertheless, many OEMs allow CMs to handle the strategic sourcing of standard lower value parts (Liston et al. 2008), possibly to leverage lower component prices through quantity buys (Carbone 2000, 2001). Many papers suggest that delegation stems from limitations in the resources necessary for communication and information processing (Melumad et al. 1992, Radner 1993, Laffont and Martimort 1998, Van Zandt and Radner 2001). Regardless of the outcome of this debate, another fundamental issue exists. In this paper, we determine whether or not delegating supplier selection authority to competing CMs reduces an OEM's ability to obtain credible supply channel capacity information.

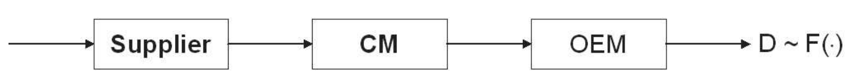
Our model insights do not hinge upon determining equilibrium bidding strategies for competing CMs or suppliers. Jap (2003) asserts that, unlike the assumptions of theoretical literature, "suppliers in the marketplace may not understand how competitive their offer is." In addition, theoretically, no equilibrium may exist for our sealed bid auction with a standard tie-breaking rule and discrete set of possible capacity levels (Hansen 1988, Maskin and Riley 1985, 2000). Hence, we make no assumptions concerning a CM's rationality or his knowledge about either his competitors' business or even how many competitors he has. Instead, we focus on the goal of maximizing expected profit and on how this goal translates into an incentive to exaggerate available production capacity.

We organize the remainder of this paper as follows. In Section 2, we describe the supply chain selection problem and define the objectives of participating firms. In Section 3, we establish an effective RFQ design strategy to elicit credible capacity information when the OEM utilizes an existing supplier relationship. In Section 4, we do the same for the case in which the OEM delegates supplier selection to the CMs. In Section 5, we summarize our results and provide some concluding remarks.

SUPPLY CHAIN SELECTION PROBLEM

We consider the problem of an original equipment manufacturer (OEM) establishing a supply chain for the production of a new make-to-order product. Once in place, the supply chain appears as in Figure 1. The OEM outsources production of the make-to-order product to a contract manufacturer (CM). The CM, in turn, outsources production of a key component to an independent supplier. Both CM and OEM requests for quotation generate bids of unit price and available production capacity. The CM chooses his component supplier, and the OEM selects a supply channel composed of a CM-supplier pair. Next, we introduce cost and capacity parameters for an established supply chain.

FIGURE 1
DEDICATED SUPPLY CHAIN FOR MAKE-TO-ORDER PRODUCT



Problem Parameters

The supplier of Figure 1 is chosen from among all suppliers in the industry *qualified* to produce the key component for the OEM's make-to-order product. By qualified, we mean that this supplier has the technology, expertise, and quality certifications indicating ability to produce the component to CM, OEM, and customer specifications. Materials and processing techniques well-known to such qualified suppliers results in a unit production cost of c^s per component. Furthermore, the supplier can produce up to K^S within the supply chain's necessary order-to-delivery time. Before production begins, the supplier and the

CM sign a contract under which the CM agrees to pay unit price w^S for all components he procures. Also under this contract, both firms commit to preparing production capacity $K = min(K^C,K^S)$. Here, K^C is the CM's limit on the number of make-to-order units he can complete within the supply chain's necessary order-to-delivery time, considering both his own production time and his wait time to receive components from the supplier. Note that available production capacity is not a decision variable in this supply chain.

The CM in Figure 1 is one of several CMs qualified to produce the OEM's make-to-order product, where we define *qualified* as for the supplier. Materials and processing techniques well-known among qualified CMs yield unit production cost c^C, which does not include procurement cost for the key component. The CM signs a contract with the OEM, under which the OEM agrees to pay unit price w^C for up to K units of the make-to-order product.

The OEM in Figure 1 has a new product line to compete in a make-to-order market, so order-to-delivery time is a critical competitive factor. We assume the OEM has previously conducted market research to determine unit selling price r that generates nonnegative demand D distributed according to $f(\cdot)$ with mean $E[D]$. However, if D exceeds what the supply chain can produce within an order-to-delivery time defined by the competitive market, customers choose to go elsewhere rather than wait. As a result, the OEM experiences *upside risk*, a potential loss when demand exceeds available production capacity K. Lost sales come with a unit goodwill cost $g^O \geq 0$, which could represent compensation or the OEM's cost of providing a substitute product at a loss to herself.

