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Achieving Efficiency in Capacity Procurement

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ABSTRACT

This chapter studies a capacity procurement problem in which a buyer meets an uncertain demand using a combination of spot purchases and supply options that are offered by a number of competing suppliers. The specific setting we consider involves the suppliers each owning a block of capacity and the buyer restricted to reserving the entire block or none. For this setting, we are interested in understanding the buyer's optimal procurement strategy and the suppliers' competitive bidding behavior in the supply option market. To this end, we first examine the buyer's optimal decision given a set of supply options, and then study the suppliers' optimal bidding strategies in equilibrium. We find that it is optimal for suppliers to set execution price at cost and hence make a profit only through the reservation payment. We also prove that when all the blocks have the same size the buyer's optimal profit as a function of supplier set is submodular. This property allows us to characterize an equilibrium in which the supply chain optimum is achieved, each supplier makes a profit equal to their marginal contribution to the supply chain and the buyer takes the remaining profit. When the blocks have different sizes, we develop a recursive procedure to characterize a class of equilibria in which the supply chain efficiency is achieved.

1

Motivation and Description of the Problem

The work described in this chapter is based on Anderson *et al.* (2017). In today's increasingly competitive markets there is a pivotal role for effective procurement. However, procurement firms face significant challenges due to a multitude of uncertainties, such as demand uncertainty and purchase price volatility. To manage those risks, firms often use a portfolio of procurement arrangements. In practice, a combination of spot purchases and supply options has seen wide applications in capital-intensive industries, such as commodity chemicals, electric power, and semiconductors (Kleindorfer and Wu, 2003; Wu and Kleindorfer, 2005). Spot purchases provide firms with flexibility but also come with great price uncertainty. Supply options allow procurement firms to tailor their purchase volumes to realized demand and spot price, but a reservation fee has to be paid in advance. Thus, an optimal procurement strategy requires a good balance between cost and flexibility.

Besides the uncertainty-driven challenges, there are some additional institutional restrictions and specifications that further complicate the capacity procurement problem. When a production facility needs to be built or made available in its entirety, the buying firm may be required to reserve capacity in *blocks*. An example of this sort occurs within the UK's system for purchasing Short Term Operating Reserve (STOR) for electricity supply. This is a scheme under which the National Grid maintains a reserve generation ability in case of sudden demand variations or plant failures. In this market, the bids come as blocks of capacity so the National Grid determines the optimal set of blocks to reserve.

This chapter seeks to address these challenges in a capacity procurement setting where a buyer, facing an uncertain future demand and volatile spot market, would like to determine an optimal portfolio of procurement arrangements. The demand will be met using both a spot market and supply options from multiple competing suppliers. In the model, each supplier is able to dedicate a capacity block that is bid into the supply option market. The suppliers each simultaneously submit a bid consisting of a reservation price and an execution price to the buyer, and given these supplier bids, the buyer decides which blocks to reserve prior to knowing the actual demand and spot price. When demand and spot price uncertainties are resolved, the buyer decides how much reserved capacity to use as well as how much to purchase from the spot market. In this setting, we are interested in understanding the buyer's optimal procurement strategy as well as the suppliers' competitive bidding behavior.

Supply options have been extensively studied in the operations management literature (see e.g., Barnes-Schuster *et al.*, 2002; Burnetas and Ritchken, 2005; Fu *et al.*, 2010; Secomandi and Wang, 2012). This literature began with an investigation of a buyer's optimal purchasing decision given a fixed set of supply options (see e.g., Martínez-de-Albéniz and Simchi-Levi, 2005), and has been extended to examine option contract design problems in a Stackelberg game between a buyer and a supplier (**Pei2011**). Further extensions have also been made to study supplier competition in an option market (Wu and Kleindorfer, 2005; Martínez-de-Albéniz and Simchi-Levi, 2009).

