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Simple Contracts to Assure Supply Under Noncontractible Capacity and Asymmetric Cost Information

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Abstract. This paper studies a global sourcing problem where a buyer sources a product from a supplier to satisfy uncertain market demand. With the increasing length and complexity of today's global supply chains, the buyer may face two issues when designing the sourcing contract: adverse selection (i.e., the supplier's cost structure is private information) and noncontractible capacity (i.e., the supplier's capacity investment is not contractible). We show that noncontractible capacity does not necessarily lead to a lower profit for the buyer, but it may require a more complex contract format to achieve the optimal (second-best) profit. Interestingly, we find that a single, linear contract (or a two-part tariff) could be optimal for the buyer under certain conditions. Even when such a contract is suboptimal, it can deliver close-to-optimal profit for the buyer for a wide range of situations. These findings indicate that the value of using a complex menu of contracts is negligible in such a supply chain setting. A simple two-part tariff is an attractive option for buyers whose goal is to ensure supply while facing both cost uncertainty and contractibility issues. The paper also provides a new explanation for the prevalence of such simple contracts in practice.

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Keywords: supply contracts • sourcing • information asymmetry • noncontractibility • linear contracts • two-part tariff

1. Introduction

Increasing competition in the global market has forced many firms to outsource their production processes to focus on core competencies such as product design and marketing. While this practice may help firms reduce costs and improve competitive advantage, it also gives rise to new challenges on how to manage their supply chains. Consider a buyer who sources an input (e.g., a product or a component) from a supplier. The buyer is unsure about market demand and, due to procurement time lags, the supplier needs to make capacity-related decisions before the demand is realized. The buyer wants the supplier to be flexible enough to deal with any demand fluctuations, whereas the supplier needs to keep the risk of overages to a minimum in case the demand for his output ceases. How to achieve sufficient supply to satisfy uncertain demand is a central issue for such supply chain settings. Failing to do so may cause substantial losses in profits and market shares for both individual firms and the supply chain. Anecdotal evidence abounds in both business media and academic literature. For example, Sony Ericsson's third-quarter sales fell short of analysts' expectations in 2010 because of component shortages, including printed circuit boards (Parker 2010). In 2012 Qualcomm executives reported that a capacity shortage at an overseas foundry supplier might prevent the company from meeting strong market demand (McGrath 2012). More recently, Tesla Motors revealed that severe Model X supplier parts shortages might delay delivery of the new electric cars to customers (Stevens 2016). In view of these lessons, practitioners surely understand the importance of securing supply and have taken this into consideration when designing sourcing strategies. Sun Microsystems claims that availability and flexible supply will be critical when making their sourcing decisions (Carbone 2005). Similarly, Apple tends to push suppliers to expand their manufacturing facility to meet the rush demand for its new products (Dou and Luk 2014).

Two practical issues may arise in a buyer's supply contracting problem. First, firms in a decentralized supply chain are independent organizations and thus often have disparate information. In particular, the supplier's cost structure is highly confidential information because it conveys significant bargaining power when negotiating a contract. Thus, when devising a sourcing strategy, the buyer often does not have perfect information about the supplier's cost structure, which gives rise to the so-called adverse selection issue.

Second, the suppliers' actions may not be verifiable or enforceable; see, for example, the discussions in Cachon and Lariviere (2001) and Kaya and Özer (2009) on the supplier's compliance on capacity and quality agreements, respectively. In many supply chain relationships, the buyer's desired capacity level may not be optimal for the supplier who builds the capacity. In such cases, the contracted capacity may not be enforceable for a couple of reasons: First, capacity is a complex decision that involves many factors, including the supplier's managerial effort (thus, when a supplier fails to deliver the promised quantity, it might be hard to verify whether this is due to underinvestment in effort or reasons beyond the supplier's control). Second, if the cost of enforcement (e.g., the cost of capacity verification and the cost of a lawsuit) is prohibitively high, contract terms that penalize a dishonest supplier might not be credible. Due to lack of enforcement, the supplier may purposely deviate from the agreed capacity, making capacity investment a noncontractible decision. We may call this the capacity contractibility (or moral hazard) issue.

Empirical findings suggest that both information asymmetry and moral hazard are important determinants of contract design in the buyer-supplier relationship (Costello 2013). The trend of globalization has made these issues more prominent because of increased length and complexity of supply chains. Research has shown that long distance between parties may increase information asymmetry (Noordewier et al. 1990 and Hortacsu et al. 2009). Thus, it is not uncommon that in global supply chains, buyers do not have precise information about the cost structure of their suppliers located overseas. Moreover, it is known that regulatory institutions and law enforcement are weak in emerging economies, which may give rise to contractibility issues due to higher contract enforcement costs (Antras 2015). The World Bank (2008) provides a comparison of the judicial system's efficiency in resolving commercial disputes in different countries or regions. The report shows that developing countries are often associated with less efficient judicial systems (e.g., longer wait time, higher litigation fees, and more complex procedures), which present a major obstacle for these countries to attract foreign businesses and investments (see also Ahlquist and Prakash 2010). According to a Deloitte survey, 70% of executives were extremely or very concerned about suppliers' compliance risks in emerging markets (Sinha 2014). For instance, in global supply chains of products such as apparel, reneging on a contract could be a significant concern (Narayanan and Raman 2000). According to Dickinson (2016), when outsourcing to Chinese suppliers, firms need to be cautious about potential short deliveries on agreed-upon purchase orders. It is not surprising that many global supply chains are prone to the above problems because firms are located in different countries and contract agreements are written long before final delivery.

In this paper, we study how firms can deal with information asymmetry and contractibility issues that may both be present in supply contracting. These challenges, made increasingly prominent by the trend of globalization, may have significant implications for firms' contracting strategies. The purpose of this paper is to understand how firms should design sourcing contracts to assure supply in the presence of these challenges. We propose a stylized model where a newsvendor buyer sources a product from a supplier. The buyer does not know the exact capacity cost of the supplier but has an unbiased belief about its distribution. Since capacity investment is not contractible, we assume that both parties need to contract based on the actual delivery quantity rather than the supplier's capacity. This gives rise to the first question we investigate: How does this constraint due to lack of contractibility affect the contract efficiency? While most of the contracting literature is dedicated to designing the mechanism to maximize the principal's profit, there is a stark discrepancy between the complexity of the theoretically optimal contracts and the simplicity of many real-world contracts (Caillaud et al. 1992). As a result, many studies have tried to reconcile this discrepancy by studying the performance of suboptimal but simpler contracts. Following this literature, we investigate the second question: Are there simple contracts that perform well for our sourcing problem?

The main contribution of the paper is twofold. First, we find that with properly designed incentives, the lack of contractibility does not result in efficiency loss for the buyer. We show that contracting on the delivery quantity can induce the optimal (second-best) profit. Further, the existence of an optimal menu of linear contracts depends critically on the cost uncertainty faced by the buyer. For ease of exposition, later we will introduce the *modified reverse hazard rate* (MRHR) for the supplier's cost distribution. When there is a decreasing MRHR, the buyer can achieve the second-best solution by offering a menu of linear contracts. Each contract in the menu is essentially a two-part tariff, where the buyer pays the supplier a wholesale price for each product delivered and charges the supplier a lump-sum payment. However, if the MRHR is strictly increasing for any cost range, then the second-best solution can no longer be implemented using linear contracts; instead, the buyer can use a menu of quadratic contracts to achieve the second-best solution.

Second, we show that the optimal menu of contracts reduces to a simple two-part tariff when there is a constant MRHR, i.e., a single, linear contract could be optimal (second-best) for the buyer. This condition holds, for example, when the supplier's cost follows a uniform distribution, which corresponds to situations where the buyer has very limited cost information. When it is optimal for the buyer to exclude some high cost types, the two-part tariff will further simplify to a wholesale price. This is essentially the pull contract that has been widely observed in practice, where the supplier undertakes the capacity risk and charges the buyer a wholesale price for each unit delivered. In addition, it has been shown that even when the simple two-part tariff is not optimal, it still yields near-optimal profit in a wide range of situations. This implies that the value of using a complex menu is negligible in our problem setting. From the supply chain's viewpoint, the two-part tariff is also preferred over the optimal menu of contracts because it generally yields higher supply chain efficiency. We provide an explanation for why a simple contract performs well from both the firm's and the supply chain's perspectives.