An RFQ may specify additional quotation parameters that become part of the contract between two members of the final supply chain. Without additional parameters, the expected profit functions for the supplier, CM, and OEM are shown in (1).

$$\begin{aligned}
&\Pi^S(w^S,K) = (w^S - c^S)E[min(D,K)] \\
&\Pi^C(w^S,w^C,K) = (w^C - w^S - c^C)E[min(D,K)] \\
&\Pi^O(w^C,K) = (r - w^C)E[min(D,K)] - g^O(E[D] - E[min(D,K)])
\end{aligned} \tag{1}$$

A CM or a supplier determines the existing production capacity available to conduct business with the OEM. We express K^C and K^S in units of the OEM's product and constrain the set of possible available production capacities to $\{K_1,\ldots,K_m\}$, where $K_{i+1} = K_i + k$ for $i \in \{1,\ldots,m - 1\}$. The value of k represents a natural batch size or run size due to processing equipment or other resource requirements. We assume that lower bound K_1 is a minimum capacity requirement to justify resource or equipment allocation and that upper bound K_m is an estimate of the total relevant capacity at any CM or supplier.

Firm Objectives

Central to our analysis is comprehension of two possibly conflicting goals that each CM and each supplier faces when submitting a quotation: *profitability* and *competitiveness*. We describe these goals and their impacts as follows.

Profitability

We assume that the OEM, candidate CMs, and candidate suppliers in the supply channel selection problem each wish to maximize expected profit from the make-to-order product. When submitting a quotation, the CM wants to maximize his expected profit if he wins the OEM's business. We define *profitability* as the value of this potential expected profit.

From Equation (1), the following observations are immediately apparent. All firms in the make-to-order supply chain earn higher expected profits when the supply channel has larger available production capacity K. The CM wants a higher unit price w^C, while the OEM wants w^C to be lower. Similarly, the supplier wants a higher component unit price w^S, while the CM wants w^S to be lower. When two candidate CMs differ in both w^C and K, the OEM chooses the one that maximizes her expected profit in Equation (1). This fact leads to the conflicting goal for a CM or supplier: competitiveness.

Competitiveness

Regardless of profitability, a CM's expected profit from the make-to-order product is zero unless he wins the OEM's business. We define *competitiveness* as the degree to which a firm is able to submit a winning quotation. If multiple CMs tie in providing maximum OEM profitability, we assume the OEM chooses each tying CM with equal probability. The goal for CM competitiveness is to win outright, without tying. To ensure minimal competitiveness in the case without additional contract parameters imposed by any RFQ, we assume a CM quotes w^C as in (2):

$$w^C \leq r - g^O[(E[D] - E[min(D,K)]) \div (E[min(D,K)])] \tag{2}$$

so that $\Pi^O(w^C,K) \geq 0$.

In essence, competitiveness means that a CM or a supplier understands and appeals to a downstream firm's goal of profitability. As indicated by Proposition 1, the larger CM can be competitive while maintaining higher profitability.

Proposition 1. When all CMs pay the same component unit price w^S, a candidate CM can profitably beat a supply channel that has less available production capacity.

Small supply channels compete by offering smaller unit prices, thereby increasing the OEM's marginal profit. Significantly larger available production capacity can increase the OEM's expected profit beyond the impact of this increase in marginal profit. The CM with larger supply channel production capacity may quote w^C just low enough that a smaller CM can only win by quoting a unit price below production cost $w^S + c^C$.

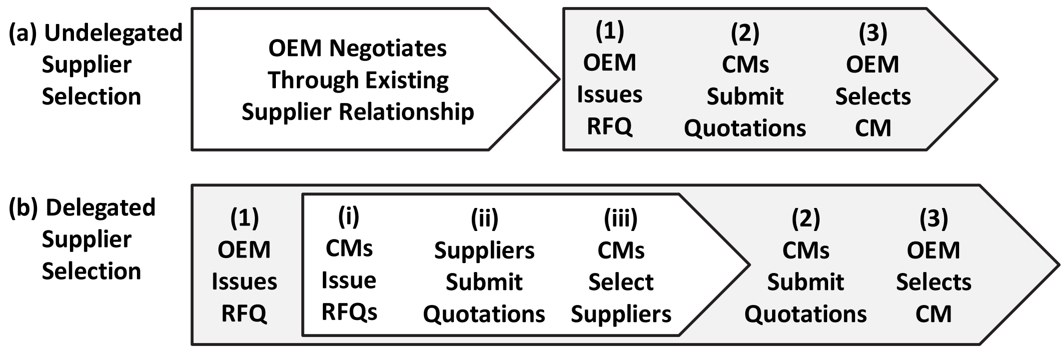
In what follows, we consider whether or not a firm credibly quotes available production capacity along with unit price. Incentives to misrepresent capacity arise when doing so can increase either profitability or competitiveness.