Wu and Kleindorfer (2005) consider the case of multiple competing suppliers where an open spot market provides an alternative source of supply for the buyer. They show that a competitive equilibrium between the suppliers will deliver an efficient solution for the supply chain as a whole. Our model is different since we have uncertainty in demand as well as in the spot price. Moreover, we have a restriction that capacity is only available in discrete blocks – the buyer has to reserve it all or none. We show that some results of Wu and Kleindorfer (2005) extend to our setting with suppliers offering contracts with an execution price equal to cost, and an equilibrium that is efficient for the whole supply chain. However, the equilibrium strategies and profit allocations are different in our model, and our efficiency result is due to a different driving force.

The model considered by Martínez-de-Albéniz and Simchi-Levi (2009) is also close to ours, with competing suppliers offering reservation and execution prices to a buyer who has to meet an uncertain demand. Their model does not include a spot market, but a more significant difference is that they assume that each supplier has an (infinitely) scalable capacity, and the buyer can decide how *much* capacity to reserve from each supplier. In our model, however, we assume that capacity comes as a block, so that the buyer is faced with a combinatorial optimization problem. Such model differences result in contrasting findings.

2

Modelling Approach and Methodology

We consider a supply chain with n suppliers and one buyer. Each supplier $i \in N = \{1, \ldots, n\}$ has a fixed capacity K_i. Recognizing the fact that the buyer must reserve all or none of the capacity, we say each supplier owns a capacity block with block size K_i. There are costs incurred by the suppliers associated with the reservation and execution of their capacity, and we let e_i be the unit reservation cost and c_i be the unit execution cost. The buyer faces random demand D. Before demand occurs, the buyer can reserve capacity that is offered in blocks by these n suppliers and pay a reservation price. After demand occurs, the buyer will meet the demand (up to the total amount of capacity reserved) and at this point pays an additional (execution) price for the capacity that is used. In addition to the reserved capacity, there is also an open spot market from which the buyer can purchase to meet demand. In the open spot market, no player can exercise market power to manipulate the (random) spot price P_0. Denote by $\overline{G}(t, p)$ the complement of the joint cumulative probability distribution for demand and spot price, i.e., $\overline{G}(t, p) = \Pr[D \geq t, P_0 \geq p]$.

Decisions on the capacity to reserve are made prior to P_0 and D being realized, but the actual use of that capacity relies on there being sufficient demand and the spot market price being sufficiently high. The buyer is paid a price ρ for each unit of demand that can be met. We assume the upper bound of P_0 is no greater than ρ so that demand will be always fulfilled. This is without loss of generality, because if this restriction is violated, we can define a new variable $\widetilde{P}_0 = \min(\rho, P_0)$ and replace P_0 with $\widetilde{P}_0$, then the results will follow.

We analyze a two-stage model. In the first stage, the suppliers each independently maximize their expected profits by choosing unit reservation prices r_i and unit execution prices p_i, where $i \in N$, and simultaneously submit their bids to the buyer. Given these supplier bids, the buyer then decides which blocks to reserve. Note that all these decisions are made under uncertainties in the demand and spot price. In the second stage, both demand and spot price are realized, and the buyer decides how much reserved capacity to use and how much to purchase from the spot market. We can see that this is a Stackelberg game where the suppliers are leaders and the buyer is a follower. Meanwhile, the suppliers play a non-cooperative game by competing in the option market, and we use the Nash equilibrium concept to study the suppliers' bidding behavior.

For convenience of presentation, we assume that all execution prices $\{p_i : i \in N\}$ are distinct, and label the bids so that $p_1 < p_2 < \cdots < p_n$. Suppliers will not offer an execution price higher than the unit revenue, so it is reasonable to assume $p_n \leq \rho$. We suppose that the joint distribution $\overline{G}$ and unit revenue ρ together with all the costs e_i and c_i $(i = 1, 2, ..., n)$ are common knowledge.

