Supply Contracting under Information Asymmetry and Delivery Performance Consideration

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1 Introduction

A global economy and rapidly-changing market conditions have greatly intensified industry competition. This, in turn, has led to an ever-increasing level of outsourcing/offshoring activities by firms in order to gain cost advantage and market share (Friedman 2005, Hausman et al. 2005). According to the Department of Commerce (2006), typical U.S. manufacturers spend more than half of their revenue on goods and services obtained from external suppliers. As a result, supply management has become a significant issue for many companies that rely more on their suppliers for the delivery of components, products, and services. When sourcing from outside suppliers, a buyer should consider both price and non-price factors. One of the major non-price factors is the supplier's delivery performance. The benefit of fast, reliable deliveries from a supplier is quite clear from an operations management perspective: It enables the buyer to lower inventory and provide superior service. In other words, the more responsive the supplier is, the lower the buyer's operating cost (e.g., inventory holding cost plus penalty cost for backorders).

The importance of supplier delivery performance in procurement has been emphasized by both practitioners and academics (Burt 1989, Pyke and Johnson 2003). It has been reported that many firms rank price, quality, and delivery performance as the top three criteria for selecting and evaluating suppliers (Kay 2005, CAPS Research 2006). For example, Sun Microsystems considers procurement cost and delivery performance the two most important dimensions when choosing suppliers (Farlow et al. 1996). With the help of recent advances in information technologies, there has been a drastic increase in the use of online auction as a procurement tool (Rangan 1998, Wise and Morrison 2000, Pinker et al. 2003). A challenge in procurement auction design for B2B exchanges is how to bring non-price factors into consideration, including supplier delivery performance (Elmaghraby 2004). These observations call for theoretical research that can generate useful managerial guidelines for procurement process design while taking delivery performance into account.

This chapter studies a buyer's supply contract design problem under delivery performance consideration. A supplier's delivery performance depends on the supplier's capacity (if the supplier makes to order) or inventory (if the supplier makes to stock), both of which are costly to invest. For most practical situations, the supplier is a self-interested, independent organization. Thus the buyer needs to offer appropriate incentives to induce sufficient capacity or inventory investment from the supplier. In addition, the supplier may have private information about the cost for providing fast delivery. For instance, the buyer does not know the supplier's exact capacity or production cost when contracting with the supplier. This means the buyer often faces cost uncertainty when designing the procurement contract.

The objective of this chapter is to identify efficient and easy-to-implement procurement mechanisms for the buyer. We consider scenarios where the supplier is either a make-to-order service provider or a make-to-stock manufacturer. For both scenarios, we propose some simple mechanisms and evaluate their performances along two dimensions. First, we compare the buyer's profit in the simple mechanisms with the profit in the optimal (profit-maximizing) mechanism. This sheds light on how efficient the simple mechanisms are from the buyer's standpoint. Second, we examine the supply chain's performance under the simple mechanisms by comparing it to the supply chain's optimal solution. This reveals whether the simple mechanisms are efficient from the entire chain's perspective.

The rest of the chapter is organized as follows. §2 reviews the related literature. §3 studies a make-to-order supplier and §4 considers a make-to-stock supplier. §5 discusses some contracting issues and we conclude with §6.

2 Related Literature

The models and analyses in this chapter are based on the studies by Zhang (2004), Cachon and Zhang (2006), and Zhang (2009). We outline the model settings and summarize the main results from these studies. Below we briefly review the representative papers in the literature (this is by no means an exhaustive list of all related papers).

This chapter is closely related to the supply chain coordination literature. Most of the studies in this literature focus on the design of coordination contracts for decentralized supply chains under complete information. A comprehensive survey is provided by Cachon (2003). A few of the most relevant papers include Cachon and Zipkin (1999) and Ray et al. (2005) for serial inventory systems, Caldentey and Wein (2003) for production-inventory systems, Chen et al. (2001) for distribution systems, and Bernstein and DeCroix (2006) and Zhang (2006) for assembly systems.

Complete information is not a realistic assumption for most decentralized supply chains. This has inspired a stream of research that studies supply chain contracting under asymmetric information. Corbett and de Groote (2000), Corbett (2001), Corbett et al. (2004) and Ha (2001) are some of the representative studies that consider asymmetric cost information, whereas Cachon and Lariviere (2001), Özer and Wei (2006), and Burnetas et al. (2007) consider asymmetric demand information in a supply chain setting. Recently, Yang et al. (2009) analyze a manufacturer's sourcing strategy when the supplier possesses private information on supply disruption. Gümüş et al. (2010) study the effect of supply guarantees when a buyer procures from two suppliers with different price and reliability characteristics. This chapter also falls into the category of supply contracting under asymmetric information, but with quite different model settings.

There is an extensive literature on procurement in economics. It focuses primarily on two issues. The first is how to select a cost-efficient supplier from a potential supplier pool, and the second is how to induce the selected supplier to invest in R&D and other improvement efforts. These two issues have been addressed by the auction theory and the theory of incentives. Surveys of this literature can be found in Klemperer (1999) and Laffont and Martimort (2002). The procurement papers in the economics literature are different from this chapter because they do not take operations factors such as delivery performance into consideration.

We study a multi-attribute procurement problem because the buyer cares about both price and delivery performance. A few papers also study multi-attribute procurement. Che (1993) and Branco (1997) study a multi-dimensional auction in which price and quality are the two attributes in procurement. Chen et al. (2005) study procurement auction design for a third-party auctioneer with a focus on the price and transportation cost aspects. Multi-attribute multi-round auctions have been studied in Beil and Wein (2003), where the buyer can learn about the suppliers in each round. Kostamis et al. (2009) consider a procurement problem where both price and non-price factors are used for contract award decisions and the buyer may release the information about the suppliers' non-price factors.

Besides incentive contracts, a buyer may motivate suppliers to improve delivery performance through various competition mechanisms. In particular, the buyer may adopt a multi-sourcing strategy and allocate business to suppliers based on their past performance; see Gilbert and Weng (1998), Ha et al. (2003), Cachon and Zhang (2007), and Benjaafar et al. (2007) in the operations management literature for a few examples.

There are papers that study a buyer's procurement or replenishment strategies given exogenous suppliers characteristics (such as delivery lead time and price). Examples include Anupindi and Akella (1993), Li and Kouvelis (1999), Ramasesh et al. (1991), and Federgruen and Yang (2008, 2009). A review of this literature can be found in Elmaghraby (2000). In this chapter, the suppliers' delivery performance is endogenous and can be influenced by the buyer's procurement strategy. There is also a growing literature on supply risk management, which analyzes mitigation strategies for buyers to manage various supply risks (e.g., price fluctuations and supply disruption). Reviews of this literature can be found in Tang (2006) and Tomlin (2006).

The importance of simplicity in contract design has been emphasized both in the economics and operations management literatures. Holmstrom and Milgrom (1987) and Bhattacharyya and Lafontaine (1995) point out that most real-world incentive schemes seem to take less extreme forms than the sophisticated policies predicted by economic theory. See Bower (1993), Chu and Sappington (2005), and the references therein for more discussion of the performance of simple incentive contracts. In recent years, there has been a growing literature in operations management that investigates the performance of simple procurement contracts, including Kayış et al. (2007), Taylor and Plambeck (2007), and Tunca and Wu (2009). Bolandifar et al. (2010) study the supply contract design problem for a newsvendor who faces uncertain demand for a single selling season. They demonstrate that a simple wholesale price could be theoretically optimal even under information asymmetry about the supplier's capacity cost. These papers do not consider suppliers' delivery performance and therefore generate quite different insights.

3 Contracting with Make-to-order Supplier

This section focuses on the scenario where the buyer sources an input from a make-to-order supplier. For example, in the contract manufacturing industry, many firms assemble highly customized components for their customers on a make-to-order basis (Thurm 1998 and Bulkeley 2003). In this case, the supplier does not hold inventory and thus can be modeled as a queueing system. An alternative interpretation is that the buyer procures a certain service from the supplier. The scenario where the supplier can hold inventory to improve delivery performance will be studied in §4.

3.1 Basic Model

A buyer (e.g., a manufacturer or a retailer) procures a product or service from a supplier (e.g., a contract manufacturer or service provider) to satisfy consumer demand. Throughout the chapter we will use "she" for the buyer whereas "he" for the supplier. Consumer demand follows a Poisson arrival process with rate λ. The buyer uses a base-stock policy to manage her inventory. Let s be the base-stock level at the buyer. The buyer has to incur a cost rate h for holding each unit of the product. In the basic model we assume that h is fixed and independent of the procurement price the buyer pays the supplier. §3.4.2 relaxes this assumption and demonstrates that the qualitative insight will remain unchanged. Unmet demand at the buyer can be backlogged and there is a unit penalty cost rate b for backlogged demand.

The supplier adopts a make-to-order production strategy and does not hold inventory. Let μ be the capacity (production or service rate) chosen by the supplier. For a given μ, the production time is exponentially distributed with mean $1/\mu$. There is a constant unit cost rate c for maintaining a certain capacity level, which is a random draw from a distribution F (density f) on a support $[\bar{c}, \underline{c}]$. We follow the literature to assume that F is log-concave, i.e., $F(c)/f(c)$ is an increasing function. This condition holds for most commonly used distribution functions (see Bagnoli and Bergstrom 1995 for details). The distribution F represents the cost uncertainty for delivering the product. Such an uncertainty may be associated with research and development (R&D), production yield, and other random factors. The supplier observes the realization of c, whereas the buyer does not. However, we assume that the buyer has an unbiased belief about the distribution F.

