Title
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Journal
Management Science, 53(12)

ISSN
0025-1909

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Publication Date
2007-12-01

DOI
10.1287/mnsc.1070.0731

Peer reviewed

MANAGEMENT SCIENCE
Vol. 53, No. 12, December 2007, pp. 1872–1886
ISSN 0025-1909 | EISSN 1526-5501 | 07 | 5312 | 1872

informs

DOI 10.1287/mnsc.1070.0731

Implications of Renegotiation for Optimal Contract Flexibility and Investment

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In a stylized model of biopharmaceutical contract manufacturing, this paper shows how the potential for renegotiation influences the optimal structure of supply contracts, investments in innovation and capacity, the way scarce capacity is allocated, and firms' resulting profits. Two buyers contract for capacity with a common manufacturer. Then, the buyers invest in innovation (product development and marketing) and the manufacturer builds capacity. Finally, the firms may renegotiate to allow a buyer facing poor market conditions to purchase less than the contractual commitment and a buyer facing favorable conditions to purchase more. We show that renegotiation can greatly increase the firms' investments and profits, provided that the contracts are designed correctly. Failing to anticipate renegotiation leads to contracts that allow too much flexibility in the buyer's order quantity, and perform poorly relative to contracts designed to anticipate renegotiation. We provide clear conditions under which quantity flexibility contracts with renegotiation coordinate the system. Where quantity flexibility contracts fail, employing tradable options improves performance.

Key words: renegotiation; biform games; bargaining; contract manufacturing; capacity pooling and allocation; quantity flexibility contracts
History: Accepted by Sunil Chopra, operations and supply chain management; received October 7, 2004. This paper was with the authors $6\frac{1}{2}$ months for 3 revisions. Published online in *Articles in Advance* October 26, 2007.

1. Introduction

After entering into supply contracts, firms often later renegotiate the terms (price, quantity, etc.) of those contracts (Cahn 2000, Serant and Ojo 2001). In contrast to a decision by one party to default on the contract and pay court-imposed damages, renegotiation is a multilateral decision in which all parties agree to replace the original contract with a new one. This paper examines the role of renegotiation in the context of biopharmaceutical manufacturing.

Biopharmaceutical manufacturing capacity is expensive and the lead time for building this capacity is three to five years (Molowa 2001). Therefore, before making important investments in drug development and clinical trials, pharmaceutical companies are contracting for capacity with a leading biopharmaceutical contract manufacturer, Lonza. Their quantity flexibility contracts stipulate the time frame (typically three years from the time of contracting), the amount of capacity that the buyer will take, with some limited flexibility, and the price per unit capacity. In addition, the pharmaceutical company makes a transfer payment to Lonza at the time of contracting to defray the cost of building capacity. Before setting the contract parameters and building capacity, Lonza carefully evaluates the prospects and capacity requirements for each buyer's drug. At the time of contracting, the buyers' capacity requirements are highly uncertain. Therefore, the quantity flexibility contracts are frequently renegotiated after demand is realized. When one buyer has greater demand than anticipated and another buyer has low demand, Lonza renegotiates the contracts with the buyers to achieve a more profitable allocation of its fixed capacity (Thomas 2001).

In a stylized model of biopharmaceutical contract manufacturing, this paper shows how the potential for renegotiation affects the optimal structure of supply contracts, investments in innovation and capacity, the way scarce capacity is allocated, and firms' resulting profits.

Economists have studied renegotiation in a supply chain with a single supplier and single buyer, where the supplier invests in reducing the production cost and the buyer invests in increasing the value of the good. Prior to investing, the firms sign a simple contract (e.g., a "price-only" contract specifying the price at which they trade the good, if trade occurs). If the realized value exceeds the production cost, the parties will renegotiate the price, if necessary, to ensure that trade takes place. The initial price affects their payoffs in the renegotiation game, and hence the incentives for investment. The objective