Given the set of supplier bids $\mathcal{B} = \{(p_i, r_i, K_i) : i \in N\}$, the buyer decides which blocks to reserve. For any $S \subseteq N$, we denote by $S(\mathcal{B})^*$ the optimal set of bids for the buyer given that the choice is made from amongst bidders in S. Here the optimality is with respect to maximizing the total expected profit for the buyer. This depends on the set of suppliers available, and we write $\Pi_{\mathcal{B}}(X)$ for the profit given bidders in X, so that

$$S(\mathcal{B})^* = \arg\max_{X \subseteq S} \Pi_{\mathcal{B}}(X). \tag{2.1}$$

The solution to the right-hand side of equation (2.1) may not be unique. Since the buyer's choice has an impact on the suppliers' decisions, we need to give a definite description of the buyer's behavior, when different choices yield the same expected profit for the buyer. As mentioned earlier, the problem faced by the suppliers and the buyer forms a Stackelberg game with multiple leaders, and thus involves bilevel optimization (see, e.g., Dempe, 2002). Drawing on the bilevel programming literature, we will adopt the *optimistic* approach with the economic interpretation that the follower is willing to support the leaders. Formally, we assume that if two sets of blocks give the same (maximum) expected profit, the buyer chooses the set of more blocks. Note that this rule avoids a situation where a supplier has an incentive to constantly adjust his bidding so that his marginal contribution to the total expected profit of the buyer remains positive (to keep himself selected by the buyer) but is infinitesimally small.

To deal with ties in which two choices have an equal number of blocks, we introduce the following desirable property of preference: If two sets of blocks give the same marginal expected profit in the optimal selection of the buyer, then her preference of one over another is independent of other blocks in her optimal selection. This property says that the prices of the other blocks in the buyer's optimal selection do not affect her preference between two sets of blocks that contribute the same marginal expected profit to the buyer. Such a property is known as *Independence of Irrelevant Alternatives* in decision theory.

3

Main Results and Insights

To understand the dynamics in the Stackelberg game, we follow the standard backward induction approach: we first consider an optimal policy for the buyer given an arbitrary set of supplier bids, and then turn to considering the optimal bidding behavior and the equilibria for the suppliers, anticipating the buyer's optimal reaction to their bids.

3.1 The buyer's procurement problem

The buyer makes a two-stage decision that involves the reservation choice prior to knowing actual demand and spot price, and the execution decision when both demand and spot price are known. We begin with the analysis of execution decision given the buyer's reservation choice.

Given bids $\mathcal{B} = \{(p_i, r_i, K_i) : i \in N\}$, suppose the buyer's reservation set is $\{(p_i, r_i, K_i) : i \in S \subseteq N\}$, where

$$S = \{j_1, \ldots, j_v\} \quad \text{with} \quad j_1 < \cdots < j_v. \tag{3.1}$$

It is convenient to denote by Y_i the total capacity of the first i blocks in S when ordered by the prices p_i. Thus

$$Y_i = \sum_{m=1}^{i} K_{j_m}, \; i = 1, \ldots, v. \tag{3.2}$$

At the time when actual demand and spot price are known, the buyer can fulfil customer demand by using the reserved capacity and spot purchases. Our first observation is that once a set of blocks has been reserved (and reservation payments made), when demand occurs the blocks that are used will be those that have the cheapest execution prices. Mathematically, for any realized demand t and spot price p_0, we denote by $x_i(t, p_0)$ the amount of capacity from supplier j_i that is used, and obtain

$$x_i(t, p_0) = \begin{cases} \min\left\{(t - Y_{i-1})_+, K_{j_i}\right\}, & \text{if } p_{j_i} \le p_0, \\ 0, & \text{otherwise,} \end{cases}$$

where $(z)_+ = \max\{z, 0\}$, and the purchase amount from the spot market is $t - \sum_{i=1}^{v} x_i(t, p_0)$. Then the buyer's expected profit from reserving S in the option market (as well as purchasing in the spot market) is

$$\Pi_{\mathcal{B}}(S) = \sum_{i=1}^{v} \left((\rho - p_{j_i})\mathbb{E}_{D,P_0}\left[x_i(D, P_0)\right] - r_{j_i} K_{j_i}\right) \\ + \mathbb{E}_{D,P_0}\left[(\rho - P_0)\left(D - \sum_{i=1}^{v} x_i(D, P_0)\right)\right], \tag{3.3}$$

where the expectations are taken over the joint distribution of D and P_0. The first and second terms in $\Pi_{\mathcal{B}}(S)$ represent the buyer's profits from purchasing in the option market and the spot market, respectively.