The buyer is assumed to act as a Stackelberg leader in the contracting process. This applies to situations where the buyer is a major player in the industry and has an advantageous bargaining position. Both firms are risk-neutral and aim at maximizing the expected payoff function per unit of time. In addition, we assume that the supplier has a zero opportunity cost (the best outside alternative yields zero profit). Including a positive opportunity cost does not change the essence of the problem. The chronology of events is as follows: First, the supplier's capacity cost c is realized and only observed by the supplier; second, the buyer offers a take-it-or-leave-it contract to the supplier; if the contract is accepted, then the supplier invests in capacity μ and the procurement price R is determined accordingly; the buyer then chooses the base-stock level s; finally, the system runs over an sufficiently long horizon. In this chapter we use superscript "o" to denote the optimal mechanism for the buyer and "$*$" denote the optimal solution for the supply chain. Let E be the expectation operation, and let a prime denote the derivative of a function of a single variable. Define $(x)^+ = \max(0, x)$ and $(x)^- = \max(0, -x)$.

The above model setup is based on Zhang (2004) and Cachon and Zhang (2006). Some modifications have been made on the notations (to maintain consistency with the notations in §4). For example, here we use c for the capacity cost, b for the backorder cost, C for the firms' cost functions, and subscripts 1 and 2 to denote the buyer (stage 1) and the supplier (stage 2), respectively. More details can be found in Cachon and Zhang (2006), which provides a comprehensive treatment of the problem.

Next we derive the supply chain's optimal solution as preliminary analysis. Suppose the supplier has a capacity level μ and the buyer adopts a base-stock level s. Let N be the number of outstanding orders at the supplier in steady state, which follows a geometric distribution. Then the buyer's operating cost (inventory and backorder costs) is given by

$$C(\mu, s) = E[h(s-N)^{+} + b(N-s)^{-}] = h\left(s - \frac{\lambda}{\mu-\lambda}\right) + (h+b)\left(\frac{\lambda}{\mu}\right)^{s}\frac{\lambda}{\mu-\lambda}. \qquad (1)$$

To derive a closed-form expression for the optimal s, let us assume s is large enough so that we can treat it as a continuous variable. The buyer's (or the supply chain's) cost-minimizing base-stock level can be shown to be

$$s^{*}(\mu) = -\ln\left(\left(\frac{h}{h+b}\right)\left(\frac{\mu/\lambda-1}{\ln(\mu/\lambda)}\right)\right)/\ln(\mu/\lambda). \qquad (2)$$

Plugging $s^{*}(\mu)$ into the buyer's operating cost function gives

$$C(\mu) = C(\mu, s^{*}(\mu)) = h\left[\frac{1-\ln\left(\left(\frac{h}{h+b}\right)\left(\frac{\mu/\lambda-1}{\ln\mu/\lambda}\right)\right)}{\ln\mu/\lambda} - \frac{1}{\mu/\lambda-1}\right]. \qquad (3)$$

Then the supply chain total cost is $C_{sc}(c,\mu) = c\mu + C(\mu)$, where the subscript sc stands for the supply chain.

Theorem 1 *The buyer's operating cost $C(\mu)$ and the supply chain total cost $C_{sc}(c,\mu)$ are convex in $\mu \geq \lambda$.*

The proofs can be found in Cachon and Zhang (2006) and Zhang (2009) and therefore are omitted in this chapter. The above theorem implies that the supply chain's optimal capacity $\mu^{*}(c)$ must satisfy

$$C'(\mu^{*}) = -c. \qquad (4)$$

The cost functions $C(\mu)$ and $C_{sc}(c,\mu)$ are quite complex, and there is no closed-form expression for the supply chain's optimal solution. Cachon and Zhang (2006) offer an approximation of these cost functions. Notice the exponential distribution is the continuous counterpart of the geometric distribution. Hence we may use an exponential distribution with mean $E(N)$ to approximate the geometric distribution for N. This approximation can be justified in a heavy-traffic queuing system (Caldentey and Wein 2003). It tends to underestimate the average delivery lead time; however, Cachon and Zhang (2006) also demonstrate that this approximation is quite accurate when the system utilization is reasonably high. In the rest of the analysis, we will use $\hat{}$ to denote the variables under the approximation. Specifically, the supply chain's optimal solution is given by

$$\hat{\mu}^{*}(c) = \lambda + \sqrt{\alpha/c} \text{ and } \hat{s}^{*}(c) = \sqrt{c\alpha/h^{2}}, \qquad (5)$$

where $\alpha = h\lambda\ln((h+b)/h)$ is a constant. We will adopt this approximation for later analysis.

3.2 Buyer's Procurement Mechanisms

We present the buyer's procurement contracts in this subsection. (We will use the words "mechanism" and "contract" exchangeably in this chapter.) Three contracts are considered: optimal mechanism (OM), late-fee mechanism (LF), and lead-time mechanism (LT). The performances of these contracts will then be compared in the next subsection.

3.2.1 Optimal mechanism (OM)

The buyer needs to design a procurement mechanism to offer to the supplier. The mechanism is a mapping from the supplier's information space to the space of all possible action and payment schedules. Based on the revelation principle (Laffont and Martimort 2002), there exists an optimal mechanism that is both direct (i.e., the supplier's information space is identical to his private cost values) and truth-inducing (i.e., it is in the supplier's best interest to announce the true cost). Thus, without losing generality, we will restrict our attention to direct, truth-inducing mechanisms when searching for the optimal one.

The buyer's optimal mechanism consists of a pair of functions $\{\mu(\cdot), R(\cdot)\}$: If the supplier announces a cost x (which may not necessarily equal the true cost c), then the supplier will build a capacity $\mu(x)$ and receives a unit price $R(x)$ from the buyer. The optimal mechanism must satisfy two constraints. The first is the incentive compatibility (IC) constraint, i.e., the supplier will truthfully announce his cost under the optimal mechanism:

$$c = \arg\max_x \pi_2(x) = R(x)\lambda - c\mu(x), \tag{6}$$

where π_2 is the supplier's profit function. The second is the individual rationality (IR) constraint, i.e., all supplier types will participate:

$$\pi_2(c) \geq 0 \text{ for all } c \in [\bar{c}, \underline{c}]. \tag{7}$$

An implicit assumption is that even the least efficient supplier will earn a non-negative profit. That is, the buyer is willing to contract with all supplier types. The possibility of excluding certain supplier types will be discussed in §5.

The buyer's mechanism design problem can be now written as

$$\begin{aligned} &\min_{\mu(\cdot),R(\cdot)} \int_{\underline{c}}^{\bar{c}} \left(R(x)\lambda + C(\mu(x))\right) f(x)dx \\ &\text{s.t. } (6), (7) \end{aligned} \tag{8}$$

where $R(x)\lambda + C(\mu(x))$ is the buyer's total cost function for a given supplier cost x. The following theorem characterizes the buyer's optimal procurement mechanism.

Theorem 2 *The buyer's optimal mechanism $\{\mu^o(x), R^o(x)\}$ (i.e., the solution to (8)) is characterized by*

$$C'(\mu^o(x)) = -x - F(x)/f(x) \tag{9}$$

$$R^o(x)\lambda = x\mu^o(x) + \int_x^{\bar{c}} \mu^o(y)dy. \tag{10}$$

Recall $C(\mu)$ is the buyer's optimal operating cost function for a given μ. From (9) and (4), we see that there is $\mu^o(x) \leq \mu^*(x)$. This means that the optimal mechanism induces a capacity level lower than the optimal solution of the supply chain. Generally, we do not have closed-form expression for the optimal functions $\mu^o(x)$, $R^o(x)$ and their associated total cost for the buyer. However, later we will use numerical method to evaluate the optimal mechanism.

3.2.2 Lead-time mechanism (LT)

The optimal mechanism (OM) can maximize the buyer's expected payoff function, but it is quite complex and may be difficult to implement in practice. Cachon and Zhang (2006) also consider two suboptimal, but simpler mechanisms for the buyer. The first simple mechanism is called a lead-time mechanism (LT): The buyer posts a target (average) delivery lead time and sets a unit price. That is, the lead-time mechanism consists of two parameters, μ^t and R^t, the supplier's required capacity and the buyer's price per unit, respectively (the superscript t denotes the lead time). Note there is a one-to-one relationship between the supplier's capacity μ^t and the average lead time $(\mu^t - \lambda)^{-1}$. The practice of specifying a target delivery performance has been widely used in service outsourcing (Lacity and Willcocks 1998) and online procurement auctions (Rangan 1998).

The supplier's expected profit is $\pi_2(c) = \lambda R^t - c\mu^t$ under the lead-time mechanism. Hence the optimal unit price must be $R^t(\mu^t) = \bar{c}\mu^t/\lambda$ to ensure participation. Then the buyer's total cost can be written as

$$C_1^t(\mu^t) = C\left(\mu^t\right) + \lambda R^t\left(\mu^t\right) = C\left(\mu^t\right) + \bar{c}\mu^t,$$

which is the supply chain's cost with the highest capacity cost, $C_{sc}(\bar{c}, \mu^t)$. Thus the buyer will choose the supply chain's optimal capacity at cost $\bar{c}$: $\mu^t = \mu^*(\bar{c})$. Accordingly, the buyer pays the supplier $R^t(\mu^*(\bar{c}))$ to ensure participation. In fact, under the lead-time mechanism, the buyer sells the supply chain to the supplier and charges a price that is equal to the supply chain's optimal profit with the highest cost $\bar{c}$.

3.2.3 Late-fee mechanism (LF)

The second simple mechanism studied by Cachon and Zhang (2006) is called a late-fee mechanism (LF): The buyer pays the supplier a unit price R^f and meanwhile charges the supplier η^f for each outstanding order per unit time. The superscript f stands for late fee. This mechanism is quite intuitive, and has been observed in practice (Beth et al. 2003). For transparent analysis, we take advantage of the exponential approximation for N as described in § 3.1. Under this approximation, recall $\hat{\mu}(c) = \lambda + \sqrt{\alpha/c}$ minimizes the supply chain's total cost $\hat{C}_{sc}$.