In summary, we show that in a sourcing problem where the buyer is exposed to demand risk, noncontractible capacity, and asymmetric capacity cost information, a menu of linear or quadratic contracts can achieve the second-best solution for the buyer. However, the value of using a complex menu is insignificant, which suggests that a more effective way to improve buyer profit is to reduce the information asymmetry rather than designing sophisticated contracts. However, if reducing the uncertainty in supplier cost is not a viable strategy, then we recommend the two-part tariff to managers—it has a simple format, yields nearly optimal profit, and does not require enforcement on the supplier's capacity investment. This finding corroborates the prevalence of such simple contracts in practice.

The rest of the paper is organized as follows. Section 2 reviews the literature, and Section 3 introduces the model. Section 4 first presents a benchmark scenario with contractible capacity and then studies the scenario with noncontractible capacity. Section 5 studies simple contracts and their performances. This paper concludes with Section 6. All proofs are given in the online appendix.

2. Literature Review

There is a growing body of literature that studies supply chain management under asymmetric cost information. A detailed review of earlier studies can be found in Chen (2007). Among these studies, the closest work to our study is Ha (2001). Ha (2001) considers a similar supply chain setting except that the retailer is a price-setting newsvendor with private cost information. It has been shown that a menu of contracts with a cutoff level is optimal for the supplier, and the optimal order quantity is lower under asymmetric information than under complete information. Other representative studies that involve retailer private cost information include Corbett (2001), Corbett et al. (2004), and Lutze and Özer (2008). In our model, a newsvendor procures from a supplier whose capacity cost is private information, which is different from these existing studies.

This paper is closely related to the literature on capacity procurement in supply chains. Cachon and Lariviere (2001) are among the first to study supply contracting under asymmetric demand information. In particular, the manufacturer has superior demand forecast information and needs to secure sufficient capacity at the supplier. They coin the terms "forced compliance" and "voluntary compliance" to distinguish between different capacity enforcement scenarios. Voluntary compliance essentially means that the supplier's capacity is not contractible as in our model. Tomlin (2003) and Özer and Wei (2006) are two notable follow-up studies along this important line of research. By allowing an intermediate compliance scheme (i.e., the buyer has some ability to identify supplier shirking), Tomlin (2003) finds that in contrast to Cachon and Lariviere (2001), firm commitment and options contracts can be useful in increasing supplier capacity under full information (symmetric demand information). In addition, he shows that under certain conditions, the manufacturer's optimal contract is a quantity-premium price-only schedule, under which the two parties "share the gain" rather than "share the pain." Özer and Wei (2006) propose two contracts (a capacity reservation contract and an advance purchase contract) to induce credible forecast information sharing. They also discuss how the supplier's compliance scheme affects the outsourcing firm's choice of contract. Our paper contributes to this line of research by incorporating private supplier cost information and studying the interaction between asymmetric cost information and moral hazard.

Recently, the adverse selection and moral hazard issues in outsourcing have received some research attention. For example, Kaya and Özer (2009) study the quality risk in an outsourcing setting, where input quality is noncontractible and the supplier has private information about the cost of quality. Another feature is that the outsourcing firm may or may not be able to commit up-front to a price in the end market. They show that the effect of noncontractible quality could be more significant than that of private cost information under certain conditions. They also find that price commitment mitigates the adverse effect of quality risk. Kim and Netessine (2013) examine supply chain parties' incentives to collaborate on cost reduction under information asymmetry and moral hazard. Among a number of contracting strategies considered, they show that a strategy called expected margin commitment can effectively promote supply chain collaboration on cost reduction. Our paper differs from these studies in both model setting and main results. First, we study a supply chain setting in which the supplier makes a capacity investment decision (to improve product availability under demand uncertainty), rather than an effort decision (to improve cost or quality). Second, our paper demonstrates that a *single*, *linear* contract could be optimal for the buyer under certain conditions; even when it is suboptimal, the contract can yield close-to-optimal performance.

A stream of papers in the economics literature study principal-agent models with noncontractible agent actions. Laffont and Tirole (1986) consider an agent who is endowed with private cost information and can exert cost-reduction effort. Assuming the cost is uniformly distributed, they show that a menu of linear contracts based on the observed output is optimal for the principal. McAfee and McMillan (1986) extend this line of research by studying a general distribution for the agent's type. While McAfee and McMillan (1986) claim that in a broad set of circumstances, optimal contracts can be linear in observed output levels, Rogerson (1987) shows that this result is not true in general. Therefore, it seems that the optimality of linear contracts can be viewed as a very special property only for limited settings. Whereas linear contracts are of great interest in the economics literature (see Bose et al. 2011 and references therein), much less attention has been paid to this issue in the operations management literature. Chen (2005) is among the first to study the performance of linear contracts in an operations setting. He examines the so-called Gonik's scheme in a salesforce incentive mechanism design problem: the salespeople are endowed with private information about the market and can exert effort to sell in the market. He characterizes the optimal menu of linear contracts and finds that it dominates the Gonik's scheme using numerical experiments. In another similar work, Chen et al. (2016) compare the forecast-based contracts with a menu of linear contracts to show that with an endogenous information-acquisition effort, the menu of linear contracts may be dominated by the forecast-based contracts. In this paper, we consider a capacity procurement setting and characterize the conditions where a menu of linear contracts arises as an optimal mechanism for the buyer.

Finally, the importance of simplicity in procurement contract design has long been recognized in the literature. Hart and Holmstrom (1987) point out that there is a contrast between the complexity of theoretically optimal contracts and the simplicity of many real-world arrangements. A number of economics studies have been devoted to explaining such a discrepancy between theory and practice. Please refer to Chu and Sappington (2015) for an extensive overview of this literature in economics. Recently, there have been a growing number of studies in operations management that investigate the performance of simple procurement mechanisms, including Cachon and Zhang (2006), Kayış et al. (2013), Zhang (2010), and Duenyas et al. (2013). Our paper is in a similar spirit by searching for simple procurement mechanisms in supply chain settings. However, both the model and insights in our paper are quite different from these existing studies.

3. Model Description

We consider a two-stage supply chain in which a buyer trades with a supplier. Hereafter we use "she" to refer to the buyer and "he" the supplier. The buyer can be viewed as a newsvendor firm. She sources a perishable product from the supplier and then sells it to customers in a single selling season. There is an exogenously given market price p, and market demand is uncertain. Let D denote the random demand with distribution function Φ and density function ϕ. For ease of exposition, we assume that the salvage value for any excess capacity is zero. Also, there is no penalty cost for unsatisfied demand during the selling season. Including a positive salvage value or penalty cost will not change the qualitative results from our model.

Due to long acquisition lead times, the supplier needs to make capacity investments before the selling season starts. The capacity may refer to all the resources (e.g., raw materials, production facility, and labor) that are needed to produce the product for the buyer. We assume the capacity can be instantly converted into the product at zero cost. Alternatively, we may assume the supplier builds up inventory to satisfy the buyer's order, which is quite common in the supply contracting literature. Thus, the concepts of capacity and inventory are interchangeable in this paper. There is a unit capacity cost c, which is the supplier's private information. Due to various uncertain factors (e.g., technology, production yield, and raw material price), the buyer does not know the exact cost c, but she has an unbiased belief about its distribution. Without loss of generality, let $[0, \bar{c}]$ ($\bar{c} > 0$) be the support of c, and let F and f denote its distribution and density functions, respectively. We assume F has a decreasing *reversed hazard rate* (RHR), i.e., $f(x)/F(x)$ is decreasing in x. This is equivalent to the log-concavity assumption widely adopted in mechanism design problems. We use the decreasing RHR assumption rather than the log-concavity assumption because we will introduce a *modified reversed hazard rate* (MRHR) later in this paper. Most commonly used distributions have a decreasing RHR, including uniform, normal, exponential, and logistic distributions (see Bagnoli and Bergstrom 2005 for details).

As discussed in the introduction, firms' actions are not always contractible, which may happen when the firms' actions are not verifiable or enforcing the contract terms is prohibitively costly. As a result, there could be noncontractibility issues in the supply chain (e.g., the global supply chain for apparel products described in Narayanan and Raman 2000). This can be seen as a moral hazard problem since after signing a contract the supplier might have an incentive to distort his effort (i.e., his capacity investment) when contracting terms are not enforceable. In this case, it is no longer viable for firms to devise a contract as a function of capacity investment from the supplier. For example, the buyer cannot specify a target capacity investment for the supplier and then penalize the supplier if he fails to meet the target. This is because the supplier can always claim that the shortage is not due to underinvestment in capacity but for reasons beyond his control. Noncontractibility of firms' actions results in contracting on output level. In this paper, we study how firms can optimally contract on the output level to deal with any noncontractibility issue.