is to design a simple contract that maximizes the firms' total expected profit by inducing a Nash equilibrium of the first-best investments. (Implicitly, the firms can make transfer payments at the time of contracting to allocate this total expected profit.) Hart and Moore (1988) show that investment is inefficient under any price-only contract. In contrast, an option contract, in which the supplier has the right but not the obligation to deliver the good at the specified price, implements the first-best investments (Noldeke and Schmidt 1995). Aghion et al. (1994) implement the first-best investments with a contract that specifies the price and quantity to be traded, and a penalty for delay in the renegotiation process, which serves to allocate the gain from renegotiation to one firm. Che and Hausch (1999) assume that the supplier's investment (e.g., in quality) increases the value of the good to the buyer, rather than reduce the production cost. Then, simple contracts cannot induce the first-best investments, and the firms should simply rely on ex post negotiation, rather than contract and renegotiate. Tirole (1986) surveys the extensive economics literature on renegotiation, which focuses on bilateral trade; our paper is differentiated by the interaction of multiple buyers for the supplier's capacity.

Although renegotiation should occur whenever the action dictated by the contract is revealed to be suboptimal, many well-known papers in operations management exclude contract renegotiation. (Renegotiation may be excluded on the grounds that the associated transactional costs are prohibitive or on the grounds of tractability, because allowing for renegotiation can substantially complicate the analysis.) Next, we highlight how allowing for renegotiation changes analysis and results.

Renegotiation is pertinent to capacity allocation. Van Mieghem (1999) considers a manufacturer and subcontractor that build capacity before realizing demand. By fixing the per-unit price in advance, the firms could create incentives for capacity investment, but would also cause inefficient allocation of capacity between the manufacturer's and supplier's markets. Van Mieghem concludes that the firms may be better off waiting until demand is realized to negotiate the price. However, when renegotiation is allowed, the firms should initially set a per-unit price to induce efficient capacity investment, and then renegotiate that price after demand is realized to achieve efficient capacity allocation. Cachon and Lariviere (1999a, b) consider a supplier that specifies a rule for allocating its limited capacity to buyers based on their orders. However, because the resulting allocation is typically inefficient, all the firms can benefit by renegotiating the allocation rule. Knowing that the allocation rule will be renegotiated changes the incentives for ordering and capacity investment. The theme that emerges from these three papers is the theme that we explore in this paper: renegotiation ex post changes incentives for investment ex ante, and this in turn influences how the original contract should be structured.

Renegotiation is also pertinent in settings with asymmetric information. A number of authors consider "screening" contracts, where either the buyer or the supplier has private information about his own cost structure, the uninformed firm offers a menu of contracts, and the privately informed firm selects his profit-maximizing contract corresponding to his cost structure (Corbett and de Groote 2000, Corbett 2001, Ha 2001, Corbett et al. 2004, Iyer et al. 2005, Cachon and Zhang 2006). In constructing the optimal menu of contracts for the uninformed firm to offer, these papers assume that the firms will not subsequently renegotiate. This assumption is inconsistent with profit maximization. To limit the profit captured by the informed firm, the optimal menu of contracts causes distortion from the full-information solution. In selecting a contract, the privately informed party reveals his information, and because the actions called for under the contract are suboptimal, both firms will benefit from renegotiation. (Cachon and Zhang 2006 undertake a numerical study of the increase in profit from renegotiation.) However, if the firms anticipated this renegotiation, the original equilibrium would be destroyed. Thus, the prospect of renegotiation, which benefits the firms ex post, may hurt the firms ex ante because it undermines the credible transmission of private information. A similar phenomenon occurs with "signaling models," in which the informed party offers the contract. For example, in Cachon and Lariviere (2001) and Ozer and Wei (2006), the prospect of renegotiation would destroy the equilibrium wherein the buyer signals demand forecast information by offering a particular procurement contract.

Although renegotiation is important in practice, there has been little formal modeling of this phenomena in the operations management literature. An exception is Plambeck and Taylor (2007), in which buyers purchase a fixed quantity, invest to stimulate demand as the supplier builds capacity, and then, after demand is realized, renegotiate to the efficient capacity allocation. Their focus is on shaping investment through renegotiation design (contractual provisions that shift bargaining power from one firm to another) and through the remedy that courts impose for unilateral breach of contract (specific performance versus expectation damages). They focus on the simplest of contracts (fixed-quantity contracts) and—assuming throughout that renegotiation is feasible—characterize when fixed-quantity contracts induce optimal investments. In contrast, we consider a much more general class of contracts which

give the buyer flexibility in the order quantity; we focus on what kind of contract the firms should employ (when flexibility is required and in what form), and on the impact of renegotiation itself by examining how optimal contracts and investments change when renegotiation becomes feasible.