Firm Objectives

The central aim of our analysis is to answer the following two questions. Can the OEM obtain credible information from the candidate CMs about supply channel available production capacities through quotations? Does delegating supplier selection to the competing CMs impact the OEM's ability to obtain credible information? With this aim, we address the supply chain selection problem of Figure 2.

When not delegating supplier selection, as in Figure 2(a), the OEM has an existing relationship with a component supplier. However, she selects a CM through the process described in the second arrow. In Step (1), the OEM determines a set of qualified CMs to compete for the business and then designs an RFQ, which she issues to these qualified CMs. This RFQ includes detailed specifications for the make-to-order product, delivery lead time requirements, and all guidelines for quotations. In Step (2), competing CMs use available production capacity and cost information to submit quotations to the OEM. In Step (3), the OEM receives quotations and chooses an upstream supply chain partner to maximize her expected profit from the make-to-order product.

FIGURE 2
SUPPLY CHAIN SELECTION PROBLEM



When delegating supplier selection, as in Figure 2(b), the OEM chooses a CM-supplier pair, i.e., a *supply channel*. Steps (1)-(3) in the outer arrow constitute the OEM's supply channel selection problem. Steps (i)-(iii) in the inner arrow compose the CM's supplier selection problem. Step (i) has the same two parts as Step (1). The CMs use component specifications from the OEM's RFQ and the OEM's approved vendor list to determine a set of qualified suppliers. Then, each CM designs his own RFQ and issues it to these qualified suppliers. This RFQ similarly includes detailed specifications for the key component, delivery lead time requirements, and all guidelines for supplier quotations. In Step (ii), each supplier considers her own available production capacity K^S and unit production cost c^S to decide on the quotation she submits to the CM. In Step (iii), each CM receives supplier quotations and chooses a single supplier to include in his candidate supply channel.

While some OEMs may directly verify upstream production capacity, doing so can be very expensive in time, money, and manpower. Hence, when resources are limited or verification is not allowed, we devise RFQ design strategies for eliciting credible capacity information with both undelegated and delegated supplier selection. If delegating supplier selection does not reduce the credibility of the OEM's capacity information, the OEM may prefer to delegate.

UNDELEGATED SUPPLIER SELECTION

Initially, we assume the OEM negotiates a contract with a component supplier and obtains a reliable assessment of available supplier capacity K^S to accommodate the new make-to-order product. In practice, entrusting a CM with component procurement may result in that CM's further reducing the component unit price to a level unknown to the OEM. To avoid this concern, the OEM can exercise *price masking*, procuring components according to the negotiated supplier contract and reselling them to the CM at market unit price w^S (Jorgensen 2003, 2004). In this case, the supply chain selection problem is the undelegated problem of Figure 2(a), where we do not model contract negotiation between the OEM and her component supplier explicitly.

Unit Price Only

Suppose an OEM's RFQ asks each CM to quote unit price w^C and supply channel available production capacity κ. Unit price only contracts are common in industry because of their simplicity (Lariviere and Porteus 2001, Özer and Wei 2006). Those which include available production capacity yield the expected profit functions in Equation (1).

Prior to issuing her RFQ to candidate CMs, the OEM knows unit production costs c^S and c^C, available component production capacity K^S, and component unit price w^S. We assume this information is also available to the candidate CMs before they submit their quotations. To learn w^C and K, the OEM's RFQ requires each candidate CM to quote both unit price and available production capacity. Proposition 2 reveals that this RFQ strategy is not effective in providing the OEM with credible capacity information.

Proposition 2. In a (w^C, κ) quotation, a CM has incentive to quote $\kappa > K$.

Whatever unit price w^C a CM chooses for his quotation, he may exaggerate supply channel available production capacity to make his quotation more attractive to the OEM. The CM may gamble his credibility on the likelihood that demand will not exceed his supply channel's true available production capacity. Hence, the OEM cannot glean credible information about a supply channel's available production capacity from the CM's quotation and so cannot intelligently choose a supply channel to maximize her expected profit.