One strategy for the buyer is to reserve no capacity and rely entirely on the spot market. We write W for the expected profit under this policy. Hence, we obtain $W = \mathbb{E}_{D,P_0}[(\rho - P_0)D]$. We can then reformulate the expected profit for the buyer:

$$\Pi_{\mathcal{B}}(S) = \sum_{i=1}^{v} \mathbb{E}_{D,P_0}\left[(P_0 - p_{j_i})x_i(D, P_0) - r_{j_i} K_{j_i}\right] + W. \tag{3.4}$$

From equation (3.4) we observe that $\mathbb{E}_{D,P_0}\left[(P_0 - p_{j_i})x_i(D, P_0) - r_{j_i} K_{j_i}\right]$ measures the (expected) extra profit the buyer can make from reserving block j_i, in comparison with the profit by relying on the spot market alone. Since W is a constant, the buyer essentially maximizes the sum of these additional profits by choosing the optimal (sub)set of suppliers in the option market.

We now explore the property of the set function $\Pi_{\mathcal{B}}(\cdot)$. We can show that the set function $\Pi_{\mathcal{B}}(X)$ with $X \subseteq N$ is submodular, which implies that the marginal contribution of a block to the buyer's expected profit is smaller when the existing set of blocks is larger. Note that $\Pi_{\mathcal{B}}(X)$ is non-monotone since the marginal contribution of a block could be negative if it is forced into the choice set.

The buyer's problem is to find a set that maximizes her expected profit:

$$\max_{S \subseteq N} \Pi_{\mathcal{B}}(S), \tag{3.5}$$

where the expression of $\Pi_{\mathcal{B}}(S)$ is given in equation (3.4). In general, it is NP-hard to maximize a non-monotone submodular function. However, we can show that, with equal-size blocks, the submodularity property is inherited by the function $\Pi^*_{\mathcal{B}}(X)$, which takes the best buyer profit given a set of available blocks $X \subseteq N$:

$$\Pi^*_{\mathcal{B}}(X) = \max_{S \subseteq X} \Pi_{\mathcal{B}}(S). \tag{3.6}$$

Theorem 3.1. When blocks have the same size, the set function $\Pi^*_{\mathcal{B}}(X)$ with $X \subseteq N$ is submodular.

The theorem is complex to establish because we need to track the change of the buyer's optimal choice when an additional block is available. We offer some intuition here. With equal-size blocks, the selection of an additional block ℓ has a limited impact on the buyer's choice over existing blocks: First, any block that is not chosen in the absence of block ℓ will still not be chosen in the presence of block ℓ; second, there is at most one existing block that is chosen when block ℓ is unavailable but will not be chosen when block ℓ is available. Consequently, the additional value added by block ℓ occurs because: (i) block ℓ has a more competitive price than the dropped block; or (ii) the buyer simply requires it to meet certain demand (without affecting the existing blocks). The proof shows that, if the existing set is larger, it is less likely that block ℓ will be chosen, and less likely to be used if it is chosen by the buyer. As a consequence, the optimal buyer's profit function is submodular. Note that this result may not hold when the blocks have different sizes.

3.2 The suppliers' competitive bidding problems

After understanding the buyer's optimal reservation behavior, we are now in a position to study equilibrium bidding strategies for suppliers. That is, we will characterize the Nash equilibria for the supplier bidding game. A standard approach for studying Nash equilibrium is to first look at each supplier's best response to their competitors.