We assume the buyer takes the initiative to offer a take-it-or-leave-it contract to the supplier. Both supply chain firms are risk neutral, and the objective is to maximize their own expected profit. In general, the supplier may have a reservation profit, which is defined as the value of the best outside option. A higher reservation profit corresponds to a more advantageous bargaining position for the supplier. We normalize the supplier's reservation profit to zero because adding a positive reservation profit does not generate much new insight. All parameters are common knowledge except the supplier's capacity cost, c. The sequence of events is as follows: (1) the buyer offers a menu of contracts to the supplier; (2) the supplier chooses a contract from the menu and then invests in capacity accordingly; (3) market demand is confirmed and the buyer orders from the supplier to satisfy demand. For simplicity, we assume there will be no renegotiation after the supplier reveals his cost information.

Define $\bar{\Phi} = 1 - \Phi$. Let E denote the expectation operation and K be the supplier's capacity level. Then the supply chain's expected profit can be written as $\pi_{sc}(K) = pE_D[\min(K, D)] - cK$ (we use subscript sc for supply chain), and the optimal capacity that maximizes $\pi_{sc}(K)$ is given by the critical fractile solution $K^*(c) = \Phi^{-1}((p-c)/p)$ (we use superscript $*$ for the supply chain optimal solution). It is clear that if the buyer knows the supplier's cost, then she will choose the supply chain optimal capacity and extract all the surplus. This is the so-called *first-best* solution in the literature. Next, we study the buyer's contract design problem when she is not perfectly informed about the supplier's cost; in this case, the buyer's optimal contract is commonly referred to as the *second-best* solution. Given the existence of information asymmetry, we will use the second-best solution as the benchmark to evaluate other suboptimal contracts. Thus, in the rest of the paper, by "optimal" we refer to the "second-best" outcome. For example, the buyer's optimal profit is defined as her profit in the second-best solution.

4. Analysis of Optimal Contracts

This section presents the optimal contracts that maximize the buyer's profit when capacity is noncontractible. As a reference point, first we characterize second-best solution when capacity is contractible. Solving the buyer's optimal contract is essentially an optimal mechanism design problem. According to the revelation principle (see Bolton and Dewatripont 2005, Laffont and Mattrimort 2002), we can focus on the direct and truth-inducing mechanisms in this section.

4.1. Adverse Selection with Contractible Capacity

First we study the buyer's contract design problem when supplier's capacity is contractible, i.e., the supplier will faithfully invest in contracted capacity so there is no moral hazard. Due to the presence of information asymmetry, the buyer needs to offer a menu of contracts to the supplier. By choosing a contract from the menu, the supplier essentially announces his capacity cost. Consider the following menu of contracts $\{K(x), T(x)\}$: If the supplier announces his capacity cost to be x (by choosing the corresponding contract), then the supplier will build a total capacity $K(x)$ and receive a lump-sum payment $T(x)$ from the buyer. Next we derive the optimal functions $\{K^o(x), T^o(x)\}$ that maximize the buyer's expected profit (we use superscript o for the second-best solution).

Suppose the supplier's true cost is c but he announces x; then the supplier's profit function is (we use subscript s for supplier) as follows:

$$\pi_s(x; c) = T(x) - cK(x). \tag{1}$$

In the profit function, x is a decision variable while c is a parameter. The buyer's profit can be written as (we use subscript b for buyer) follows:

$$\pi_b(x) = pE_D[\min(K(x), D)] - T(x). \tag{2}$$

There are two constraints imposed on the mechanism design problem. The first constraint is the incentive-compatibility constraint (IC), which guarantees supplier's truth-telling:

$$c = \arg\max_x \{T(x) - cK(x)\} \quad \text{for all } c \in [0, \bar{c}]. \tag{3}$$

The second is the individual rationality constraint (IR), which guarantees nonnegative profit for the supplier:

$$T(c) - cK(c) \geq 0 \quad \text{for all } c \in [0, \bar{c}]. \tag{4}$$

The right-hand side of the inequality is zero because we have assumed that the supplier has a zero reservation profit. Now the buyer's optimal mechanism can be solved from the following optimization problem:

$$\max_{\{K(\cdot),T(\cdot)\}} \int_0^{\bar{c}} (pE_D[\min(K(x),D)] - T(x)) f(x)\,dx \quad \text{s.t. } (3), (4), \tag{5}$$

where $\pi_b(x)$ is given in (2). Let $\hat{c}^o$ be the solution to

$$p - (x + F(x)/f(x)) = 0 \tag{6}$$

if a solution exists within $[0, \bar{c}]$; otherwise set $\hat{c}^o = \bar{c}$. Then we have the following proposition.

Proposition 1. *If capacity is contractible, the following menu of contracts $\{K^o(x), T^o(x)\}$ is optimal for the buyer: For $x > \hat{c}^o$, there is $K^o(x) = 0$ and $T^o(x) = 0$, i.e., the buyer procures nothing from the supplier; otherwise there is*

$$K^o(x) = \Phi^{-1}\left(\frac{p - (x + F(x)/f(x))}{p}\right), \tag{7}$$

$$T^o(x) = xK^o(x) + \int_x^{\bar{c}} K^o(u)\,du. \tag{8}$$

The buyer's optimal mechanism in Proposition 1 represents a threshold policy. When $\hat{c}^o < \bar{c}$, the buyer would refuse to do business with the supplier if his cost is greater than the threshold value, $\hat{c}^o$. Note that $\hat{c}^o$ only depends on the price p and the distribution function F. Similar threshold policies appear elsewhere in the literature on contracting under asymmetric information; examples include Ha (2001), Corbett et al. (2004), and Lutze and Özer (2008). Due to the decreasing reversed hazard rate property of F, an immediate result is that $K^o(x)$ is decreasing in x, i.e., a higher supplier cost leads to a lower capacity in the optimal mechanism. It is clear that $K^o(x) < K^*(x)$ for $F(x)/f(x) > 0$, i.e., the optimal mechanism does not coordinate the supply chain. This distortion is caused by the buyer's intention to maximize her own profit under asymmetric information. The lump-sum payment $T^o(x)$ in the optimal mechanism consists of two parts: the first part $(xK^o(x))$ is to compensate the supplier's capacity investment, while the second $(\int_x^{\bar{c}} K^o(u)\,du)$ is the supplier's information rent (or expected profit).

4.2. Adverse Selection with Noncontractible Capacity

We proceed to study the buyer's contracting problem when the supplier's capacity is noncontractible, i.e., there is moral hazard in capacity investment. In particular, the contract cannot force the supplier to build sufficient capacity, nor can it penalize the supplier for deviating from a target capacity level. In such situations, the buyer may offer a contract based on the supplier's delivered quantity rather than capacity level (see Pierce 2012). Consider a menu of payments $\{T(x,z)\}$ the buyer offers to the supplier, where x is the announced capacity cost (or, equivalently, the menu selected by the supplier), $z = \min(K, D)$ is the actual quantity delivered by the supplier, and T is a general function of x and z. Under this contract, the supplier chooses the cost-to-announce x and capacity decision K to maximize his profit function:

$$\pi_s(x, K; c) = E_D[T(x, \min(K, D))] - cK.$$

The first-order condition for the supplier's optimal capacity choice given cost c is

$$\frac{\partial \pi_s(x,K;c)}{\partial K} = (1 - \Phi(K))\frac{\partial T(x,K)}{\partial K} - c = 0.$$

Under truth-telling, the above first-order condition becomes

$$(1 - \Phi(K))\frac{\partial T(x,K)}{\partial K} - x = 0 \quad \text{for all } x. \tag{9}$$

The buyer's profit function given supplier cost x can be written as

$$\pi_b(x) = pE_D(\min(K,D)) - E_D[T(x, \min(K,D))]. \tag{10}$$

The IC and IR constraints are the same as in (3) and (4). Then the buyer's optimal mechanism design problem is as follows:

$$\begin{aligned} \max_{\{T(\cdot,\cdot)\}} \int_0^{\bar{c}} & (pE_D(\min(K,D)) \\ & - E_D[T(x, \min(K,D))]) f(x)\,dx \\ \text{s.t. } & \arg\max_x \pi_s(x, K(x,c)) = c, \\ & \pi_s(c, K(c,c)) \ge 0, \end{aligned} \tag{11}$$

for all $c \in [0, \bar{c}]$, where $K(x,c)$ satisfies $(1 - \Phi(K)) \cdot (\partial T(x,K)/\partial K) - c = 0$.