Unit Price with Shortfall Penalty

Suppose the OEM's RFQ requires the winning CM to pay a unit penalty for surprise limitations in his ability to satisfy demand.

In addition to asking candidate CMs to quote unit price w^C and available production capacity κ, the OEM specifies a shortfall penalty p^C. If $\kappa > K$ and this discrepancy results in surprise limitations in available production capacity, the CM pays unit shortfall penalty p^C for unsatisfied demand $min(D,\kappa) - min(D,\kappa,K)$. In this case, expected profit functions for the CM and OEM are shown in (3) below.

$$\Pi^C(w^S,w^C,p^C,K,\kappa) = (w^C - w^S - c^C)E[min(D,K,\kappa)] - p^C(E[min(D,\kappa)] - E[min(D,K,\kappa)]) \tag{3}$$
$$\Pi^O(w^C,p^C,K,\kappa) = (r - w^C)E[min(D,K,\kappa)] - g^o(E[D] - E[min(D,K,\kappa)])$$
$$+ p^C(E[min(D,\kappa)] - E[min(D,K,\kappa)])$$

Proposition 3 reveals that a shortfall penalty does not generate credible capacity information.

Proposition 3. In a (w^C, κ) quotation with unit shortfall penalty p^C, a CM has incentive to quote $\kappa > K$ for $\Pi^C(w^S,w^C,p^C,K,\kappa) \geq 0$.

Exaggerating available production capacity reduces CM profitability but increases his competitiveness. Hence, as long as a CM's expected profit is nonnegative, he may sacrifice a possible shortfall penalty in exchange for a better chance at winning OEM business.

However, a CM's desire for nonnegative profitability generates the idea for a shortfall penalty *function* $p^C(w^C, \kappa)$. Specifically, when a CM quotes unit price w^C and available production capacity $\kappa = K_i$ for some $K_i \in \{K_1,\ldots,K_m\}$, he effectively agrees to pay shortfall penalty $p^C(w^C,K_i)$. We write the resulting expected profit functions in (4).

$$\Pi^C(w^S,w^C,p^C(w^C,K_i),K,K_i) = (w^C - w^S - c^C)E[min(D,K,K_i)]$$
$$- p^C(w^C,K_i)(E[min(D,K_i)] - E[min(D,K,K_i)]) \tag{4}$$
$$\Pi^O(w^C,p^C(w^C,K_i),K,K_i) = (r - w^C)E[min(D,K,K_i)] - g^o(E[D] - E[min(D,K,K_i)])$$
$$+ p^C(w^C,K_i)(E[min(D,K_i)] - E[min(D,K,K_i)])$$

To eliminate the CM's incentive to misrepresent available production capacity, the OEM must ensure that $\Pi^C(w^S,w^C,p^C(w^C,K_i),K,K_i) < 0$ whenever $K\_i \neq K$. In the following proposition, we provide the necessary property for $p^C(w^C,K_i)$ to preclude the CM from misrepresenting his capacity.

Proposition 4. In a (w^C,K_i) quotation with unit shortfall penalty function $p^C(w^C,K_i)$, a CM quotes $\kappa = K$ whenever

$$p^C(w^C,K_i) > (w^C - w^S - c^C)[(E[min(D,K_{i-1})]) \div (E[min(D,K_i)] - E[min(D,K_{i-1})])] \tag{5}$$

for $K_i \in \{K_1,\ldots,K_m\}$, and this lower bound on $p^C(w^C,K_i)$ increases with i.

If the OEM knows w^S and c^C, she can design a shortfall penalty function to elicit credible reports of available production capacity at candidate CMs. Specifically, the OEM's RFQ can specify function $p^C(w^C,K_i)$ for each $K_i \in \{K_1,\ldots,K_m\}$. When quoting w^C, a candidate CM quotes his true production capacity, the only production capacity that yields nonnegative profitability with the shortfall penalty function. The monotonicity of the lower bound on $p^C(w^C,K_i)$ suggests that learning credible capacity information is more difficult when a CM has larger available production capacity. First, the likelihood of actual demand exceeding available production capacity and yielding a shortfall is smaller. Second, a CM with larger available production capacity can earn a high profit before incurring any shortfall penalty and can therefore better afford the penalty.