In the late-fee mechanism, the supplier is free to choose his capacity to maximize his own profit. It is straightforward to show that the supplier's optimal capacity depends on the late fee η^f:

$$\mu^f(c) = \lambda + \sqrt{\eta^f \lambda / c}.$$

Suppose we choose the late fee that equalizes $\mu^f(c)$ and $\hat{\mu}(c)$ (i.e., the late fee will induce a capacity that minimize the supply chain's total cost under the approximation). This requires

$$\eta^f = \alpha/\lambda. \tag{11}$$

Clearly, this may not be the buyer's optimal late fee she would like to charge. Nevertheless, it will be shown that this late fee yields excellent results for the buyer.

We need to check the individual rationality constraint. To ensure participation, the buyer must pay a unit price R^f such that

$$\pi_2(\bar{c}) = R^f\lambda - \bar{c}\hat{\mu}(\bar{c}) - \eta^f\left(\frac{\lambda}{\hat{\mu}(\bar{c}) - \lambda}\right) = 0,$$

which gives

$$R^f = \bar{c} + 2\sqrt{\alpha \bar{c}}/\lambda. \tag{12}$$

It is worth noting that with the late fee, a base-stock policy may no longer be optimal for the buyer. This is because the buyer might have incentives to manipulate the ordering policy to take advantage of the late fee charged to the supplier. Here we assume the buyer is able to credibly commit to a base-stock policy. Alternative solution has been discussed in Cachon and Zhang (2006) when the buyer is unable to make such a commitment. Assuming that the base-stock policy is used by the buyer, then the optimal base stock level should be $s^*(\hat{\mu}(c))$ (since N does not depend on s).

3.3 Comparison of Mechanisms

The simple mechanisms are intuitive and easy to implement. In addition, they do not require the supplier's information as an input to determine the contract parameters. This is a desirable property for two reasons. First, in many situations the supplier may be reluctant to reveal his true efficiency level. Second, under the simple mechanisms, the contract parameters can be determined even before the supplier's cost is realized (this gives more flexibility in contract negotiation). Despite these merits of the simple mechanisms, they do not yield the optimal profit for the buyer. We investigate the performance of the simpler contracts (LF and LT) relative to the optimal mechanism (OM) in this subsection. This will help us quantify the value of using a more complex procurement contract in practice. We first compare the procurement contracts analytically by making some simplifying assumptions, then we use an extensive numerical study to confirm the generality of the insight from the analytical comparison.

3.3.1 Analytical comparison

We compare the optimal mechanism and the late-fee mechanism analytically. The comparison of the optimal mechanism and the lead-time mechanism is similar and therefore omitted. The analysis with the actual cost functions is challenging, so we use the exponential approximation introduced in §3.1. Also, we focus on uniform distribution F for the supplier's cost c. Recall $[\underline{c}, \bar{c}]$ is the support of the supplier's cost distribution. Let $\bar{c} = \theta(1+\delta)$ and $\underline{c} = \theta(1-\delta)$, where θ is the mean cost and δ measures the cost variation.

With uniform distribution, there are $F(c) = (c - \underline{c})/2\delta\theta$, $f(c) = 1/2\delta\theta$, and $F(c)/f(c) = c - \underline{c}$. The optimal mechanism in Theorem 2 satisfies

$$C'(\mu^o) = -c - F(c)/f(c) = -2c + \underline{c}. \tag{13}$$

By replacing $C'(\mu^o)$ with $\hat{C}'(\mu^o)$ in (13), we have

$$\hat{\mu}^o(c) = \lambda + \sqrt{\frac{\alpha}{2c - \underline{c}}}.$$

The buyer's operating cost can be then written as

$$\hat{C}(c) = \hat{C}(\hat{\mu}(c), c) = \sqrt{\alpha(2c - \underline{c})}.$$

From Theorem 2, with the optimal contract the buyer's total cost is

$$\hat{C}_1^o(c) = \hat{C}(c) + c\hat{\mu}^o(c) + \int_c^{\bar{c}} \hat{\mu}(y)dy = \bar{c}\lambda + \sqrt{\alpha}\left(\frac{c}{\sqrt{2c - \underline{c}}} + \sqrt{2\bar{c} - \underline{c}}\right).$$

It can be readily shown that in the late-fee mechanism, the buyer pays the supplier $R^f\lambda = \bar{c}\lambda + 2\sqrt{\alpha\bar{c}}$, incurs an operating cost $\hat{C}(\mu^f(c)) = \sqrt{\alpha c}$, and collects total late fee $\sqrt{\alpha c}$. Thus the buyer's total cost is

$$\hat{C}_1^f = R^f\lambda = \bar{c}\lambda + 2\sqrt{\alpha\bar{c}}.$$

Note, the buyer's total cost is independent of c, which implies that with the late-fee mechanism the buyer is unable to extract any rents from efficient supplier types.

Now we are ready to compare the optimal and late-fee mechanisms. Notice that $\hat{C}_1^o(c)$ is increasing in c and $\hat{C}_1^o(\underline{c}) < \hat{C}_1^f < \hat{C}_1^o(\bar{c})$. Therefore, the buyer's expected cost with the optimal mechanism, $E[\hat{C}_1^o(c)]$, is approximately equal to the buyer's expected cost with the late-fee mechanism, $\hat{C}_1^f$, if $\hat{C}_1^o(c)$ is relatively flat. This is manifested by considering the following ratio:

$$\frac{\hat{C}_1^o(\bar{c})}{\hat{C}_1^o(\underline{c})} = \frac{\bar{c}\lambda + \sqrt{\alpha}\left(\frac{\bar{c}}{\sqrt{2\bar{c}-\underline{c}}} + \sqrt{2\bar{c} - \underline{c}}\right)}{\bar{c}\lambda + \sqrt{\alpha}\left(\sqrt{\underline{c}} + \sqrt{2\bar{c} - \underline{c}}\right)} < \frac{2 + 4\delta}{\sqrt{(1+3\delta)(1-\delta)} + (1+3\delta)}, \tag{14}$$

where the inequality follows because $\bar{c} > \sqrt{\underline{c}}\sqrt{2\bar{c} - \underline{c}}$. The right hand side of (14) equals 1.025 and 1.075 with $\delta = 0.2$ and $\delta = 0.4$, respectively. So even if the supplier's cost can vary up to 40% around its mean ($\delta = 0.4$) and the demand rate is extremely small, in the optimal mechanism the buyer's total cost with the highest cost supplier is no more than 7.5% higher than that with the lowest cost supplier. This suggests that the cost function is indeed flat, i.e., $\hat{C}_1^f$ in that case cannot be more than 7.5% higher than $E[\hat{C}_1^o(c)]$.

The above analysis suggests that the buyer's total cost is relatively insensitive to the supplier's capacity cost with the optimal mechanism. That is, asymmetric information conveys substantial protection to a supplier: An efficient supplier is able to keep essentially all the benefit from having a low cost, even when the buyer adopts the complex, optimal mechanism. This implies that the optimal mechanism is not very effective in extracting the efficiency rents from the supplier. As a result, the late-fee mechanism performs very well even if it extracts no rents at all.

Finally, it is worth pointing out that the above observation is not because the supply chain's cost function is flat. With the supply chain's optimal cost we obtain the following ratio:

$$\frac{\hat{C}_{sc}^*(\bar{c})}{\hat{C}_{sc}^*(\underline{c})} = \frac{(1+\delta)\lambda + 2\sqrt{\alpha(1+\delta)}}{(1-\delta)\lambda + 2\sqrt{\alpha(1-\delta)}} > \sqrt{\frac{1+\delta}{1-\delta}}. \tag{15}$$

The value of the ratio is 1.22 and 1.53 for $\delta = 0.2$ and $\delta = 0.4$, respectively. That is, the supply chain's cost with the least efficient supplier could be much higher than that with the most efficient supplier (53% higher when $\delta = 0.4$).

3.3.2 Numerical study

To confirm the results from the analytical comparison, Cachon and Zhang (2006) present a comprehensive numerical study with the following design: $h = 1$, $\lambda \in \{0.1, 1, 10, 100\}$,

$b \in \{3, 40, 200\}$, c follows either a uniform or normal distribution on the interval $[\underline{c}, \bar{c}]$, where $\underline{c} = \theta(1-\delta)$ and $\bar{c} = \theta(1+\delta)$, $\theta \in \{0.5, 5, 50, 200\}$ and $\delta \in \{0.05, 0.1, 0.2\}$. The value of δ measures the magnitude of cost uncertainty. For instance, $\delta = 0.05$ corresponds to reasonably small uncertainty in supplier's cost (within 5% of forecast) and the scenarios with $\delta = 0.20$ represents high uncertainty. With normal cost distribution, the mean is set to be θ and the standard deviation $\delta\theta/4$. The value of h is fixed because the buyer's total cost only depends on the relative magnitude of the parameters c, b, and h. The backorder cost b is allowed to range from a low value of three times h to a high value of two hundred times h. The mean capacity costs range from $\theta = 0.5$ to $\theta = 200$, which corresponds to very low and very high utilizations respectively. There are totally 144 scenarios in this numerical study for each cost distribution.

The results from the numerical study are summarized in Table 1. The percentiles of the buyer's percentage cost increase in each simple mechanism relative to the optimal mechanism (OM) are listed. For example, with the lead-time mechanism (LT), the 90th percentile of the buyer's percentage cost increase relative to the optimal mechanism is only 0.24%. That is, if the buyer adopts the lead-time mechanism rather than the optimal one, the percentage cost increase is less than 0.24% for 90 percent of the scenarios. Among all tested scenarios, the buyer's maximum percentage cost increase is 3.53% (with the LF mechanism and normal cost distribution). Overall, Table 1 shows that the lead-time and late-fee mechanisms perform quite well, for both uniform and normal cost uncertainties.

Why does the optimal mechanism perform poorly in extracting the supplier's information rent in this model setting? An intuitive explanation is as follows. Notice the market demand is exogenously given (and so is the supply chain's revenue). Inducing truth telling by using a cost-contingent service-level can reduce the supply chain's operating cost for satisfying the market demand; however, it is the buyer who is responsible for such an operating cost. Hence the supplier has little incentive to share the true cost information unless he will keep essentially all the benefits from a low cost realization.