The analysis of the optimal mechanism when firms' actions are not contractible is more involved because the payment schedule $T(x,z)$ is a function of both x and z. Before presenting the optimal solution, we define the *modified reversed hazard rate* (MRHR) to be

$$H(x) = \frac{xf(x)}{F(x)}. \tag{12}$$

We call it MRHR because it is defined as the RHR multiplied by x. It has been assumed there is a decreasing RHR (i.e., $f(x)/F(x)$ is decreasing in x); however, this does not guarantee the MRHR is also decreasing. In fact, the MRHR may be either increasing or decreasing in x. Later we will see that the monotonicity property of the MRHR plays an important role in the optimal mechanism. An interesting comparison can be made with the increasing *failure rate* (FR) and the increasing *generalized failure rate* (GFR) properties studied in Lariviere and Porteus (2001) and Lariviere (2006). There are two major differences here: First, here we focus on the reversed hazard rate (rather than the hazard rate or failure rate); second, MRHR is not a generalized version of RHR because a decreasing RHR does not necessarily imply a decreasing MRHR. As preparation, the following lemma characterizes the properties of the buyer's optimal mechanism.

Lemma 1. *Under noncontractible capacity, the following conditions must hold in a truth-telling optimal mechanism*:

(i) *The payment schedule $T(x,z)$ satisfies*

$$\frac{\partial T^2(x,K)/\partial x\partial K}{(1-\Phi(K))(\partial^2 T(x,K)/\partial K^2)-(\partial T(x,K)/\partial K)\phi(K)}\geq 0. \tag{13}$$

(ii) *It induces the capacity level given in* (7), *i.e.*, $K^o(x)=\Phi^{-1}((p-(x+F(x)/f(x)))/p)$.

The inequality in Lemma 1(i) is the second-order condition for truth-telling, or incentive compatibility (see the proof of Lemma 1). This condition will later help explain how $H(x)$ affects the format of the optimal mechanism. Lemma 1(ii) states that the (induced) optimal capacity when it is noncontractible should be identical to that of contractible capacity. This is intuitive because $K^o(x)$ represents the most efficient capacity investment under adverse selection according to Proposition 1. Given this condition, we only need to focus on the payment schedule that can induce the capacity $K^o(x)$. Next we present the buyer's optimal mechanism under decreasing MRHR and increasing MRHR, respectively. We first consider the case where F has a decreasing MRHR. The buyer's optimal mechanism is given by the following proposition. Although $T(x,z)$ can take any general functional format, the proposition shows that a menu of linear contracts can achieve the second-best solution for the buyer.

Proposition 2. *Suppose F has a decreasing MRHR ($H'(x)\leq 0$) for $x\in[0,\bar{c}]$. The following menu of contracts $\{T^o(x,z)=w^o(x)z+\hat{T}^o(x)\}$ is optimal for the buyer: for $x>\hat{c}^o$, there is $T^o(x,z)=0$, i.e., the buyer procures nothing from the supplier; for $x\leq\hat{c}^o$, there is*

$$w^o(x)=\frac{pH(x)}{1+H(x)}, \tag{14}$$

$$\hat{T}^o(x)=xK^o(x)-w^o(x)E_D[\min(K^o(x),D)]+\int_x^{\bar{c}}K^o(u)\,du, \tag{15}$$

where $K^o(x)=\Phi^{-1}((p-(x+F(x)/f(x)))/p)$ is the capacity induced by $T^o(x,z)$.

An important observation from Proposition 2 is that when $H'(x)\leq 0$, the buyer's second-best solution can be implemented using a menu of linear contracts. That is, for each contract in the menu, the buyer offers a wholesale price $w^o(x)$ to induce the desired capacity $K^o(x)$, and then uses a side payment $\hat{T}^o(x)$ to split the profit between the two parties. This format represents the commonly observed two-part tariff arrangement; see Vettas (2011) for practical examples of such a contract format in retail, wholesale, and technology licensing markets. This contract has a linear format, so we will use linear contract and two-part tariff interchangeably in the rest of the paper. The two-part tariff contractual format has been widely studied in the literature. It is well known that such a contract can coordinate a decentralized distribution channel (see, e.g., Moorthy 1987). Although our optimal contract $\{T^o(x,z)=w^o(x)z+\hat{T}^o(x)\}$ has the same format as the traditional two-part tariff contract, its underlying rationale is different. In a coordinating two-part tariff contract, the unit price must be equal to the supplier's marginal cost to avoid double marginalization. However, here w^o must be greater than the supplier's marginal cost in our setting due to the distortion in the optimal capacity (i.e., $F(x)/f(x)$), which guarantees the supplier's truth-telling.

We continue to study the buyer's optimal mechanism when the MRHR can be strictly increasing, i.e., $H'(x)>0$, for some x.

Proposition 3. *Suppose F has a strictly increasing MRHR ($H'(x)>0$) for some x in $[0,\bar{c}]$. Then, if capacity is noncontractible, the second-best solution cannot be achieved using a menu of linear contracts. However, there is a menu of quadratic contracts $\{T^o(x,z)=w_1^oz^2+w_2^o(x)z+\hat{T}^o(x)\}$ that can achieve the second-best solution for the buyer.*

Proposition 3 indicates that under strictly increasing MRHR, the buyer can still achieve the second-best profit under noncontractible capacity; however, a more complicated contract format (e.g., a quadratic payment schedule) is required for implementation. The explanation of this result is as follows. Suppose there is a linear payment function $T(x,z)=w(x)z+\hat{T}(x)$. Then the condition in Lemma 1(i) becomes

$$\frac{w'(x)}{-w(x)\phi(K)}\geq 0,$$

or simply $w'(x)\leq 0$. That is, the second-order condition for truth-telling reduces to $w'(x)\leq 0$. Under such a linear payment scheme, the supplier faces a newsvendor problem and his optimal capacity satisfies $\Phi(K)=(w(x)-x)/w(x)$. Together with Lemma 1(ii), we get

$$w(x)=\frac{px}{x+F(x)/f(x)}=\frac{pH(x)}{1+H(x)}.$$

Clearly, $w'(x)\leq 0$ if and only if $H'(x)\leq 0$. To better understand the decreasing MRHR condition, we may compare the capacity functions $K^*(x)=\Phi^{-1}((p-x)/p)$ and $K^o(x)=\Phi^{-1}((p-(x+F(x)/f(x)))/p)$ under the first-best and second-best solutions, respectively. The term $F(x)/f(x)$ denotes the capacity distortion in the second-best solution (optimal mechanism) to induce truth-telling from the supplier. Under contractible capacity, a decreasing RHR (i.e., $f(x)/F(x)$) is sufficient for the existence of a separating equilibrium, as shown by Proposition 1. In contrast, under noncontractible capacity, a decreasing MRHR (i.e., $xf(x)/F(x)$) is needed to guarantee a separating equilibrium under linear contracts. This is a stronger condition because a decreasing $xf(x)/F(x)$ requires $f(x)/F(x)$ not only to be decreasing, but also to be decreasing fast enough. In fact, it implies that the distortion in capacity has to be significant enough (i.e., $F(x)/f(x)$ increases fast enough). Note that a large enough capacity distortion helps discourage the supplier from misreporting his true cost. Thus, for the menu of wholesale prices to induce the right capacity and satisfy the truth-telling condition at the same time, we need a decreasing MRHR. Given the importance of the property of MRHR, we have examined many commonly used distribution functions. It can be shown that exponential, gamma, beta, chi, and chi-squared distributions have decreasing MRHR, and for normal, logistic, and extreme value distributions, the condition $H'(x)\le 0$ is violated for at most one interval on the support; the details are relegated to the online appendix.

Propositions 2 and 3 indicate that the noncontractibility of capacity does not necessarily result in efficiency loss for the buyer. Similar findings have been reported in different procurement settings (e.g., Laffont and Tirole 1986, Rogerson 1987, and Kaya and Özer 2009). In particular, Kaya and Özer (2009) study an outsourcing problem with noncontractible quality and asymmetric cost information. They find that when the buyer can commit to a sales price before observing quality, noncontractibility does not reduce the outsourcer's profit. We demonstrate that the similar result holds in an outsourcing setting with noncontractible capacity.

Although the buyer can still achieve the second-best profit, the quadratic payment schedule is complex and less intuitive. The simplicity of the linear format has been lauded in the incentive literature, and much attention has been devoted to characterizing environments where optimal contracts can be implemented through linear contracts (see, e.g., Bose et al. 2011 and references therein). What will happen if the buyer is restricted to a linear contract format? We also investigate this question and find that under the more practical linear format, there will be bunching in the optimal mechanism because the buyer may be unable to screen all the supplier types. The next proposition formalizes this result. It can be shown that $H'(x)>0$ holds for at most one interval for many commonly used distributions; therefore, for illustration purpose we will focus on this case in the following proposition.