DELEGATED SUPPLIER SELECTION

We now assume the OEM delegates strategic sourcing of the key component to candidate CMs. The OEM may specify an approved vendor list but entrusts CMs with the task of obtaining competitive component pricing. In this case, the supply chain selection problem is the delegated problem of Figure 2(b). We begin by demonstrating the limitations of unit price contracts both without and with a shortfall penalty. We then propose a new RFQ design that elicits credible capacity information through a mechanism of upside risk sharing.

Unit Price Only

When selecting a component supplier from the OEM's approved vendor list, each candidate CM knows his own available production capacity K^C and unit production costs c^S and c^C. Each candidate supplier knows only c^S and K^S but suspects $K^C=\check{K}^C$. To learn w^S and K^S, the CM's RFQ requires each supplier to quote both unit price and available production capacity. Proposition 5 reveals that this RFQ strategy does not provide the CM with credible capacity information. We let κ^S represent a supplier's available production capacity quote.

Proposition 5. In a (w^S, κ^S) quotation, a supplier has incentive to quote $\kappa^S > K^S$ when $\check{K}^C > K^S$.

When $\check{K}^C > K^S$, quoting $\kappa^S > K^S$ makes the supplier with unit price w^S appear to yield greater profitability and greater competitiveness for the CM, so the CM cannot glean any credible information about a supplier's available production capacity from her quotation. When $K^S \geq \check{K}^C$, the supplier believes supply channel available production capacity cannot exceed $\check{K}^C$, so quoting $\kappa^S > K^S$ does not enhance the supplier's competitiveness.

When CMs select their own suppliers, Proposition 2 continues to hold for available production capacity K that a CM *believes* his supply channel has. However, Proposition 5 tells us the CM may have an inflated sense of K. So, using this RFQ strategy for both the CM's supplier selection problem and the OEM's supply channel selection problem exacerbates OEM difficulty in choosing the supply channel that truly maximizes her expected profit.

Unit Price with Shortfall Penalty

Both the OEM and candidate CMs want upstream supply chain partners to quote available production capacity credibly. Here we begin by analyzing the RFQ design strategy with shortfall penalties for the CM's supplier selection problem.

CM's Supplier Selection Problem

Suppose a CM's RFQ specifies K^C and a shortfall penalty p^S, asking each supplier to quote unit price w^S and available production capacity κ^S. Initially, we assume the CM credibly announces his available production capacity K^C through his RFQ. Later, we show that the CM has no incentive to misreport his available capacity information to the supplier. After choosing a supplier, the CM submits his most strategic quotation given the available production capacity he believes that his supply channel has. If $\kappa^S >$

K^S for the CM's chosen supplier and the CM wins the OEM's business, this discrepancy may result in surprise limitations in available production capacity. Regardless of any penalty owed to the OEM, the CM also loses expected profit. In consequence, the supplier pays unit shortfall penalty p^S for unsatisfied demand $[min(D,K^C,\kappa^S)-min(D,K^C,K^S,\kappa^S)]$ due to a surprise limitation. In this case, (6) shows expected profit functions for the supplier and the CM.

$$
\begin{aligned}
&\Pi^S(w^S,p^S,K^C,K^S,\kappa^S) = (w^S - c^S)E[min(D,K^C,K^S,\kappa^S)] \\
&- p^S(E[min(D,K^C,\kappa^S)] - E[min(D,K^C,K^S,\kappa^S)]) \\
&\Pi^C(w^S,w^C,p^S,K^C,K^S,\kappa^S) = (w^C - w^S - c^C)E[min(D,K^C,K^S,\kappa^S)] \\
&+ p^S(E[min(D,K^C,\kappa^S)] - E[min(D,K^C,K^S,\kappa^S)])
\end{aligned} \tag{6}
$$

Proposition 6 reveals that a shortfall penalty does not generate credible capacity information.

Proposition 6. In a (w^S,κ^S) quotation with unit shortfall penalty p^S, a supplier has incentive to quote $\kappa^S > K^S$ for $\Pi^S(w^S,p^S,K^C,K^S,\kappa^S) \geq 0$.

As long as her potential expected profit remains nonnegative, a supplier may sacrifice profitability for competitiveness. Hence, the supplier still has incentive to exaggerate her available production capacity under a constant unit shortfall penalty.