Table 1. Buyer's percentage cost increase relative to the optimal mechanism (with a single supplier).

		average	90^{th} percentile	maximum
Uniform cost distribution	LT	0.09%	0.24%	0.56%
	LF	0.20%	0.19%	2.85%
Normal cost distribution	LT	0.50%	1.20%	2.39%
	LF	0.60%	1.38%	3.53%

Cachon and Zhang (2006) also consider the firms' incentives to renegotiate the contract in such a problem setting. In particular, they compare the supply chain performance under these mechanisms to the supply chain's centralized optimal performance using the same scenarios above. The result is given in Table 2 (the case with two suppliers is also presented; see Section 3.4.1 for the analysis of multiple competing suppliers). Interestingly, the numerical study indicates that these mechanisms are generally associated with very small supply chain inefficiency, i.e., there is a negligible renegotiation value for the supply chain firms. This also suggests that supply chain coordination can be nearly achieved even when the buyer is self-interested and chooses her own procurement mechanism under information asymmetry.

Table 2. Supply chain's percentage cost increase relative to the supply chain optimal solution, i.e., the supply chain inefficiency or the value of renegotiation (with uniform cost distribution).

		average	90^{th} percentile	maximum
	OM	0.08%	0.23%	0.51%
Single	LT	0.10%	0.30%	0.67%
supplier	LF	0.25%	0.36%	3.53%
	OM	0.05%	0.14%	0.30%
$n = 2$	LT	0.06%	0.18%	0.41%
suppliers	LF	0.25%	0.39%	3.78%

There are a couple of additional observations in the more detailed numerical analysis in Cachon and Zhang (2006). First, it has been found that η^f is nearly optimal from the buyer's standpoint (recall η^f is derived by equating the induced capacity with the supply chain's optimal capacity), and therefore it is not necessary to search for the true optimal late fee. However, this approximation causes the LT mechanism to perform slightly better than the LF mechanism as shown in Table 1. Second, they also test extremely large cost uncertainty with $\delta = 0.40$ and obtain similar results. This confirms the robustness of the results in Tables 1 and 2.

3.4 Extensions

3.4.1 Multiple competing suppliers

We first extend the basic model to include multiple competing suppliers. In this case, the buyer may select the most efficient supplier through competitive bidding. Suppose there are $n \geq 2$ suppliers. Each supplier's cost c^i is a random draw from a common distribution F (density f). Let $\mathbf{c} = (c^1, \cdots, c^n)$ be the cost vector of the suppliers. Similar to the single-supplier case, the buyer's optimal mechanism consists of a menu of contracts, $\{q^i(\cdot), \mu^i(\cdot), R^i(\cdot)\}$, $i = 1, 2, ..., n$. Under this mechanism, if the suppliers announce their costs to be $\mathbf{x} = (x^1, \cdots, x^n)$, then supplier i is the winner with probability $q^i(\mathbf{x}) \geq 0$ and $\sum q^i(\mathbf{x}) = 1$, supplier i receives a unit price $R^i(\mathbf{x})$ from the buyer, and finally, the winner builds capacity $\mu^i(\mathbf{x})$.

To derive the buyer's optimal mechanism, we start with the suppliers' bidding behavior. Each supplier aims to maximize his own profit. Thus for supplier i we have

$$\max_{x^i} \pi_2^i = E_{\mathbf{x}^{-i}}[R^i(\mathbf{x})\lambda - q^i(\mathbf{x})c^i\mu^i(\mathbf{x})],$$

where $\mathbf{x}^{-i} = (x^1, \cdots, x^{i-1}, x^{i+1}, \cdots, x^n)$ and π_2^i is supplier i's expected profit. Again, by the revelation principle, we have the following incentive compatibility and individual rationality constraints:

$$c^i = \arg\max_{x^i} \pi_2^i(x^i) \tag{16}$$

and

$$\pi_2^i(c^i) \geq 0. \tag{17}$$

Hence the buyer's problem can be written as

$$\begin{array}{ll} \min_{\{q^i(\cdot),\mu^i(\cdot),R^i(\cdot)\}} & E_{\mathbf{c}}\{\sum_i R^i(\mathbf{c})\lambda + \sum_i [q^i(\mathbf{c})C(\mu^i(\mathbf{c}))]\} \\ \text{s.t.} & (16) \text{ and } (17) \end{array} \tag{18}$$

Theorem 3 *The buyer's optimal mechanism with $n \geq 2$ competing suppliers is as follows: The buyer offers the suppliers identical menu of contracts $\{q^o(\cdot), \mu^o(\cdot), R^o(\cdot)\}$ characterized by*

$$\begin{aligned} C'(\mu^o(x)) &= -x - F(x)/f(x), \\ R^o(x)\lambda &= (1-F(x))^{n-1} x \mu^o(x) + \int_x^{\bar{c}} (1-F(y))^{n-1}\mu^o(y)dy \\ q^o(x) &= \begin{cases} 1 & \text{if } x = \min(x^1, \cdots, x^n) \\ 0 & \text{otherwise} \end{cases}. \end{aligned}$$

The suppliers announce their true costs and the most efficient supplier will be chosen.

A couple of observations can be made about the above optimal mechanism with $n \geq 2$ suppliers. First, the capacity function $\mu^o(x)$ is independent of the number of suppliers, n. This suggests that as in the single-supplier case, the optimal mechanism results in less capacity than optimal for the supply chain when there are multiple competing suppliers. Second, this optimal mechanism does not have an intuitive format. Notice that every losing bidder will receive a payment even though they do not build any capacity for the buyer. However, it can be shown that such a strange mechanism can be implemented with an equivalent auction where only the winner receives a payment (see Zhang 2004 for details).

A natural extension of the lead-time mechanism with a single supplier to $n \geq 2$ potential suppliers is as follows: The buyer announces the lead time the winning supplier must deliver and then ask the suppliers to bid on price. In particular, we assume the buyer uses a second-bid auction (i.e., the supplier with the lowest bid wins but he only needs to fulfil the second-lowest bid). Zhang (2004) considers first-bid auctions and shows that they yield the same expected payoff for the buyer (i.e., revenue equivalence holds in this case). However, the revenue equivalence may fail to hold if the buyer specifies a price and asks the suppliers to bid on lead time; this is because the lead time bids have different variances in the first-bid and second-bid auctions. Since there is a one-to-one relationship between the average lead time and the supplier's capacity, it is equivalent for the buyer to announce a required capacity, μ^t, rather than a lead time.

Theorem 4 *In the lead-time mechanism with $n \geq 2$ competing suppliers, the weakly dominant strategy for a supplier with capacity cost x is to bid $R^t(x) = \mu^t x/\lambda$. The buyer's expected total cost is convex in μ^t.*

Alternatively, the buyer may specify a late fee η^f for each outstanding order and ask the suppliers to bid on price. Again we focus on the second-bid auctions. Because the suppliers' capacity choice depends on the late fee but not the price bid, the winner with a cost x will choose capacity $\hat{\mu}(x)$. As with one potential supplier, we assume the buyer sets $\eta^f = \alpha/\lambda$. Although this is not the buyer's optimal late fee, later we show that it performs very well.

Theorem 5 *In the late-fee mechanism with $n \geq 2$ competing suppliers, the suppliers' dominant strategy is to bid $R^f(x) = \hat{C}^*_{sc}(x)/\lambda$ and the winner chooses capacity $\mu^f(x) = \hat{\mu}(x)$.*

Finally, a numerical study is used to compare the mechanisms with $n \geq 2$ suppliers. Since the qualitative results are similar for different n values, here we focus on $n = 2$. The parameter values are the same as in §3.3.2. Table 3 summarizes the results from this numerical study. We see that the simple mechanisms again are nearly optimal when there are multiple competing suppliers.

Table 3. Buyer's percentage cost increase relative to the optimal mechanism (with $n = 2$ suppliers).

		average	90^{th} percentile	maximum
Uniform	LT	0.18%	0.31%	0.59%
cost distribution	LF	0.32%	0.31%	3.27%
Normal	LT	0.02%	0.06%	0.12%
cost distribution	LF	0.23%	0.27%	3.40%

3.4.2 Generalized holding cost

We have assumed in the basic model that the buyer's inventory holding cost is a constant and independent of the procurement price. Now we consider a generalized holding cost. Let h be a function of the unit cost, $h = h_0 + rv$, where h_0 is a constant representing the physical holding cost, r is the interest rate and v is the buyer's effective unit cost. Notice that the effective unit cost may not equal the unit price R. For example, the buyer's effective unit cost with a late fee is the unit price minus the late fee. The buyer's operating cost is

$$C(\mu, v) = (h_0 + rv)\left[\frac{1 - \ln\left(\left(\frac{h_0+rv}{h_0+rv+b}\right)\left(\frac{\mu/\lambda-1}{\ln \mu/\lambda}\right)\right)}{\ln \mu/\lambda} - \frac{1}{\mu/\lambda - 1}\right]. \tag{19}$$

The evaluation of the optimal mechanism with this new holding cost structure is quite difficult. There are two major complications. First, $C(\mu, v)$ is not always jointly convex. Second, the payment and the capacity functions are inter-dependent in the optimality conditions (i.e., they cannot be solved separately). As a result, we need to evaluate the optimal mechanism via a full enumeration over the contract space. Specifically, we can only determine the optimal mechanism when the suppliers' costs are drawn from a discrete distribution and the suppliers are only allowed to choose capacities from a discrete set.

The process for evaluating the lead-time mechanism does not require an adjustment due to the generalized holding cost. On the other hand, the late-fee mechanism requires an adjustment because the supply chain optimal capacity with the exponential approximation, $\hat{\mu}(c)$, no longer takes a simple form proportional to $\sqrt{1/c}$. We first find the capacity that minimizes the supply chain's cost when $c = \theta$ (recall θ is the mean of the cost distribution):

$$\mu_\theta = \arg\min_{\mu}(C(\mu, \theta) + \theta\mu).$$

Because there is no closed-form solution for μ_θ, a one-dimensional search is needed to find μ_θ. Given the late fee η^f, the supplier's optimal capacity is $\mu^f = \lambda + \sqrt{\eta^f \lambda/\theta}$. Equating μ_θ with μ^f yields

$$\eta^f = \theta(\mu_\theta - \lambda)^2/\lambda.$$

Hence, we set the late fee to coordinate the supply chain with the average cost supplier. With a single potential supplier, R is chosen so that the high cost supplier earns zero profit:

$$R^f = \bar{c} + 2\sqrt{\eta^f \bar{c}/\lambda}.$$

With two or more suppliers, an auction sets the price R^f.