Proposition 4. *Suppose F has a strictly increasing MRHR ($H'(x)>0$) for a single interval in $[0,\bar{c}]$. Then, the linear contract $\{T(x,z)=w(x)z+\hat{T}(x)\}$ will lead to a bunching interval $[c_1,c_2]$, within which the contract reduces to a constant payment $\{T^o(z)=w^o z+\hat{T}^o\}$. In particular, we can solve $\{c_1,c_2,w^o\}$ from the following simultaneous equations*:

$$w^o=\frac{pH(c_1)}{1+H(c_1)}, \tag{16}$$

$$w^o=\frac{pH(c_2)}{1+H(c_2)}, \tag{17}$$

$$0=\int_{c_1}^{c_2}\left(\frac{x}{\phi(K(x))(w^o)^2}\right)\cdot[(p\bar{\Phi}(K(x))-x)f(x)-F(x)]\,dx, \tag{18}$$

where $K(x)=\Phi^{-1}((w^o-x)/w^o)$. If bunching starts at the lower bound of the support, then we replace (16) by $c_1=0$; if bunching ends at the upper bound of the support, then we replace (17) by $c_2=\bar{c}$. The transfer payment $\hat{T}^o$ on the bunching interval is given by

$$\hat{T}^o=c_2K(c_2)-w^oE_D[\min(K(c_2),D)]+\int_{c_2}^{\bar{c}}K(u)\,du. \tag{19}$$

The optimal menu $\{T^o(x,z)=w^o(x)z+\hat{T}^o(x)\}$ for $x\notin[c_1,c_2]$ is the same as in Proposition 2.

When $H'(x)>0$, the linear payment schedule will violate the incentive compatibility constraint. Thus, the buyer needs to offer constant contract terms to certain supplier types; the inability to screen the supplier types (i.e., pooling) leads to a lower profit for the buyer compared to the case of full separating. This brings about another question: What is the trade-off between simplicity and lost profit under simple contracts with strictly increasing MRHR? In Section 5 we will shed some light on this question by examining performance of simple contracts in general settings.

5. Simple Contracts

The optimal (second-best) contracts characterized in Section 4 are still complicated and thus may not be straightforward to implement in practice: First, they involve contract menus that are difficult to derive and explain to managers; second, they require the supplier to announce its cost, which imposes communication and evaluation burdens on the supply chain firms. So what is the value of using a complex menu in supply contracting? To answer this question, we study a single two-part tariff $\{w^o,T^o\}$ in this section, i.e., the buyer pays a wholesale price w^o and a lump-sum payment T^o

to the supplier. This contract is simpler than the optimal contracts in Section 4 because it only involves a single, linear payment function. Next, we derive the conditions for such a simple contract to be optimal; then we examine the performance of this contract in more general settings (i.e., even when it is suboptimal).

5.1. When Simple Contracts Are Optimal

Recall from Proposition 2 that the buyer's second-best solution can be implemented by a menu of two-part tariffs $\{w^o(x), T^o(x)\}$, where $w^o(x) = pH(x)/(1+H(x))$. If $H(x)$ is a constant ($H'(x) = 0$), then both $w^o(x)$ and $T^o(x)$ will be independent of x. This indicates that the optimal contracts may reduce to a single two-part tariff under certain conditions. The following proposition confirms this conjecture.

Proposition 5. *If $H'(x) = 0$ for all $x \in [0, \bar{c}]$, then the optimal menu of contracts reduces to a single two-part tariff $\{w^o, T^o\}$. This happens if and only if the supplier's cost has a density $f(x) = \delta x^{\eta-1}$, $\delta > 0$, $\eta > 0$. Additionally, if $\hat{c}^o \leq \bar{c}$, then $w^o = \hat{c}^o$ and $T^o = 0$, i.e., the optimal menu of contracts reduces to a single wholesale price.*

Proposition 5 states that a two-part tariff consisting of only two numbers $\{w^o, T^o\}$ could be optimal for the buyer when $H'(x) = 0$ for all $x \in [0, \bar{c}]$. Further, if $\hat{c}^o \leq \bar{c}$, then there must be $T^o = 0$ and the $\{w^o, T^o\}$ contract further reduces to a single wholesale price $w^o = \hat{c}^o$ that can be easily determined. Note $\hat{c}^o \leq \bar{c}$ means the buyer wishes to exclude some high cost types, which tends to happen if the supplier has too wide a cost support (or $\bar{c}$ is relatively large compared to p). In this case, an exceedingly simple arrangement is optimal for the buyer: The two parties agree upon a unit price, and the supplier decides on how much capacity to invest. This is essentially a *pull contract* widely observed in practice, under which the buyer pulls inventory from the supplier and meanwhile pays a wholesale price. Cachon (2004) discusses an example of a pull contract from the high-end bicycle industry. In the semiconductor equipment industry, buyers often share a demand forecast with their suppliers. The demand forecast serves as an informal or soft order intended to guide the supplier's production decisions. After observing the actual demand, a buyer is able to cancel or renegotiate the soft order (see Cohen et al. 2003 and Johnson 2003). Similarly, Kurt Salmon Associates Reports (1993) indicate that 80% of the wholesale transactions in the grocery industry are "forward buy" in nature, where buyers place tentative orders in anticipation of demand growth. They are prone to cancelling their orders if the actual demand falls short of what they expected. In all of these examples, wholesale price arrangements are used, and the buyer simply pulls inventory from the supplier when demand arrives.

To help the buyer choose the optimal contract format, we examine the distributions satisfying the condition in Proposition 5, i.e., $f(x) = \delta x^{\eta-1}$ with $\delta > 0$ and $\eta > 0$. Such a condition may hold under either increasing ($\eta > 1$), decreasing ($\eta < 1$), or constant ($\eta = 1$) density functions. In particular, f is a uniform distribution when $\eta = 1$. A uniform distribution means that the buyer has no reason to believe that certain cost realizations are more likely to happen than the others. Hence, Proposition 5 indicates that a two-part tariff or even a pull contract could achieve the optimal profit if the buyer has extremely limited information about the supplier's capacity cost. Interestingly, the adoption of a uniform cost distribution is in line with the Laplace principle on decision making under uncertainty. The principle states that in the absence of a reason to do otherwise, a decision maker may assume each of the possible outcomes of the random event has an equal likelihood of occurrence. This suggests that if the buyer does not know the supplier well (which could be quite common, especially when the supplier is new or located far away), then the buyer may follow such a principle to assume a uniform cost uncertainty distribution, and our result indicates that the simple pull contract is optimal for the buyer.

The significance of Proposition 5 would be more clear if we posit it within the existing literature on the performance of simple contracts. It has been shown that under conditions such as limited liability (Garrett 2014) or minimax criterion (Chung and Ely 2007, Carroll 2015), a single contract could be optimal in certain circumstances. We show that the optimality of a single contract may hold in the classical supply chain under study, without any assumption on the limited liability or minimax criterion. Such a result has not been previously reported in the literature, which may provide a new explanation of the wide use of simple contracts in supply chains (e.g., wholesale price or pull contracts). A few papers have tried to obtain lower bounds on the performance of simple contracts. Rogerson (2003) studies performance of the fixed price cost reimbursement (FPCR) contract in Laffont and Tirole's framework. Assuming that just one unit of a product is required, he shows that if the agent's cost follows a uniform distribution, an optimally designed FPCR contract can secure at least 75% of the optimal complex contract. Chu and Sappington (2007) extend Rogerson's analysis to the case of power distribution where high cost agents are more likely. They show that the good performance of simple FPCR contract may no longer hold. Instead they identify another type of simple contracts that can capture at least 73% of the optimal profit. Later, Chu and Sappington (2015) consider a multiunit framework and show that in this more complex setting, a simple FPCR contract still captures at least 75% of the optimal attainable profit. Our paper offers a stronger result in our supply chain setting: for both uniform and power distributions, 100% of the optimal performance can be secured through a single two-part tariff contract.