Nevertheless, a CM's RFQ can elicit credible supplier capacity information by using unit shortfall penalty *function* $p^S(w^S,K_i)$. When a supplier quotes component unit price w^S and available production capacity $\kappa^S = K_i$ for some $K_i \in \{K_1,\ldots,K_m\}$, she effectively agrees to pay shortfall penalty $p^S(w^S,K_i)$. We write the resulting expected profit functions as in (7).

$$
\begin{aligned}
&\Pi^S(w^S,p^S(w^S,K_i),K^C,K^S,K_i) = (w^S - c^S)E[min(D,K^C,K^S,K_i)] \\
&- p^S(w^S,K_i)(E[min(D,K^C,K_i)] - E[min(D,K^C,K^S,K_i)]) \\
&\Pi^C(w^S,w^C,p^S(w^S,K_i),K^C,K^S,K_i) = (w^C - w^S - c^C)\, E[min(D,K^C,K^S,K_i)] \\
&+ p^S(w^S,K_i)(E[min(D,K^C,K_i)] - E[min(D,K^C,K^S,K_i)])
\end{aligned} \tag{7}
$$

The CM eliminates a supplier's incentive from Proposition 6 to misrepresent available production capacity by choosing $p^S(w^S,K_i)$ such that $\Pi^S(w^S,p^S(w^S, K_i),K^C,K^S,K_i) < 0$ whenever $K_i \neq K^S$. In the following proposition, we provide the necessary property for $p^S(w^S,K_i)$ to preclude the supplier from misrepresenting her capacity.

Proposition 7. For $K^C = K_u$, in a (w^S,K_i) quotation with unit shortfall penalty function $p^S(w^S,K_i)$, a supplier quotes K_i whenever

$$p^S(w^S,K_i) > (w^S - c^S)[(E[min(D,K_{i-1})]) \div (E[min(D,K_i)] - E[min(D,K_{i-1})])]$$

for $K_i \in \{K_1,\ldots,K_u\}$ and

$$p^S(w^S,K_i) > (w^S - c^S)[(E[min(D,K_{u-1})]) \div (E[min(D,K_u)] - E[min(D,K_{u-1})])]$$

for $K_i \in \{K_{u+1},\ldots,K_m\}$.

In summary, a CM can design a shortfall penalty function to elicit a credible report of available production capacity from a supplier. Specifically, the CM's RFQ can specify function $p^S(w^S,K_i)$ for each $K_i \in \{K_1,\ldots,K_m\}$. In consequence, when quoting w^S, a candidate supplier quotes her true available production capacity.

We now consider the assumption that the CM credibly announces K^C to candidate suppliers.

Proposition 8. When applying an effective shortfall penalty function, a CM has no incentive to report $\kappa^C \neq K^C$.

According to Proposition 8, the CM does not benefit from misreporting K^C to candidate suppliers, and the suppliers therefore believe the available production capacity the CM reports in his RFQ. Using this insight and Proposition 7, we note that we now have a successful RFQ design strategy for the CM's supplier selection problem.

OEM's Supply Channel Selection Problem

For the OEM's supply channel selection problem, we next determine an RFQ design strategy to transmit capacity information credibly to the OEM.

When CMs choose their own component suppliers, Proposition 3 continues to hold. Yet, according to Proposition 4, the OEM must know w^S to use a shortfall penalty function strategy. Hence, while the CM can learn his supply channel's available production capacity, the OEM still does not have a credible means to elicit this capacity information.

Unit Price with Upside Risk Sharing

We now suppose that supply chain partners agree to sign a contract under which an upstream firm shares the risk, or potential loss, from not having sufficient production capacity to meet high demand. An upstream firm does *not* pay a penalty for discrepancies between quoted and actual available production capacity. Instead, an upstream firm agrees to pay a portion of the supply chain's goodwill payment. Intuitively, upstream firms having larger available production capacity can afford to share the risk of goodwill payments for high demand without requiring the compensation of charging high unit prices. Next, we analyze the effectiveness of upside risk sharing in inducing credible capacity information sharing.

CM's Supplier Selection Problem

Suppose a CM's RFQ asks each supplier to quote component unit price w^S and also specifies a unit goodwill payment g^S, through which he asks his supplier to share upside risk. This RFQ design insinuates that the CM himself faces a unit goodwill payment g^C to the OEM. Specifically, candidate suppliers agree to pay g^S $(\leq g^C)$ of the CM's loss on unsatisfied demand $[min(D,K^C) - min(D,K^C,K^S)]$. Note that the supplier only pays when demand is unsatisfied because of limits in *her* available production capacity. That is, if $K^C \leq K^S$, the supplier can satisfy as much demand as the CM can, so the supplier owes no goodwill payment from additional capacity limitations. Initially, we assume the CM credibly announces available production capacity K^C when issuing an RFQ. Later, we show that the CM has no incentive to misreport this information to candidate suppliers. Expected profit functions given unit goodwill payment g^S are shown in (9).