To test this version of the late-fee mechanism, we take the original set of 144 scenarios and add three interest rate levels, $r = \{0.05, 0.1, 0.2\}$, to arrive at 432 scenarios. For each scenario, we divide the cost support $[\theta(1-\delta), \theta(1+\delta)]$ into $m-1$ equal intervals and assume each are equally likely (i.e., a discrete uniform distribution). Similarly, we divide the range $[1.1\lambda, 10\lambda]$ into $l-1$ equal intervals and use the l interval boundaries as the feasible capacities. As m and l are increased, our discrete problem approaches the continuous problem we studied with a fixed holding cost. However, as we already mentioned, the computational burden increases rapidly with m and l. In our numerical study, we set $m = 5$ and $l = 20$.

Table 4 shows the performance of the lead-time and late-fee mechanisms relative to the optimal mechanisms. Even with this holding cost, both mechanisms are nearly optimal with a single supplier. With multiple suppliers the mechanisms perform well, but now the average cost increase is a noticeable 2.61% with either mechanism. We suspect that this gap with the optimal mechanism is in large part due to the coarse discretization because the gap decreases quickly as the number of supplier cost realizations (m) increases (a sample of the scenarios $m = 7$ and $m = 9$ have been tested). Overall, we conclude that the lead-time and late-fee mechanisms perform reasonably well when the holding cost is a linear function of the buyer's procurement cost.

Table 4. Buyer's percentage cost increase relative to the optimal mechanism (with generalized holding cost $h = h_0 + rv$).

		average	90^{th} percentile	maximum
Single	LT	0.15%	0.66%	2.22%
supplier	LF	0.18%	0.64%	3.70%
$n = 2$	LT	2.61%	4.53%	12.19%
suppliers	LF	2.61%	4.60%	11.87%

3.4.3 Make-to-order buyer

In the basic model the buyer can hold inventory as a buffer to mitigate the consequence of slow delivery from the supplier. One may wonder whether the main results continue to hold when the buyer cannot hold inventory (e.g., the buyer is a make-to-order manufacturer). This also covers an important situation where the buyer is a service provider. Hence, in this section we investigate the performance of the lead-time and late-fee mechanisms when $s = 0$.

Consider the single-supplier case. Now the buyer's operating cost only consists of the waiting cost: $C(\mu) = \lambda b/(\mu - \lambda)$. We can derive the optimal mechanism as in Theorem 2. The simple mechanisms for the buyer are as follows. The buyer's optimal lead-time mechanism specifies capacity $\mu^t = \lambda + \sqrt{b\lambda/\bar{c}}$ and charges unit price $R^t(\mu^t) = \bar{c} + \sqrt{b\bar{c}/\lambda}$.

In the optimal late-fee mechanism, the late fee η^f and R^f are given by

$$\eta^f = \left(\frac{E(\sqrt{c})}{2\sqrt{\bar{c}} - E(\sqrt{c})} \right) b, \quad (20)$$

$$R^f = \bar{c} + 2\sqrt{\eta^f \bar{c}/\lambda}. \quad (21)$$

The mechanisms with multiple suppliers can be derived similarly. The details can be found in Cachon and Zhang (2006).

Table 5 reports the results from a numerical study using the same scenarios defined in §3.3.2 and uniform cost distribution. We see that both the lead-time and the late-fee mechanisms perform well relative to the optimal mechanism. Thus the simple mechanisms continue to perform well even if the buyer is unable to use inventory to buffer the supplier's lead time performance.

Table 5. Buyer's percentage cost increase relative to the optimal mechanism (with uniform cost distribution and $s = 0$).

		average	90^{th} percentile	maximum
Single	LT	0.13%	0.40%	0.55%
supplier	LF	0.03%	0.08%	0.12%
$n = 2$	LT	0.21%	0.43%	0.51%
suppliers	LF	0.14%	0.20%	0.24%

4 Contracting with Make-to-stock Supplier

We proceed in this section to study another common situation that may arise in practice: The supplier adopts a make-to-stock strategy and thus may hold inventory to improve customer service. Specifically, we model the supply chain as a two-echelon inventory system, which requires quite different analysis from that in §3.

4.1 Basic Model

A buyer needs an input (say, a product) from a supplier to satisfy market demand. The supplier's marginal production cost c is private information and modeled as a random draw from a log-concave distribution F (density f) with support $[\underline{c}, \bar{c}]$. The buyer knows the distribution function F, but not the exact cost at the supplier. Thus F represents the cost uncertainty faced by the buyer. This information structure is the same as in §3 except that now c is the production cost rather than the cost rate for maintaining a certain capacity.

We consider a two-echelon inventory system under periodic review. Again we use subscripts 1 and 2 for the buyer and supplier, respectively. The supplier either manufactures the product or obtains it from an ample external source. Assume there is a constant production or replenishment lead time L_2 for the supplier. The transportation time from the suppliers to the buyer is L_1, which may also represent the assembly time at the buyer. To maintain tractability, assume both the supplier and the buyer adopt stationary base stock policies. Let s_1 and s_2 denote the local base-stock levels adopted by the buyer and the supplier. We define the service level as the fill rate provided by the supplier (i.e., the expected percentage of an order that can be fulfilled immediately). It is clear that there is a one-to-one relationship between the base stock level s_2 and the fill rate. That is, all else being equal, a more responsive delivery performance is equivalent to a higher base-stock level s_2.

The firms incur linear inventory holding cost. The buyer's holding cost rate is h_1, and the supplier's holding cost rate is $h_2 = h_0 + rc$, where h_0 is a constant and r is the interest rate. Here we follow the basic model in §3.1 to assume that h_1 is independent of the procurement price. This applies to consignment arrangements under which the buyer pays the supplier only after the product is sold. Also §3.4.2 demonstrates that generalizing this holding cost assumption does not change the qualitative insight (with a make-to-order supplier).

The buyer faces a random demand in each period and the demand distribution is i.i.d. across periods. Use D^τ to denote the demand over τ periods, so D^{L_j} is the lead time demand for stage j ($j = 1, 2$). Define $\omega^\tau = E(D^\tau)$ as the mean demand over τ periods. Let ω denote the single-period mean demand. Let Φ^τ and ϕ^τ be the cumulative distribution function and density function, respectively, of demand over τ periods. Assume $\Phi^\tau(x)$ is differentiable for all positive integers τ. In other words, the demand has continuous density. Furthermore, assume $\Phi^1(0) = 0$, so only positive demand occurs in each period. Unmet demand in each period is backlogged and the buyer incurs a backorder cost b for each backlogged unit.

The timing of the model is similar to that with a make-to-order supplier (see §3.1). The only difference is that now the supplier chooses the base-stock level s_2 instead of the capacity level μ. Both firms are risk-neutral in this model. The buyer wants to minimize the expected total cost in each period, i.e., the procurement price plus the operating cost. The supplier's objective is to maximize the expected profit per period, which equals the procurement price paid by the buyer minus the production and inventory holding costs. For concision, define $x \wedge y = \min(x, y)$ and $x \vee y = \max(x, y)$.

This model is based on the two-echelon inventory system studied by Zhang (2009). He considers a more general setting where the buyer can set price to influence market demand. In this section we focus on a special case with exogenous demand. This simplifies the analysis but sharpens the insight we would like to emphasize. We will follow the cost accounting scheme proposed by Chen and Zheng (1994) for the analysis.

4.2 Buyer's Procurement Mechanisms

4.2.1 Optimal mechanism (OM)

As preparation, we first derive the buyer's optimal base stock level s_1 given the supplier's base stock level s_2. Define

$$\tilde{G}_1(x) = h_1(x)^+ + b(x)^-.$$

Let y be the buyer's inventory position in period t. Then the cost incurred at the buyer in period $t + L_1$ is:

$$\begin{aligned} G_1(y) &= E[\tilde{G}_1(y - D^{L_1+1})] \\ &= h_1(y - \omega^{L_1+1}) + (h_1 + b) \int_y^\infty (x - y)\phi^{L_1+1}(x)dx. \end{aligned}$$

It can be readily shown that $G_1(y)$ is strictly convex. Let $H_1(s_1, s_2)$ denote the buyer's operating cost function (inventory holding cost plus backorder cost). Using function G_1, $H_1(s_1, s_2)$ can be written as

$$H_1(s_1, s_2) = E[G_1(s_1 \wedge (s_1 + s_2 - D^{L_2}))], \tag{22}$$

where $s_1 + s_2$ is the echelon base stock level for the supplier. It is straightforward to show that $H_1(s_1, s_2)$ is convex in s_1 and, hence, there is a unique optimal base stock level $s_1(s_2)$ for given s_2. We have the following Lemma.

Lemma 6 *(i) $s_1(s_2)$ is decreasing in s_2;*
(ii) $s_1(s_2) \to \hat{s}_1$ as $s_2 \to \infty$, where $\hat{s}_1 = (\Phi^{L_1+1})^{-1}(b/(h_1 + b))$.

It can be shown that $H_1(s_1(s_2), s_2)$ may not be convex in s_2. However, we can prove the following useful properties about $H_1(s_1(s_2), s_2)$.

Lemma 7 *(i) $\frac{dH_1(s_1(s_2),s_2)}{ds_2} = 0$ for $s_2 = 0$ and $\frac{dH_1(s_1(s_2),s_2)}{ds_2} < 0$ for $s_2 > 0$;*
(ii) $\left(\frac{dH_1(s_1(s_2),s_2)}{ds_2}\right) / \Phi^{L_2}(s_2)$ is increasing in s_2.