3.2.1 Suppliers' best response

Let us start with an examination of a supplier's best response to the bids of the other suppliers. Specifically, we look at how supplier ℓ responds to bids of suppliers in the set $L = N\backslash\{\ell\}$ by making a choice of (p_ℓ, r_ℓ). We write N^* and L^*, respectively, for the optimal buyer's choice from the set of bids N and L. We write $\pi_\ell(p_\ell, r_\ell)$ for the expected profit of supplier ℓ if he makes an offer with execution price p_ℓ and reservation price r_ℓ, assuming a fixed set of bids by the suppliers L, $\{(p_i, r_i, K_i) : i \in L\}$.

Theorem 3.2. Given bids $\{(p_i, r_i, K_i) : i \in L\}$ it is optimal for supplier ℓ to choose execution price $p_\ell = c_\ell$.

Theorem 3.2 shows that, in an optimal solution, suppliers charge only costs for their execution prices, but make profits from the buyer's reservation payments. We find that at the optimal execution price of supplier ℓ, which we write as $p^*_\ell = c_\ell$, the total supply chain surplus is maximized. By choosing the reservation price as high as possible subject to still being chosen by the buyer, the buyer makes the same profit as she does when her choice is restricted to choosing from $\{(p_i, r_i, K_i) : i \in L\}$. The consequence is that, since the supplier's profit equals the total surplus less the buyer's original profit $\Pi^*_{\mathcal{B}}(L)$, such a bidding strategy must also maximize the supplier's profit. Let $\mathcal{B}' = \{(p_i, r_i, K_i) : i \in L\} \cup \{(c_\ell, e_\ell, K_\ell)\}$, so that block ℓ is offered at cost. The proof of the theorem reveals that, for the optimal solution with $p^*_\ell = c_\ell$, we have an optimal choice of reservation price $r^*_\ell = (\Pi^*_{\mathcal{B}'}(N) - \Pi^*_{\mathcal{B}}(L))/K_\ell$. Therefore, supplier ℓ's optimal expected profit is $\pi^*_\ell = \Pi^*_{\mathcal{B}'}(N) - \Pi^*_{\mathcal{B}}(L)$. This is the supplier ℓ's marginal contribution to the supply chain with the existing bids $\{(p_i, r_i, K_i) : i \in L\}$. Supplier ℓ is able to extract all the marginal surpluses, because the buyer in our model makes an all-or-nothing decision, which significantly limits her choice flexibility.

3.2.2 Equilibria with blocks of an equal size

Having established the best response for each supplier, we now investigate Nash equilibria among the n suppliers. We start with a special case of the problem in which blocks are of an equal size and then consider the more general problem where suppliers may have blocks of unequal sizes.

Without loss of generality we take the block sizes as $K_i = 1$, $i = 1, 2, \ldots, n$. Based on Theorem 3.2 we can assume that each supplier chooses an execution price $p_i = c_i$.

We characterize the equilibrium for suppliers in the theorem below.

Theorem 3.3. When all blocks have the same size, the bids $\mathcal{B}^* = \{(c_i, r_i^*) : i \in N\}$ form a Nash equilibrium, where $r_i^* = e_i + \Pi_{\mathcal{C}}^*(N) - \Pi_{\mathcal{C}}^*(N\backslash\{i\})$ for $i \in N$ where $\mathcal{C} = \{(c_i, e_i) : i \in N\}$. Moreover, at any equilibrium with $p_i^* = c_i$, $i \in N$, the buyer chooses the supply chain optimal set $N(\mathcal{C})^*$, and supplier i makes a profit $\pi_i^* = \Pi_{\mathcal{C}}^*(N) - \Pi_{\mathcal{C}}^*(N\backslash\{i\})$.

Theorem 3.3 shows that, at equilibrium each supplier charges his execution cost and adds a margin to his reservation cost, and the margin is equal to the additional supply chain profit that is obtained with the inclusion of his block. The equilibrium stated in Theorem 3.3 is not unique. This occurs because the unchosen suppliers can set their reservation prices to any values no less than their reservation costs. Despite the fact that there may be multiple equilibrium bidding strategies, all equilibria lead to the same profit allocation: Each supplier makes a profit equal to his marginal contribution to the supply chain optimal profit, and the buyer takes the remaining profit. Theorem 3.3 also implies that the existence of an equilibrium is guaranteed in our model.