5.2. Performance of Simple Contracts

We proceed to investigate the performance of the $\{w^o, T^o\}$ contract in more general settings, even when it is suboptimal. We first derive analytical bounds on the performance for specific settings and then use a comprehensive numerical study to confirm the robustness of the findings. Specifically, consider a family of density functions for capacity cost uncertainty: $f(x) = \alpha + \delta x^{\eta-1}$, where $\alpha > 0$, $\delta > -\alpha/\bar{c}^{\eta-1}$, $\eta > 1$, and $x \in [0, \bar{c}]$. This functional format represents a reasonable approximation of many monotone density functions. To maintain analytical transparency, we assume that the random demand is uniformly distributed over a support $[\beta - \theta, \beta + \theta]$, where β is the mean and $\theta/\sqrt{3}$ is the standard deviation of demand. Let π_b^{OM} and π_b^S denote the buyer's profits under optimal mechanism and simple contract, respectively. Then the ratio $(\pi_b^{OM} - \pi_b^S)/\pi_b^S$ (i.e., the percentage profit gain by using the optimal mechanism) can be used to measure the value of using a menu of contracts, which, equivalently, also measures the performance of the simple contract. The following proposition characterizes the effect of different parameters on the value of using the optimal menu of contracts.

Proposition 6. *Consider the density functions and uniform demand distribution described above. The performance of the simple contract for the buyer* (i) *improves in β, and* (ii) *deteriorates in θ.*

Proposition 6 indicates that a higher mean demand (measured by β) would improve the performance of the simple contract, while a larger demand variability (measured by θ) would deteriorate its performance. These results are also consistent with the observations from later numerical studies (i.e., Tables 1–4). They are not surprising because the buyer's expected profit increases in mean demand while it decreases in demand uncertainty. We have also tried to analyze how the performance of the simple contract depends on the capacity cost distribution. It turns out that the effect of capacity cost distribution is ambiguous: In the numerical studies, the performance may be either increasing or decreasing in the coefficient of variation of the capacity cost distribution.

While for the above density function we can solve for the performance of the simple contract in closed-form, we still need to put more structure on this distribution to derive analytical bounds on the performance. The following proposition assumes the linearity of the cost density.

Proposition 7. *Suppose $f(x) = \alpha + \delta x$ on a support $[0, 1]$ and Φ is uniform on $[0, 1]$. Assume $\hat{c}^o \geq 1$ and $w^o \geq 1$, i.e., no supplier type is excluded under both contracts. Then the ratio $(\pi_b^{OM} - \pi_b^S)/\pi_b^S$ has an upper bound $1/48$ ($\approx$2.08%) for $0 \leq \delta \leq 2$, and an upper bound $5/208$ ($\approx$2.40%) for $-1 \leq \delta < 0$. In addition, the ratio decreases in p in both cases.*

Proposition 7 indicates that the simple contract yields close-to-optimal performance in this special case, since the value of using a menu of contracts is bounded by a small number (2.40%). In addition, the profit difference tends to decrease in market price (or profit margin). This proposition indicates that even when the simple contract is suboptimal (the conditions in Proposition 5 do not hold), its performance might be close to optimal. Note the bound (2.40%) is much tighter than the ones reported in the literature (e.g., Rogerson 2003; Chu and Sappington 2007, 2015), despite the challenging setting that involves both cost and demand uncertainties.

An analytical comparison between the simple and optimal contracts is challenging for general distributions (see the analysis in the online appendix). Therefore, it is instructive to evaluate the performance of simple contracts numerically for more general settings. In the first numerical study, we generalize the linear density in Proposition 7 to the densities mentioned earlier: $f(x) = \alpha + \delta x^{\eta-1}$. We construct 1,200 scenarios in total using the following parameter values. The market demand D follows a gamma distribution with mean $\mu = 50$ and coefficient of variation $CV \in \{0.2, 0.4, 0.6, 0.8, 1.0\}$. We vary the CV while fixing μ to investigate the impact of demand variability. The rest of the parameters are allowed to range from very low values to very high values so that the numerical study covers a wide range of practical situations: the supplier's cost c has a support $[0, \bar{c}]$, where $\bar{c} = \{1, 5, 10\}$, $\eta \in \{1.5, 2.0, 2.5, 3.0\}$, and $\delta = \eta(1 - \alpha\bar{c})/\bar{c}^{\eta}$. To ensure $\delta > 0$ (or $1 - \alpha\bar{c} > 0$), we set $\alpha = \delta_\alpha/\bar{c}$, where $\delta_\alpha = \{0.01, 0.1, 0.5, 0.9\}$. Since the lower bound of the cost support is fixed at zero, the supplier's mean cost increases in $\bar{c}$. Thus we set market price $p = \delta_p \bar{c}$ with $\delta_p \in \{0.5, 1, 1.5, 2, 2.5\}$, where δ_p measures the magnitude of market price relative to the cost (or the profit margin of the product).

For each of the above scenarios, we calculate the ratio $(\pi_b^{OM} - \pi_b^S)/\pi_b^S$. Table 1 reports the performance of the simple contract, measured by $(\pi_b^{OM} - \pi_b^S)/\pi_b^S$, across all scenarios. We group the data by different levels of

Table 1. Performance of Simple Contracts ($(\pi_b^{OM} - \pi_b^S)/\pi_b^S$) for Cost Density Function $f(x) = \alpha + \delta x^{\eta-1}$ ($\delta > 0$)

Demand CV	Average (%)	90th percentile (%)	Maximum (%)
0.2	0.09	0.20	0.39
0.4	0.10	0.23	0.68
0.6	0.15	0.28	1.10
0.8	0.21	0.41	1.65
1.0	0.28	0.58	2.34

demand uncertainties (i.e., CV values). For instance, under $CV = 0.2$, the buyer enjoys a 0.20% or less profit increase for 90% of the scenarios with an average of 0.09% among all scenarios. We highlight several observations from this numerical study. First, the value of using a menu of contracts is quite small: the average profit increase is 0.17% with a maximum of 2.34% among the 1200 tested scenarios. Second, we find that the simple contract tends to perform better for large p values and low CV values. Third, consistent with Proposition 5, we observe that $T^o = 0$ as long as $\hat{c}^o \le \bar{c}$ in this numerical study, i.e., the two-part tariff reduces to a pull contract when the optimal mechanism excludes some high cost types. This happens among 55% of the tested scenarios.

Tables 2 to 4 present similar findings from three additional numerical studies. These numerical studies are similar to the first except that the supplier's cost follows different distributions. In Table 2, the cost densities are given by $f(x) = \alpha + \delta x^{\eta-1}$ with $\delta < 0$, i.e., the density is decreasing in x. Due to the negative sign of δ, we have used $\delta_\alpha = \{1.01, 0.5\eta/(\eta-1), 0.9\eta/(\eta-1)\}$ in this numerical study. (To ensure $\delta < 0$, we need $1 - \alpha\bar{c} < 0$, or $\delta_\alpha > 1$. Further, we need $f(x) = \alpha + \delta x^{\eta-1} \ge 0$ for all x, which yields $\alpha \le \eta/(\bar{c}(\eta-1))$, or $\delta_\alpha \le \eta/(\eta-1)$.) There are 900 scenarios in Table 2. Since we show that both uniform and power distributions can secure the second-best solution, the good performance of these distributions is expected. To further check for robustness of our findings, we have tested many more log-concave cost distributions, including normal, gamma, logistic, exponential, extreme value, chi-square, Laplace, and beta distributions. This wide range of distributions allows for nonmonotone distributions. Tables 3 and 4 present our findings for normal and gamma distributions with 375 scenarios each. The results for the remaining cost distributions are similar and are thus given in the online appendix. In Table 3, we consider (two-sided) truncated normal cost distributions. The unimodal normal distribution is quite natural from a practical perspective. The normal distribution has a mean of $\bar{c}/2$ and takes CV values from $\{0.1, 0.3, 0.5, 0.7, 0.9\}$; the truncated probability is evenly distributed on the support $[0, \bar{c}]$. The numerical study in Table 4 considers (truncated) gamma cost distribution, which generalizes the normal distribution to allow skewed density curves. In sum, through comprehensive numerical studies, we show that the simple contract (i.e., two-part tariff) yields close-to-optimal performance under a wide range of circumstances.