Now we derive the buyer's optimal mechanism. Suppose the buyer offers a menu of contracts $\{s_2(\cdot), T(\cdot)\}$ to the supplier. If the supplier announces the cost to be x (x is not necessarily the true cost c), then he is supposed to receive a unit price $T(x)$ and adopt a base stock level $s_2(x)$. Define

$$H_2(c, s_2) = (h_0 + rc)\{E[s_2 - D^{L_2}]^+ + \omega^{L_1}\}$$

as the supplier's operating cost (i.e., inventory holding cost). Given the above contract, the supplier's profit is as follows:

$$\pi_2(x) = \omega(T(x) - c) - H_2(c, s_2(x)).$$

According to the revelation principle, we only need to consider the truth-inducing contracts (i.e., the IC constraint):

$$c = \arg\max_x \pi_2(x). \tag{23}$$

In addition, the buyer needs to make sure that the supplier will accept the contract even with the highest cost $\bar{c}$ (i.e., the IR constraint):

$$\pi_2(\bar{c}) \geq 0. \tag{24}$$

The buyer's problem is then given by

$$\min_{\{s_2(\cdot),T(\cdot)\}} \int_{\underline{c}}^{\bar{c}} \left[H_1(s_1, s_2(x)) + \omega T(x)\right] f(x)dx \tag{25}$$
$$\text{s.t. (23) and (24).}$$

Theorem 8 *The buyer's optimal menu of contracts $\{s_2^o(\cdot), T^o(\cdot)\}$ (i.e., the solution to (25)) is characterized by*

$$\frac{dH_1(s_1(s_2^o), s_2^o)/ds_2^o}{\Phi^{L_2}(s_2^o)} = -[h_0 + rx + rF(x)/f(x)] \tag{26}$$

$$\omega T^o(x) = \omega\bar{c} + H_2(\bar{c}, s_2^o(\bar{c})) - \int_x^{\bar{c}} (h_0 + ry)s_2^{o\prime}(y)\Phi^{L_2}(s_2^o(y))dy. \tag{27}$$

Because the left-hand side of Equation (26) is increasing in s_2 (see Lemma 7) and the right-hand side is decreasing in x, we know that $s_2^o(x)$ is a decreasing function in the optimal mechanism. This implies that in the optimal mechanism, a less efficient supplier will use a lower stocking level. Although a closed-form solution to the stocking level function $s_2^o(x)$ is not available, we are able to show in the next theorem that in the optimal mechanism, the buyer tends to induce a fill rate that is lower than the supply chain optimal. This distortion is because the buyer wants to reduce the information rent paid to the supplier to minimize cost. Let (s_1^*, s_2^*) denote the supply chain's optimal inventory policy, where s_1^* and s_2^* are the local base-stock levels at the buyer and the supplier, respectively.

Theorem 9 *The stocking level specified by (26) in the optimal mechanism is lower than the supply chain's optimal stocking level, i.e.,* $s_2^o(x) \leq s_2^*(x)$ *for all* x.

4.2.2 Fixed service-level contract (FS)

A widely observed supply agreement in practice is that the buyer specifies a service-level requirement and compensates the supplier with a price. Call this a fixed service-level contract (FS). Practical examples of contracts involving inventory service-level agreements can be found in Thonemann et al. (2005), Thomas (2005), and Katok et al. (2008). In such a contract, the buyer needs to propose a price so that the supplier is willing to participate. Note that specifying a fill rate is equivalent to specifying the base stock level s_2. Given a base stock level s_2, the supplier's total cost per period is

$$C_2(s_2) = c\omega + H_2(c, s_2).$$

To ensure supplier participation, the buyer needs to pay the supplier

$$\omega T = \bar{c}\omega + H_2(\bar{c}, s_2).$$

The buyer's total cost in fixed service-level contract is then given by

$$C_1(s_2) = H_1(s_1(s_2), s_2) + \bar{c}\omega + H_2(\bar{c}, s_2).$$

It can be readily shown that $C_1(s_2)$ is quasiconvex and has a unique global minimizer.

To minimize total cost, the buyer will choose an s_2 which is optimal for the supply chain with production cost $\bar{c}$. Hence in the fixed service-level contract, the buyer essentially sells the supply chain to the supplier and charges a price that is equal to the supply chain's optimal profit with cost $\bar{c}$.

4.3 Comparison of Mechanisms

In this subsection, we compare the performances of the two procurement mechanisms in §4.2. Because obtaining closed-form expressions for the buyer's profit is difficult in such an inventory system, we concentrate on a numerical study for the comparison. The following parameter values are used. Fix $h_0 = 1$ (the result of the numerical study only depends on the relative magnitude of the parameter values). We assume the supplier's cost c follows either a uniform distribution or normal distribution on the support $[\underline{c}, \bar{c}]$, where $\underline{c} = \theta(1-\delta)$ and $\bar{c} = \theta(1+\delta)$, $\theta \in \{10, 100, 1000\}$ and $\delta \in \{0.1, 0.2, 0.3\}$. With normal distribution, we set the standard deviation to be $\delta\theta/4$. Note that with $\delta = 0.3\theta$, the ratio $\bar{c}/\underline{c} \approx 1.86$, which represents an unusually high uncertainty in the supplier's production cost. As to the supplier's holding cost, we set $r \in \{1\%, 5\%, 10\%\}$. In view of the 15% annual opportunity cost rate commonly found in textbooks, $r = 10\%$ is quite large for a biannually-reviewed inventory model, not to mention even shorter review periods. In the numerical study, we set $h_1 = \alpha_h(h_0 + r\bar{c})$ and choose $\alpha_h \in \{2, 4\}$ (this implies $h_1 > h_2$, which is commonly assumed in the literature). Similarly, we let $b = \alpha_b h_1$ and choose $\alpha_b \in \{1, 10, 40\}$. Finally, the single-period demand follows a normal distribution with a mean of 20 and a standard deviation of 5 (there is a negligible probability for negative demand), and the lead times are $L_1 = 4$ and $L_2 \in \{2, 4, 8\}$. There are 486 combinations in total in this numerical study. Among the 486 parameter combinations, the expected fill rate in the optimal mechanisms ranges from 64% to 98%.

Table 6 presents the percentage cost increase of the FS mechanism relative to the optimal mechanism (OM). We see that the simple mechanism is nearly optimal: The maximum cost increase among all tested scenarios is only 0.42%. This observation has been confirmed by additional numerical experiments conducted in Zhang (2009) (e.g., the demand follows a gamma distribution and the supplier's cost has a highly skewed two-point distribution).

Table 7 provides data on the supply chain efficiency in different procurement mechanisms (OM and FS). (The analysis for $n = 2$ suppliers is given in the next subsection.) The data represents the percentiles of the percentage cost increase in the supply chain for different mechanisms, as compared to the supply chain optimal solution. Interestingly, both mechanisms create negligible inefficiency to the supply chain: The maximum efficiency loss for the supply chain is 0.09% in this numerical study.

In sum, we have extended the results from the previous section (§3 with a make-to-order supplier) to the situation with a make-to-stock supplier. That is, the simple mechanism is quite attractive from both the buyer's and the system's perspectives.

Table 6. Buyer's percentage cost increase relative to the optimal mechanism (with a single supplier).

		average	90^{th} percentile	maximum
Uniform cost distribution	FS	0.01%	0.03%	0.07%
Normal cost distribution	FS	0.08%	0.18%	0.42%

Table 7. The expected supply chain inefficiency in different procurement mechanisms (with uniform cost distribution).

		average	90^{th} percentile	maximum
Single	OM	0.01%	0.03%	0.08%
supplier	FS	0.01%	0.04%	0.09%
$n = 2$	OM	0.01%	0.02%	0.06%
suppliers	FS	0.01%	0.03%	0.07%

4.4 Multiple Competing Suppliers

As in §3.4.1, we may extend the basic model to consider $n \geq 2$ potential suppliers. In this case, the buyer can design a competition mechanism for the suppliers and select the most efficient one to source from. The same notations in §3.4.1 will be used here.

First we derive the optimal mechanism with $n \geq 2$ suppliers. Consider the following menu of contracts: $\{q^i(\cdot), s_2^i(\cdot), T^i(\cdot)\}$, $i = 1, 2, ..., n$. That is, if the suppliers announce their costs to be $\mathbf{x} = (x^1, ..., x^n)$, then supplier i is the winner with probability $q^i(\mathbf{x}) \geq \mathbf{0}$; supplier i receives a payment $\omega T^i(x^i)$; the winner serves the buyer by using a base stock level $s_2^i(x^i)$; and the losers do nothing but enjoy the payment.

The analysis starts with the supplier's bidding behavior. Supplier i maximizes the expected profit:

$$\max_{x^i} \pi_2^i = E_{\mathbf{x}^{-i}}[\omega T^i(x^i) - q^i(\mathbf{x})(c^i\omega + H_2(c^i, s_2^i(x^i))].$$

We focus on truth-inducing mechanisms, i.e.,

$$c^i = \arg\max_{x^i} \pi_2^i(x^i). \tag{28}$$

The participation constraint or individual rationality constraint is

$$\pi_2^i(c^i) \geq 0. \tag{29}$$

Then the buyer's problem is

$$\begin{aligned} &\min_{\{q^i(\cdot), s_2^i(\cdot), T^i(\cdot)\}} E_{\mathbf{c}}\{\textstyle\sum_i^n \omega T^i(c^i) + \sum_i^n [q^i(\mathbf{c}) H_1(s_1, s_2^i(c^i))]\}. \\ &\text{s.t. (28) and (29)} \end{aligned} \tag{30}$$

The following theorem gives the solution to (30).