3.2.3 Equilibria with blocks of unequal sizes

Next we show how to construct an equilibrium when suppliers have blocks of unequal sizes. Let $\mathcal{C} = \{(c_i, e_i, K_i) : i \in N\}$, and $N(\mathcal{C})^* = \{j_1, \ldots, j_m\}$, which is an optimal buyer's choice when each supplier offers at cost. Following Theorem 3.2, we focus on the bidding strategies with execution prices equal to execution costs. We adjust suppliers' reservation prices by following a recursive procedure. Define $\{\mathcal{B}^{(k)} : k = 0, \ldots, m\}$ recursively as follows:

$$\mathcal{B}^{(0)} = \mathcal{C};$$
$$\mathcal{B}^{(k)} = \mathcal{B}^{(k-1)} \backslash \{(c_{j_k}, e_{j_k}, K_{j_k})\} \cup \{(c_{j_k}, r^*_{j_k}, K_{j_k})\}, \; k = 1, \ldots, m,$$

where

$$r^*_{j_k} = \left(\Pi^*_{\mathcal{B}^{(k-1)}}(N) - \Pi^*_{\mathcal{B}^{(k-1)}}(N \backslash \{j_k\})\right) / K_{j_k} + e_{j_k}. \tag{3.7}$$

At the initial step ($k = 0$), we set price to be cost for every block. Thus, solving the buyer's problem is equivalent to solving the supply chain optimization problem. In the next, we adjust the reservation prices for the blocks in $N(\mathcal{C})^*$ one at a time. Specifically, at step $k > 0$, we keep increasing the reservation price of block j_k until it is dropped by the buyer. This leads to the maximum allowable increase $\left(\Pi^*_{\mathcal{B}^{(k-1)}}(N) - \Pi^*_{\mathcal{B}^{(k-1)}}(N \backslash \{j_k\})\right) / K_{j_k}$. Thus, equation (3.7) gives the maximum reservation price $r^*_{j_k}$. It is easy to see that $r^*_{j_k} \geq e_{j_k}$, and hence no suppliers will make a loss by using the above bidding strategies. At the end of the final step m, the procedure returns a set of bids $\mathcal{B}^{(m)} = \{(c_i, e_i, K_i) : i \in N \setminus N(\mathcal{C})^*\} \cup \{(c_i, r^*_i, K_i) : i \in N(\mathcal{C})^*\}$, and it can be shown to form an equilibrium as stated in the following theorem.

Theorem 3.4. When supplier blocks may have different sizes, the set of bids $\mathcal{B}^{(m)}$, defined above, forms an equilibrium.

Theorem 3.4 states that, in the above equilibrium, the suppliers who are not in the supply chain optimal set, set price to cost, while the suppliers in the supply chain optimal set add a margin to their reservation costs. The equilibrium constructed in the procedure ensures that the buyer's optimal choice matches the supply chain optimal set, showing that even with different block sizes, the supply chain efficiency can still be achieved. It also implies that there is always a Nash equilibrium for the case with general-size blocks.

4

Future Research

In this chapter, we have studied supplier competition in a capacity procurement setting where a buyer meets demand by using spot purchases and supply options. Our model considers a setting where each supplier's capacity comes as a block so that the buyer has to reserve the block in its entirety. Our focus is on understanding the buyer's optimal procurement strategy and the suppliers' competitive bidding behavior in the supply option market. For this, we have characterized an equilibrium in which the supply chain efficiency can be restored in this non-cooperative game.

There are many possible extensions and we mention two of them here. First, like most models in this literature, our model considers a linear cost for suppliers. In practice, however, supplier costs may be nonlinear as capacity investment often involves a one-off setup cost or there may be scale (dis)economies in production. Thus, it is interesting to examine how suppliers compete in this environment, although this could be technically challenging. Second, an important assumption underpinning our model is that suppliers have complete information about each other's cost. Extending our work to an asymmetric information setting will be another avenue for future research.

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