Table 2. Performance of Simple Contracts ($(\pi_b^{OM} - \pi_b^S)/\pi_b^S$) for Cost Density Function $f(x) = \alpha + \delta x^{\eta-1}$ ($\delta < 0$)

Demand CV	Average (%)	90th percentile (%)	Maximum (%)
0.2	0.07	0.14	0.33
0.4	0.11	0.24	0.42
0.6	0.14	0.34	0.61
0.8	0.16	0.38	0.83
1.0	0.19	0.44	0.96

Table 3. Performance of Simple Contracts ($(\pi_b^{OM} - \pi_b^S)/\pi_b^S$) for Normal Cost Distribution

Demand CV	Average (%)	90th percentile (%)	Maximum (%)
0.2	0.23	0.39	0.66
0.4	0.40	0.76	0.91
0.6	0.60	1.19	1.49
0.8	0.83	1.68	2.23
1.0	1.08	2.31	3.13

Table 4. Performance of Simple Contracts ($(\pi_b^{OM} - \pi_b^S)/\pi_b^S$) for Gamma Cost Distribution

Demand CV	Average (%)	90th percentile (%)	Maximum (%)
0.2	0.29	0.48	0.73
0.4	0.55	0.96	0.98
0.6	0.84	1.53	1.60
0.8	1.18	2.20	2.39
1.0	1.54	2.97	3.37

5.3. Why Simple Contracts Perform Well

The above analysis and numerical studies show that the two-part tariff $\{w^o, T^o\}$ (or sometimes a pull contract w^o) is nearly optimal for the buyer (i.e., it yields almost the same profit as the optimal menu of contracts). Why does the simple contract perform so well? Cachon and Zhang (2006) study a contract design problem in which the supplier is modeled as a make-to-order manufacturer with private capacity cost. They demonstrate that the buyer's profit is very flat in capacity cost under the optimal mechanism; therefore, some simple contracts with fixed parameters yield nearly optimal performance. However, in our problem setting, the buyer's profit in the optimal contract is found to be highly variable in capacity cost. So the insight from Cachon and Zhang (2006) does not apply here.

The first observation that contributes to the good performance of a simple contract is that it induces similar expected capacity as the optimal contract. The capacity plays a key role in our model setting because it determines both the supply chain's profit as well as the supplier's profit. Let $K^s(x) = \Phi^{-1}((w^o - x)/w^o)$ denote the capacity level induced by the simple contract. Then, $E(|(K^o(x) - K^s(x))/K^s(x)|)$ denotes expected *absolute* percentage capacity difference between the optimal and the simple contracts. The following proposition shows that this value can be bounded above by a small value under specific circumstances.

Proposition 8. *Suppose $f(x) = \alpha + \delta x$ on a support $[0, 1]$ and Φ is uniform on $[0, 1]$. Assume $\hat{c}^o \ge 1$ and $w^o \ge 1$, i.e., no supplier type is excluded under both contracts. Then the ratio $E(|(K^o(x) - K^s(x))/K^s(x)|)$ has an upper bound*

$\approx 5.6\%$ for $0 \le \delta \le 2$, and an upper bound $\approx 7.8\%$ for $-1 \le \delta < 0$. In addition, the ratio decreases in p in both cases.

In our numerical experiments, we find the mean, 90th percentile and maximum values of the ratio to be 2.84%, 8.70%, and 17.53%, respectively. This shows that in such a supply chain setting, the simple contract induces quite close capacities as those stipulated by the optimal menu. To further investigate this observation, notice that Equation (18) satisfied by the optimal w^o can be rewritten as follows:

$$\int_0^{\min\{\bar{c},\hat{c}^o\}} \frac{x}{\phi(K(x))(w^o)^2}[CF^o(x) - CF^S(x)]\,dx = 0,$$

where $CF^o = 1 - (x + F(x)/f(x))/p$ and $CF^S = 1 - x/w^o$ are the newsvendor critical fractiles that determine $K^o(x)$ and $K^s(x)$, respectively, for the optimal and simple contracts. Since $(x/(\phi(K(x))(w^o)^2)) \geqslant 0$, there must be $K^o(x) > K^s(x)$ for some x, whereas $K^o(x) < K^s(x)$ for the others. In other words, compared to the optimal mechanism, the simple contract would result in both over-investment and under-investment in capacity, depending on the supplier's type. This implies that the ratio bounds in Proposition (8) would be even smaller if one considers the expected percentage capacity difference $E((K^o(x) - K^s(x))/K^s(x))$ (i.e., by taking out the absolute sign).

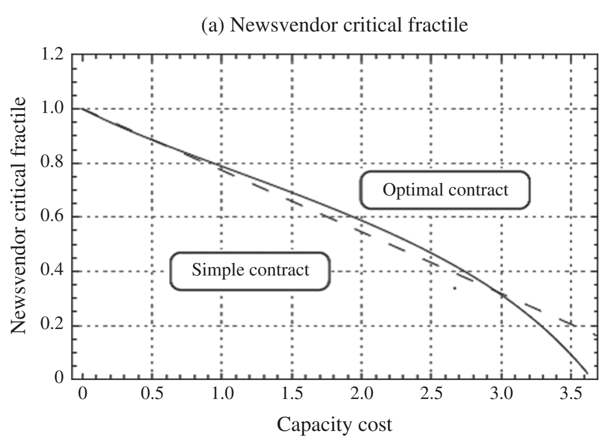
To visualize this observation, we present an example in Figure 1. It can be seen that the newsvendor critical fractile for the optimal contract is quite close to that induced by the single contract (Figure 1(a)). It is not surprising that this results in quite similar capacities and therefore small expected absolute percentage capacity differences between optimal capacity and the one induced by the simple contract (Figure 1(b)). Also notice that the curve of $K^s(x)$ can be either above or below that of $K^o(x)$ (i.e., over- and under-investments).

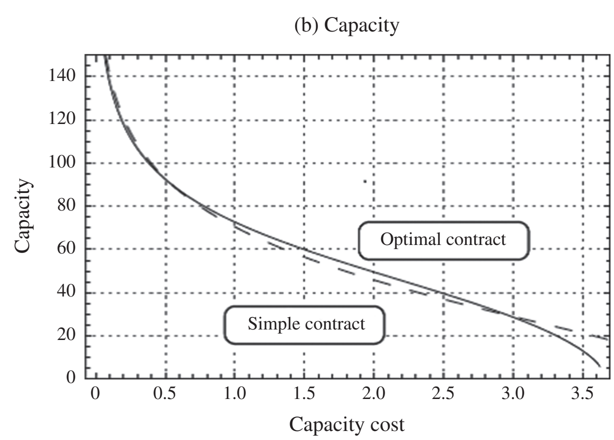
Since the supply chain profit only depends on the induced capacity, the above observation on $K^o(x)$ and $K^s(x)$ leads to a conjecture that the supply chain performances under the optimal and simple contracts are close to each other. Let π_{sc}^{OM} and π_{sc}^{S} denote the supply chain profits under the optimal and simple contracts, respectively; then the ratio $(\pi_{sc}^{OM} - \pi_{sc}^{S})/\pi_{sc}^{S}$ may be used to measure the improvement in supply chain performance by adopting the optimal mechanism. We find that among all four numerical studies, the ratio is -0.41% on average and 0.10% at the maximum. Thus, we can see that the simple and optimal mechanisms perform closely for the supply chain as well. Note that these ratios are smaller than the ratios for the expected absolute percentage capacity difference, which can be explained as follows. Recall that there are $K^o(x) < K^*(x)$ (due to the distortion effect as shown in Proposition 1) and $K^s(x) < K^*(x)$ (due to double marginalization). Thus, the simple contract yields a higher supply chain profit than the optimal mechanism if $K^s(x) > K^o(x)$ and vice versa. Since there are both $K^s(x) > K^o(x)$ and $K^s(x) < K^o(x)$, the effects of over-investments and under-investments on supply chain profit will cancel out each other in expectation, which leads to even smaller ratios that measure the difference in supply chain profit under the two contracts.

The buyer's profit under the optimal contract can be expressed as supply chain profit minus the supplier's profit (information rent). Thus, to complete the explanation why simple contracts perform well for the buyer, we are left to show that the simple contract does not leave the supplier with excessive profit compared to the optimal one. From Proposition 1, we know that the supplier's profit can be written as $\int_x^{\bar{c}} K^o(u)\,du$. Similarly, we may write the supplier's profit under the simple contract as a function of $K^s(x)$ according to the next lemma.

Lemma 2. *The supplier's expected profit under a single two-part tariff contract $\{w^o, T^o\}$ can be written as $\pi_s^S = \int_x^{\bar{c}} K^s(u)\,du$.*

Figure 1. The Capacity Difference Between the Optimal Mechanism and the Simple Contract





Note. Market demand follows a gamma distribution with mean 50 and $CV = 0.5$; capacity cost follows a normal distribution $N(\frac{5}{2}, \frac{5}{4})$, $p = 15/2$ and $\bar{c} = 5$.