Theorem 10 *The buyer's optimal mechanism with $n \geq 2$ suppliers is as follows: The buyer offers the suppliers identical menu of contracts $\{q^o(\cdot), s_2^o(\cdot), T^o(\cdot)\}$ characterized by*

$$\begin{aligned} \frac{dH_1(s_1(s_2^o), s_2^o)/ds_2^o}{\Phi^{L_2}(s_2^o)} &= -[h_0 + rx + rF(x)/f(x)] \\ \omega T^o(x) &= (1 - F(x))^{n-1}[\omega\bar{c} + H_2(\bar{c}, s_2^o(\bar{c}))] \\ &\quad - \int_x^{\bar{c}} (1 - F(x))^{n-1}[(h_0 + ry)s_2^{o\prime}(y)\Phi^{L_2}(s_2^o(y))]dy \\ q^o(x) &= \begin{cases} 1 & \text{if } x = \min(x^1, \cdots, x^n) \\ 0 & \text{otherwise} \end{cases}. \end{aligned}$$

The suppliers announce their true costs and the most efficient supplier will be chosen.

Next we derive the fixed service-level mechanism with $n \geq 2$ suppliers. In this mechanism, the buyer specifies the fill rate (or s_2 equivalently) and asks the suppliers to bid on price. Without losing generality, we focus on the second-bid auction (it is straightforward to verify that the first-bid auction yields the same total cost for the buyer). Under this auction, we can show that each supplier will bid the break-even price (i.e., a supplier with cost x will bid price $x + H_2(x, s_2)/\omega$) and the buyer's total cost is quasiconvex in s_2.

Finally, we compare the performances of the above mechanisms with $n = 2$ suppliers. The same scenarios in §4.3 are considered and the results are summarized in Table 8. Again, the simple mechanism is nearly optimal in this numerical study. The results indicate that when both procurement price and logistics performance are taken into consideration, buyers can simply post a target service level and then ask suppliers to bid only on their costs. This seems to be consistent with practical observations: In some B2B industrial exchanges, buyers post product specifications and logistics requirements and then ask suppliers to bid on contracts (Rangan 1998). It helps us understand the challenging online procurement auction design problems, especially when multiple factors that may affect the buyer-supplier relationship are taken into account (see Elmaghraby 2004 for detailed discussion).

Table 8. Buyer's percentage cost increase relative to the optimal mechanism (with $n = 2$ suppliers).

		average	90^{th} percentile	maximum
Uniform cost distribution	FS	0.58%	0.97%	1.06%
Normal cost distribution	FS	0.15%	0.26%	0.28%

5 Discussion

This section discusses several issues related to our procurement problem. First, we have assumed that the buyer is willing to contract with all supplier types including the least efficient one. This assumption is reasonable when the supplier has gone through a rigorous screening process and his cost will be within an acceptable range. However, in many other situations, the buyer may choose not to transact with the supplier if his cost is prohibitively high. For instance, the buyer may utilize a cut-off policy to exclude highly inefficient supplier types. Zhang (2009) considers the impact of such a cut-off policy in the setting described in §4. It has been found that a fixed service-level (FS) contract continues to perform very well. Similar findings can be obtained for the setting in §3. Thus the results from §3 and §4 are robust when the cut-off policy is allowed.

The observation that using a fixed service level is nearly optimal gives rise to an interesting question: Can we generalize such a result to other procurement attributes? That is, can we always use a fixed attribute rather than a complex menu in supply contract design under asymmetric information? The answer is not positive. Zhang (2009) includes price-sensitive demand in the above two-echelon inventory system. In his model, the buyer can set price to influence market demand; or equivalently, the buyer needs to determine the purchase quantity in each period. He shows that using a fixed purchase quantity may cause significant profit loss for the buyer, which implies that a complex menu for the quantity attribute could be highly valuable. He then proceeds to investigate why the service-level and quantity attributes have distinct implications for supply contract design. The following intuition has been offered. For both model settings in this chapter, the market demand is exogenously given; and, because using a cost-contingent service level only reduces the supply chain's operating cost for satisfying the fixed demand, the supplier has little incentive to share the true cost information unless he will keep the majority from a low cost realization. In contrast, when the market demand is endogenously determined, the buyer will be able to set a low price to induce more demand when the supplier's cost is low. Thus a cost-contingent quantity attribute will increase the demand and revenue for the supply chain, which benefits both the buyer and the supplier. As a result, the supplier is more willing to share true cost information and its associated benefits with the buyer. This explains why the optimal menu for the quantity attribute is more valuable for the buyer.

An implicit assumption underlying the analysis in this chapter is that both supply chain firms' actions are enforceable. In §3, the two parties can enforce a contract based on the supplier's capacity (or lead time), and in §4 the supplier must commit to the specified base-stock level. This is not a restrictive assumption when the firms care about long-term relationship or when there is a third party who is able to verify and enforce the firms' actions. When enforcement becomes an issue, the buyer has to take it into consideration and modify the supply contract accordingly. An incentive scheme has been proposed in Zhang (2009) for the buyer to induce desired supplier actions. More discussion of the impact of the enforcement issue can be found in Cachon and Lariviere (2001) and Bolandifar et al. (2010).

6 Conclusion and Future Research

Outsourcing/offshoring has been increasingly used by the industry during the past few decades. This trend brings supply management under the spotlight because many companies today depend critically on their suppliers for the delivery of components, products, and services. The purpose of this chapter is to study a buyer's procurement problem while taking a key operational element into consideration: supplier's delivery performance. It is quite clear that superior delivery performance is beneficial to the buyer, because more responsive deliveries reduce the buyer's operating cost (e.g., inventory and backorder costs). Responsive deliveries require capacity or inventory investments at the supplier, both of which are costly. As a result, the buyer needs to carefully design incentive schemes to induce the right action from the supplier. Most studies in the literature on supply contracting assume there is complete information in the supply chain. However, in practice, firms in a decentralized supply chain are independent organizations and may not have perfect information about each other. It is not uncommon that the buyer faces uncertainties about the supplier's cost structure when negotiating the supply contract. Therefore, in this chapter we focus on the buyer's supply contract design problem under both asymmetric cost information and delivery performance consideration. In particular, we aim to derive some useful managerial guidelines for practitioners when making procurement decisions.

Two problem scenarios have been considered in this chapter. In the first scenario, the supplier is a make-to-order manufacturer or a service provider; so we model the supplier as a queueing server (the delivery performance is determined by the average delivery lead time). In the second, the supplier is a make-to-stock manufacturer and may hold inventory to improve customer service (the delivery performance is the fill rate at the supplier). We present these two scenarios in separate sections because their model settings and analyses are quite different. For each scenario, we first derive the buyer's optimal (profit-maximizing) mechanism, which consists of a nonlinear menu of contracts. Then we propose some simple, but suboptimal mechanisms for the buyer. The simple mechanisms only specify a target delivery performance and do not require the supplier's cost information as an input. By comparing the simple mechanisms to the optimal benchmark, we find that fixing the delivery performance attribute yields nearly-optimal outcome for the buyer. Such a finding is quite robust: It applies to both scenarios and remains unchanged in various extensions of the basic model. The explanation of this result is as follows. Using a complex menu on the delivery performance attribute (i.e., a cost-contingent lead time or fill rate) may reduce the supply chain's operating cost for satisfying market demand. However, the buyer is ultimately responsible for such a cost, so the supplier has little incentive to share his true cost information with the buyer unless he can keep the majority of the benefit from the cost reduction. This means that for the delivery performance attribute, even using the optimal menu cannot extract much information rent from a low-cost supplier. Therefore, the simple mechanisms perform very well (relative to the optimal mechanism), although they do not extract any information rent from the supplier.

On one hand, the above finding suggests that in the presence of asymmetric information, the buyer only needs to use a fixed number (rather than a complex menu) to ensure satisfactory delivery performance from the supplier. It bodes well for procurement managers because a relatively simple contract term can be used to take care of the delivery performance attribute in the procurement process. This is consistent with the practical observations in various industries where buyer-supplier contracts often involve simple service-level agreements (Lacity and Willcocks 1998, Thonemann at al. 2005, Katok at al. 2008). On the other hand, our results indicate that instead of resorting to the complex, optimal procurement contract, the buyer should try to reduce the information disadvantage by learning more about the supplier's cost structure. A better understanding of the supplier's operating process, technology, and other cost-related activities will bring significant savings in the supply contracting process.

This research can be extended in several directions. First, it has been assumed in both scenarios that unsatisfied demand at the buyer can be backlogged. An alternative assumption is that there are lost sales. It would be worthwhile to investigate whether the lost-sales assumption will change the results. Second, in many situations, the supplier's delivery performance may depend on the random yield at the supplier. For instance, due to quality-related problems, only a fraction of the production at the supplier will be useful and delivered to the buyer. Supply disruption may occur as an extreme case if the yield is sufficiently low. How the buyer should design supply contract to induce yield-improving effort is an interesting and open research topic. Finally, this chapter focuses on sole-sourcing where the buyer selects only one supplier with whom to transact. A potential direction for future research is to study a similar contracting problem with multi-sourcing.

References

[1] Anupindi, R., R. Akella. 1993. Diversification under supply uncertainty. *Mgmt. Sci.* **39**(8) 944-963.

[2] Bagnoli, M., T. Bergstrom. 2005. Log-concave probability and its applications. *Economic Theory* **26**(2) 445-469.

[3] Beil, D., L. Wein. 2003. An inverse-optimization-based auction mechanism to support a multiattribute RFQ process. *Mgmt. Sci.* **49**(11) 1529-1545.

[4] Benjaafar, S., E. Elahi, K. Donohue. 2007. Outsourcing via service quality competition. *Mgmt. Sci.* **53**(2) 241-259.

[5] Bernstein, F., G.A. DeCroix. 2006. Inventory policies in a decentralized assembly system. *Oper. Res.* **54**(2) 324–336.

[6] Beth, S., D. Burt, W. Copacino, C. Gopal, H. Lee, R. Lynch, S. Morris. 2003. Supply chain challenges: building relationships. *Harvard Business Review*. July.

[7] Bhattacharyya, S., F. Lafontaine. 1995. Double-sided moral hazard and the nature of shared contracts. *RAND J. of Econom.* **26**(4) 761-781.