$$\begin{aligned}&\Pi^S(w^S,g^S,K^C,K^S) = (w^S - c^S)E[min(D,K^C,K^S)] - g^S(E[min(D,K^C)] - E[min(D,K^C,K^S)])\\&\Pi^C(w^S,w^C,g^S,g^C,K^C,K^S) = (w^C - w^S - c^C)E[min(D,K^C,K^S)] - g^C(E[D] - E[min(D,K^C,K^S)])\\&+ g^S(E[min(D,K^C)] - E[min(D,K^C,K^S)])\end{aligned} \tag{9}$$

The following proposition reveals that suppliers still do not credibly transmit production capacity information.

Proposition 9. In a (w^S,K_i) quotation with unit goodwill payment g^S, a supplier with available production capacity $K^S < K^C$ has incentive to quote $K_i > K^S$.

A unit goodwill payment gives each supplier the ability to benefit from the competitiveness of a larger available production capacity quotation without sacrificing profitability for exaggeration. For credible capacity information, we explore an RFQ design that asks each supplier to quote both available production capacity K_i and a unit price pair (w^S_L, w^S_H). When signing such a contract, a supplier charges unit price w^S_L if the CM does not require a goodwill payment at the time of production, and she charges unit price w^S_H if the CM requires unit goodwill payment g^S. If the CM wins the OEM's business, he claims the right to choose between the two unit prices quoted by the winning supplier at the time of production. That is, the CM decides whether (1) to require no goodwill payment and pay w^S_L per unit or (2) to require unit goodwill payment g^S and pay w^S_H. If the CM chooses not to require a goodwill payment, (10) shows the expected profit functions.

$$\Pi^S(w^S_L, K^C, K^S, K_i) = (w^S_L - c^S)E[min(D,K^C,K^S,K_i)] \tag{10}$$
$$\Pi^C(w^S_L, w^C, g^C, K^C, K^S, K_i) = (w^C - w^S_L - c^C)E[min(D,K^C,K^S,K_i)] - g^C(E[D] - E[min(D,K^C,K^S)])$$

If the CM chooses to require unit goodwill payment g^S, (11) shows the expected profit functions.

$$\Pi^S(w^S_H, g^S, K^C, K^S, K_i) = (w^S_H - c^S)E[min(D,K^C,K^S,K_i)] - g^S(E[min(D,K^C)] - E[min(D,K^C,K^S,K_i)]) \tag{11}$$
$$\Pi^C(w^S_H, w^C, g^S, g^C, K^C, K^S, K_i) = (w^C - w^S_H - c^C)E[min(D,K^C,K^S,K_i)]$$
$$+ g^S(E[min(D,K^C)] - E[min(D,K^C,K^S,K_i)])$$
$$- g^C(E[D] - E[min(D,K^C,K^S)])$$

As we note in the following proposition, the difference between w^S_L and w^S_H reveals a supplier's available production capacity.

Proposition 10. In a (w^S_L, w^S_H, K_i) quotation, a supplier with K^S optimally submits a quotation with

$$w^S_H = w^S_L + g^S[(E[min(D,K^C)] - E[min(D,K^C,K^S,K_{i,})]) \div (E[min(D,K^C,K^S,K_i)])] \tag{12}$$

where $K_i = K^S$.

The CM detects the supplier's available production capacity from unit price pair (w^S_L, w^S_H), so the supplier has no incentive to misreport K^S. Hence, the CM has the information he needs to choose the supplier that maximizes either his profitability or his competitiveness.

We now revisit the assumption that the CM credibly announces K^C to candidate suppliers.

Proposition 11. When requesting a (w^S_L, w^S_H, K_i) quotation, a CM has no incentive to report $\kappa^C \neq K^C$.

The CM does not benefit from misreporting K^C to the candidate suppliers, and the suppliers therefore believe the available production capacity the CM reports in his RFQ. Using this insight and Proposition 10, we have a second successful RFQ design strategy for the CM's supplier selection problem.