Thus, the difference in the supplier's profits under the optimal mechanism and simple contract depends on the two capacity functions $K^o(x)$ and $K^s(x)$. Again, based on the above observation on $K^o(x)$ and $K^s(x)$, one may expect the difference in the supplier's profits under the two different mechanisms to be small. Indeed, our numerical experiments show that the average percentage difference is 2.09% (more details regarding the difference in the supplier's profits between the two different mechanisms are provided in the online appendix).

A closer scrutiny reveals another subtle relationship that further contributes to the excellent performance of the simple contracts. Recall that ex post the simple contract will cause both over- and under-investments in capacity compared to the optimal mechanism (there is $K^s(x) > K^o(x)$ for some x and $K^s(x) < K^o(x)$ for the rest). For a cost realization x with $K^s(x) > K^o(x)$, the supply chain's profit is higher under the simple contract than under the optimal mechanism (note both $K^o(x)$ and $K^s(x)$ are lower than the centralized optimal capacity $K^*(x)$); however, the fact $K^s(x) > K^o(x)$ implies that the adjacent range around x would contribute more to the supplier profit under the simple contract (note the supplier profits are $\int_x^{\bar{c}} K^s(u)\,du$ and $\int_x^{\bar{c}} K^o(u)\,du$ under these two contracts). An analogous observation can be made for x with $K^s(x) < K^o(x)$. Thus, from the ex post perspective, there is a positive correlation between the supply chain's profits and the supplier's profits, whose difference determines the buyer's profit. Therefore, even when there is a gap between the capacity functions $K^o(x)$ and $K^s(x)$, its effect on the buyer's profit will be dampened due to such a positive correlation. This helps explain the bounds derived in Proposition (7) and (8) (i.e., the bounds on profit ratios are tighter than the bounds on capacity ratios).

We have identified a couple of reasons to explain the excellent performance of simple contracts in our supply chain setting. The first observation indicates that expected induced capacities are quite close under the simple and optimal contracts. As a result, both the supply chain's profits and supplier's profits are also close under these contracts. Second, the positive correlation between the supply chain profit and supplier profit suggests that any effect of over-investment and under-investment in capacity on buyer's profit under the simple contract would be dampened. Since the buyer's profit is just the difference between the supply chain's profits and supplier's profits, these two observations indicate that the simple and optimal contracts would deliver close profits for the buyer.

5.4. Managerial Implications

The above results have useful implications for sourcing contract design, especially in global supply chain settings. It has been widely acknowledged that when procuring globally, firms would be less certain about whether contractual agreements can be supported by effective legal enforcement. In such environments, proactive arrangements designed to avoid and resolve problems in the first place provide a superior alternative to reliance on formal dispute-resolution strategies. One suggestion is to tie payment schedules to actual delivery and acceptance of the buyer (see, e.g., Pierce 2012). In this study, we show that this is an effective solution for the buyer and even a single, linear contract can yield close-to-optimal profit. Thus, the single, linear contract represents an excellent option for our contracting problem in several respects: it has a simple format, does not require the capacity cost information as an input, and is enforcement-free.

The above analysis also reveals that simple contracts perform well because the induced capacity is close to that under the optimal mechanism. As a result, the supply chain performances are very close under the simple and optimal contracts as well. In fact, we find that in the majority of numerical scenarios, the supply chain profit is higher under the simple contract (this does not hold for only 367 out of 2,850 scenarios; these exceptions tend to happen for low demand CVs (coefficient of variation)). This suggests that in general, the simple contracts help improve supply chain coordination. An implication of this finding is that in the presence of asymmetric cost information, supply chain coordination may not be an appropriate benchmark because there is a conflict between the supply chain's objective and the buyer's objective (to minimize the information rent). Moreover, the supplier prefers the simple contracts because they do not screen the supplier type and hence leave him more information rent. Overall, the simple contracts are attractive to all parties in the supply chain. This bodes well for the buyer because she can easily convince the supply chain partner to adopt such contracts.

We are now in a position to discuss the impact of the two incentive issues studied in this paper. Section 4 shows that noncontractibility of capacity does not result in efficiency loss for the buyer. Through numerical experiments we may also quantify the impact of cost information asymmetry on supply chain and buyer profits. Let π_b^{FB} denote the buyer's expected profit under the first best solution (i.e., the capacity cost information is known to the buyer). Notice that π_b^{FB} also denotes the supply chain profit, since the buyer can coordinate the supply chain and leave zero profit to the supplier. Therefore, $(\pi_b^{FB} - \pi_b^{OM})/\pi_b^{FB}$ measures the profit loss for the buyer due to private capacity cost information, whereas $(\pi_b^{FB} - \pi_{sc}^{OM})/\pi_b^{FB}$ measures the lost supply chain efficiency; the difference of these two ratios measures the gain for the supplier due to safeguarding his capacity cost information.

In our numerical experiments, we find that the lost efficiency for the supply chain due to asymmetric information is 15.97% on average. This is caused by the distorted capacity function $K^o(x)$ to minimize the information rent the buyer needs to pay. More importantly, the average profit loss for the buyer is 42.17%, in contrast to 0.31%, the average value of $(\pi_b^{OM} - \pi_b^S)/\pi_b^S$ (more details about these performance measures from our numerical experiments are provided in the online appendix). Thus, we can conclude that the gap between π_b^{FB} and π_b^{OM} (i.e., the value of eliminating information asymmetry) is much higher than that between π_b^{OM} and π_b^S (i.e., the value of using the optimal menu of contracts). These results imply that information asymmetry provides a strong shield for the supplier's profit—even a well-designed complex screening contract does not extract much surplus from the supplier.

To summarize, this research provides useful messages for managers who want to ensure supply while facing demand risk, uncertain supplier capacity cost, and noncontractible capacity. Such sourcing context has become typical in today's global supply chains. First, the buyer should try every means to obtain better information about the supplier's cost structure. This corroborates industry evidence where firms exert relentless effort to educate themselves on their suppliers' cost structures (see Ask and Laseter 1998, Kaya and Özer 2009). However, if reducing the uncertainty in the supplier's cost is not a viable strategy, then the buyer may adopt a simple two-part tariff contract: it yields near-optimal profit for the buyer but does not need the supplier's cost information or the contractibility of the supplier's capacity.

6. Conclusion

This paper studies a contracting problem in a supply chain setting consisting of a newsvendor buyer and a supplier. Two incentive issues that may arise in practice have been considered when studying the buyer's contracting strategy: first, there is asymmetric cost information in the supply chain (i.e., adverse selection issue); second, the supplier may shirk from his responsibility for capacity investment (i.e., capacity contractibility issue). These issues have become more prominent in today's global sourcing environment where trading partners are often new and distant from each other. First, we find that lack of contractibility on capacity does not necessarily reduce the buyer's profit, but it may require a more complex contract format. Although the buyer's optimal (second-best) mechanism is generally complex, it may reduce to a menu of linear contracts under certain conditions (i.e., each contract in the menu represents a two-part tariff, where the buyer pays the supplier a wholesale price for each product delivered and charges the supplier a lump-sum payment). Second, we show that a single two-part tariff can be optimal for the buyer when the supplier's cost distribution represents a constant modified reverse hazard rate. Interestingly, even when the single two-part tariff is suboptimal, it performs nearly as well as the optimal mechanism for a wide range of situations. That is, a single two-part tariff contract can deliver either optimal or near-optimal profit for the buyer under both cost uncertainty and contractibility issues. These findings indicate that in a global sourcing environment, using a complex menu and achieving enforceability may provide little value to the buyer.

Our results bode well for managers facing the above incentive issues, especially in a global sourcing context: for both ease of implementation and excellent performance, a buyer can simply use a two-part tariff contract (or sometimes just a wholesale price contract) under the presence cost information asymmetry and contractibility issues. In addition, our findings suggest that the buyer should try all means to reduce the uncertainty about the supplier's cost structure, which could lead to significant losses both for the buyer and the supply chain. This is because such uncertainty provides a robust protection of the information rent the buyer has to pay to the supplier; even the complex, optimal menu of contracts does not help much in reducing the information rent.

More research is needed to study supply chain contracting that involves informational and incentive issues. There are several potential directions for future research in this area. First, in this paper, we focus on adverse selection and contractibility issues in sourcing problems; it would be interesting to study a signaling game (rather than screening game) under moral hazard. Second, one may consider the impact of noncontractibility under the presence of both asymmetric demand information and asymmetric cost information. That is, the current model setting can be extended to include private demand information for the buyer. Finally, the supply chain studied in this research represents the simplest setting with one buyer and one supplier. It would be interesting to extend our model to more general supply chain structures (e.g., there are either multiple suppliers or multiple buyers).

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