[8] Bolandifar, E., T. Feng, F. Zhang. 2010. Asymmetric information and enforcement in supply contract design. Working paper, Washington University in St. Louis.

[9] Bower, A.G. 1993. Procurement policy and contracting efficiency. *International Economic Review* **34**(4) 873-901.

[10] Branco, F. 1997. The design of multidimensional auctions. *Rand J. of Econom.* **28**(1) 63-81.

[11] Bulkeley, W. 2003. Plexus strategy: small runs of more things. *Wall Street Journal*. Oct 8.

[12] Burt, D. 1989. Managing suppliers up to speed. *Harvard Business Review*. July-Aug.

[13] Burnetas, A., S.M. Gilbert, C. Smith. 2007. Quantity discounts in single period supply contracts with asymmetric demand information. *IIE Transactions* **39**(5) 465-480.

[14] Cachon, G.P. 2003. Supply chain coordination with contracts. *The Handbook of Operations Research and Management Science: Supply Chain Management*. eds S. Graves, T. de Kok, Kluwer.

[15] Cachon, G.P., M. Lariviere. 2001. Contracting to assure supply: how to share demand forecasts in a supply chain. *Mgmt. Sci.* **47**(5) 629-646.

[16] Cachon, G.P., F. Zhang. 2006. Procuring fast delivery: sole-sourcing with information asymmetry. *Mgmt. Sci.* **52**(6) 881-896.

[17] Cachon, G.P., F. Zhang. 2007. Obtaining fast delivery in a queueing system via performance-based allocation of demand. *Mgmt. Sci.* **53**(3) 408-420.

[18] Cachon, G.P., P.H. Zipkin. 1999. Competitive and cooperative inventory policies in a two-stage supply chain. *Mgmt. Sci.* **45**(7) 936-953.

[19] Caldentey, R., L.M. Wein. 2003. Analysis of a decentralized production-inventory system. *MSOM* **5**(1) 1-17.

[20] CAPS Research. 2006. Services spend management: outsourcing/offshoring your services spend. Center for Advanced Purchasing Studies, Tempe, AZ.

[21] Che, Y.-K. 1993. Design competition through multi-dimensional auctions. *RAND J. of Econom.* **24**(4). 668-680.

[22] Chen, F., A. Federgruen, Y.-S. Zheng. 2001. Coordination mechanisms for a distribution system with one supplier and multiple retailers. *Mgmt. Sci.* **47**(5) 693-708.

[23] Chen, F., Y.-S. Zheng. 1994. Lower bounds for multiechelon stochastic inventory systems. *Mgmt. Sci.* **40**(11) 1426-1443.

[24] Chen, R., R. Roundy, R. Zhang, G. Janakiraman. 2005. Efficient auction mechanisms for supply chain procurement. *Mgmt. Sci.* **51**(3) 467-482.

[25] Chu, L.Y., D.E.M. Sappington. 2007. Simple cost-sharing contracts. *American Economic Review* **97**(2) 419-428.

[26] Corbett, C.J. 2001. Stochastic inventory systems in a supply chain with asymmetric information: cycle stocks, safety stocks, and consignment stock. *Oper. Res.* **49**(4) 487-500.

[27] Corbett, C.J., X. de Groote. 2000. A supplier's optimal quantity discount policy under asymmetric information. *Mgmt. Sci.* **46**(3) 444-450.

[28] Corbett, C.J., D. Zhou, C.S. Tang. 2004. Designing supply contracts: contract type and information asymmetry. *Mgmt. Sci.* **50**(4) 550-559.

[29] Department of Commerce. 2006. Statistics for Industry Groups and Industries: Annual Survey of Manufactures. http://www.census.gov/prod/2006pubs/am0531gs1.pdf

[30] Elmaghraby, W.J. 2000. Supply contract competition and sourcing strategies. *MSOM* **2**(4) 350-371.

[31] Elmaghraby, W.J. 2004. Auctions and pricing in E-markeplaces. Chapter 6 in Simchi-Levi, D., S.D. Wu, Z.-J. Shen (eds.), *Handbook of Quantitative Supply Chain Analysis: Modeling in the E-business Era*, Kluwer.

[32] Farlow, D., G. Schmidt, A. Tsay. 1996. Supplier management at Sun Microsystems (A). Stanford Business School Case.

[33] Federgruen, A., N. Yang. 2008. Selecting a portfolio of suppliers under demand and supply risks. *Oper. Res.* **56**(4) 916-936.

[34] Federgruen, A., N. Yang. 2009. Optimal supply risk diversification under general supply risks. *Oper. Res.* **57**(6) 1451-1468.

[35] Friedman, T.L. 2005. *The World is Flat: A Brief History of the Twenty-First Century.* Farrar, Straus and Giroux, New York.

[36] Gilbert, S.M., Z.K. Weng. 1998. Incentive effects favor nonconsolidating queues in a service system: the principle-agent perspective. *Mgmt. Sci.* **44**(12) 1662-1669.

[37] Gümüş, M., S. Ray, H. Gurnani. 2010. Supply side story: risks, guarantees, competition and information asymmetry. Working paper, McGill University.

[38] Ha, A.Y. 2001. Supplier-buyer contracting: asymmetric cost information and cutoff level policy for buyer participation. *Naval Research Logistics.* **48** 41-64.

[39] Ha, A.Y., L. Li, S.-M. Ng. 2003. Price and delivery logistics competition in a supply chain. *Mgmt Sci.* **49**(9) 1139-1153.

[40] Hausman, W.H., H.L. Lee, U. Subramaniam. 2005. Global logistics indicators, supply chain metrics and bilateral trade patterns. *World Bank Policy Research Working Paper*, November.

[41] Holmstrom, B., P. Milgrom. 1987. Aggregation and linearity in the provision of intertemporal incentives. *Econometrica* **55**(2) 303-328.

[42] Katok, E., D. Thomas, A. Davis. 2008. Inventory service-level agreements as coordination mechanisms: the effect of review periods. *MSOM* **10**(4) 609-624.

[43] Kay, E. 2005. Ways to measure supplier performance. Http://www.purchasing.com/

[44] Kayış, E., F. Erhun, E.L. Plambeck. 2007. Delegation vs. control of component procurement. Working paper, Stanford University.

[45] Klemperer, P. 1999. Auction theory: a guide to the literature. *J. of Economics Surveys.* **13**(3) 227-286.

[46] Kostamis, D., D. Beil, I. Duenyas. 2009. Total-cost procurement auctions: impact of suppliers' cost adjustments on auction format choice. *Mgmt. Sci.* **55**: 1985-1999.

[47] Lacity, M.C., L.P. Willcocks. 1998. An empirical investigation of information technology sourcing practices: Lessons from experience. *MIS Quarterly* **22**(3) 363-408.

[48] Laffont, J. J., D. Martimort. 2002. *The Theory of Incentives: The Principal-Agent Model*. Princeton, Princeton University Press.

[49] Li, C.-L., P. Kouvelis. 1999. Flexible and risk-sharing supply contracts under price uncertainty. *Mgmt. Sci.* **45**(10) 1378-1398.

[50] Özer, Ö., W. Wei. 2006. Strategic commitments for an optimal capacity decision under asymmetric forecast information. *Mgmt. Sci.* **52**(8) 1238-1257.

[51] Pinker, E., A. Seidmann, Y. Vakrat. 2003. Managing online auctions: current business and research issues. *Mgmt. Sci.* **49**(11) 1457-1484.

[52] Pyke, D, E. Johnson. 2003. Sourcing strategies and supplier relationships: alliances vs. eprocurement. *The Practice of Supply Chain Management*. Kluwer Publishers, C. Billington, H. Lee, J. Neale, T. Harrison editors, 77-89.

[53] Rangan, V. K. 1998. *FreeMarkets Online*. Harvard Business School case #9-598-109.

[54] Ramasesh, R.V., J.K. Ord, J.C. Hayya, A. Pan. 1991. Sole versus dual sourcing in stochastic lead-time (s, Q) inventory models. *Mgmt. Sci.* **37**(4) 428-443.

[55] Ray, S., S. Li, Y. Song. 2005. Tailored supply chain decision making under price-sensitive stochastic demand and delivery uncertainty. *Mgmt. Sci.* **51**(12) 1873-1891.

[56] Taylor, T.A., E.L. Plambeck. 2007. Simple relational contracts to motivate capacity investment: price-only versus price-and-quantity. *MSOM* **9**(1) 94-113.

[57] Thomas, D.J. 2005. Measuring item fill-rate performance in a finite horizon. *MSOM* **7**(1) 74-80.

[58] Thonemann, U., K. Behrenbeck, J. Küpper, K.H. Magnus. 2005. *Supply Chain Excellence im Handel (in German)*. Financial Times Deutschland/Gabler, Wiesbaden, Germany.

[59] Thurm, S. 1998. Some U.S. manufacturers prosper by easing rise of 'virtual' firm. *Wall Street Journal*. Aug. 18.

[60] Tang, C.S. 2006. Perspectives in Supply Chain Risk Management. *International J. of Production Economics*, **103**(2) 451-488.

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

[62] Tunca, T., Q. Wu. 2009. Multiple sourcing and procurement process selection with bidding events. *Mgmt. Sci.* **55**(5) 763-780.

[63] Wise, R., D. Morrison. 2000. Beyond the exchange: the future of B2B. *Harvard Business Review.*(Nov-Dec). 86-96.

[64] Yang, Z., G. Aydin, V. Babich, D.R. Beil. 2009. Supply disruptions, asymmetric information and a backup production option. *Mgmt. Sci.* **55**(2) 192-209.

[65] Zhang, F. 2004. Coordination of lead times in supply chains. Ph.D. Dissertation. University of Pennsylvania.

[66] Zhang, F. 2006. Competition, cooperation and information sharing in a two-echelon assembly system. *MSOM* **8**(3) 273-291.

[67] Zhang, F. 2009. Procurement mechanism design in a two-echelon inventory system with price-sensitive demand. Forthcoming in *MSOM*.