OEM's Supplier Selection Problem

Suppose the OEM's RFQ asks each CM to quote unit price w^C and also specifies a unit goodwill payment g^C, through which the OEM asks her CM to share her upside risk. Specifically, candidate CMs agree to pay g^C $(\leq g^O)$ of the OEM's loss on unsatisfied demand $(D - K)^+$. The expected profit function of each firm now depends upon that firm's profit margin for each unit sold, the number of units sold, and any goodwill payment paid by the CM to the OEM. That is, we have (13) as follows.

$$\Pi^C(w^S, w^C, g^C, K) = (w^C - w^S - c^C)E[min(D,K)] - g^C(E[D] - E[min(D,K)]) \tag{13}$$
$$\Pi^O(w^C, g^C, K) = (r - w^C)E[min(D,K)] - (g^O - g^C)(E[D] - E[min(D,K)])$$

The unit price pair strategy we explore for the CM's supplier selection problem solves the incentive problem for the OEM's selection problem as well. Suppose the OEM issues an RFQ requesting CM quotations of the form $(w^C{}_L, w^C{}_H, K_i)$. A CM charges unit price $w^C{}_L$ when the OEM does not require a goodwill payment, and he charges unit price $w^C{}_H$ when the OEM requires goodwill payment g^C. The OEM reserves the right to choose between the two quotations at the time of production. That is, the OEM decides whether (1) to require no goodwill payment and pay $w^C{}_L$ per unit or (2) to require unit goodwill payment g^C and pay $w^C{}_H$ per unit. If the OEM chooses not to require a goodwill payment, (14) shows the expected profit functions.

$$\Pi^C(w^C{}_L, K) = (w^C{}_L - w^S - c^C)E[min(D,K)] \tag{14}$$
$$\Pi^O(w^C{}_L, K) = (r - w^C{}_L)E[min(D,K)] - g^O(E[D] - E[min(D,K)])$$

If the OEM chooses to require goodwill payment g^C, (15) shows the expected profit functions.

$$\Pi^C(w^C{}_H, g^C, K) = (w^C{}_H - w^S - c^C)E[min(D,K)] - g^C(E[D] - E[min(D,K)]) \tag{15}$$
$$\Pi^O(w^C{}_H, g^C, K) = (r - w^C{}_H)E[min(D,K)] - (g^O - g^C)(E[D] - E[min(D,K)])$$

A proof similar to that of Proposition 10 yields the following result.

Proposition 12. In a $(w^C{}_L, w^C{}_H, K_i)$ quotation, (i) a CM with supply channel production capacity K optimally submits a quotation with

$$w^C{}_H = w^C{}_L + g^C[(E[D] - E[min(D,K_i)]) \div (E[min(D,K_i)]))] \tag{16}$$

where $K_i = K$, and (ii) a CM has an incentive to design an RFQ that elicits credible information about his supply channel's available production capacity.

From Proposition 12(i), the OEM can deduce K from the unit price pair $(w^C{}_L, w^C{}_H)$, so the CM has no incentive to misreport. This result also guarantees that $\Pi^O(w^C{}_L, K) = \Pi^O(w^C{}_H, g^C, K)$ and $\Pi^C(w^C{}_L, K) = \Pi^C(w^C{}_H, g^C, K)$. According to Proposition 12(ii), when the OEM's RFQ includes a unit goodwill cost and requests a unit price pair quotation, the CM optimally designs an RFQ that yields credible capacity information from candidate suppliers. Hence, the OEM can truly delegate the supplier selection problem to the CMs and trust the supply channel capacity information she receives in return

CONCLUSION

In a CM's supplier selection problem, each supplier has an incentive to exaggerate available production capacity. However, the CM can obtain credible capacity information in two ways. First, the CM can specify a unit shortfall penalty that is a function of a supplier's quotation. Second, the CM can apply a unit goodwill payment by which a supplier shares some of the upside risk from limitations in supply channel's production capacity, through a unit price pair quotation.

In the OEM's supply channel selection problem, we aim to transmit this capacity information credibly. When the OEM does not delegate supplier selection to CMs, she can use either of the above strategies to learn the true available production capacity of each supply channel. However, when the OEM *does* delegate supplier selection to CMs, eliciting credible capacity information requires the OEM's RFQ to specify a unit goodwill payment and request a unit price pair quotation from each CM.

From this analysis, we conclude that an OEM can receive credible capacity information regardless of whether or not she delegates supplier selection to candidate CMs. Hence, if the OEM has no advantage over CMs in component price negotiation, outsourcing strategic sourcing can achieve the same results as in-house sourcing as long as a sufficient number of candidate CMs are willing to share upside risk.

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