We use cooperative game theory to model the renegotiation. Several papers examine how firms invest in capacity/inventory and subsequently bargain cooperatively over its use, when the initial investment is not contractible (Anupindi and Bassok 1999, Van Mieghem 1999, Anupindi et al. 2001, Granot and Sosic 2003, Chod and Rudi 2006). Our paper is differentiated by incorporating renegotiable supply contracts and buyers' demand-stimulating investments in innovation. In these papers and ours, the firms have common information, so the bargaining leads to an efficient allocation.

In a bargaining game with only two players and common information, one can expect the players to split the gain from cooperation 50:50 (Nash 1953, Rubinstein 1982, Kagel and Roth 1995). With three or more players, the outcome is less predictable. Structural rules like "only player 1 can make offers" or "player 1 negotiates with player 2, and subsequently negotiates with player 3" strongly influence the outcome, as Nagarajan and Bassok (2002) demonstrate for an assembly system. For unstructured bargaining among three or more players with common information, cooperative game theory rules out some outcomes, but does not give a sharp prediction. In particular, the players will cooperate to maximize total profit and the gain for player i will not exceed his *added value* (the difference between the maximum value created when all the players cooperate, and the maximum value that can be created without the cooperation of player i); a range of different outcomes satisfy these conditions. In developing theory, one might focus on a specific outcome with desirable mathematical or fairness properties, such as the Shapley value or kernel, but such normative outcomes are not necessarily plausible or realistic (Maschler 1992). Experimental economics suggests that the outcome of unstructured bargaining depends crucially on the players' beliefs about what is fair or normal (Kagel and Roth 1995) and many business students are taught that in bargaining, a player's gain is proportional to his added value (Brandenburger and Nalebuff 1996).

Therefore, in making investments whose value will be realized through subsequent bargaining, a manager should seek to increase his added value (Brandenburger and Nalebuff 1996). Brandenburger and Stuart (2007) propose the biform game: players make strategic investments and then play a cooperative game determined by their investments. Each player i believes that he will earn a fraction α_i of his added value in the cooperative game, and the initial investments constitute a Nash equilibrium given these beliefs. The parameter α_i is interpreted as an index for the confidence of player i in his bargaining strength (in the cooperative game). A buyer's bargaining strength is influenced by many factors such as patience for negotiation, personal relationships, previous experience in negotiation, the desire to obtain future business, and market forces (Porter 1979, Shell 1999). Moreover, as demonstrated in Aghion et al. (1994), the firms can reduce α_i by adopting a contractual clause that will penalize firm i for delay in the renegotiation process; §6 shows how to increase α_i by giving the buyers the right to trade capacity. The biform game formulation is employed in Plambeck and Taylor (2005), Chod and Rudi (2006), and in this paper.

In addition, we allow the players to sign contracts before playing the biform game. As in the economics literature on renegotiation surveyed above, the contracts are designed to induce investments that maximize the total expected profit. Implicitly, the players allocate this through transfer payments at the time of contracting. As in this literature, our model is silent as to how the firms divide up the total expected profits. We draw attention to this modeling choice because it is distinctive from the approach often used in the operations management literature in which the contract design stage is modeled as a structured noncooperative bargaining game. Most commonly, all the bargaining power is assigned to one party who makes a take-it-or-leave-it contract offer. All our results hold for the special case that one party makes take-it-or-leave-it contract offers to the others, or for any general allocation of bargaining power in the contract design stage. We require only that the firms have common information and can make transfer payments at the time of contracting.

This paper is organized as follows. Section 2 presents the model. Section 3 characterizes the buyers' innovation investments in the setting with renegotiation and the setting without renegotiation, and §4 characterizes the manufacturer's capacity investment. Section 5, in considering the setting with renegotiation, shows that within a broad class of contracts, quantity flexibility contracts are optimal and provides clear conditions under which such contracts with renegotiation coordinate the system. Section 5 also shows that the optimal contract has less flexibility in the setting with renegotiation. Section 6 shows that where quantity flexibility contracts fail to coordinate the system, tradable options improve performance. Section 7 provides concluding remarks.

2. Model Formulation

A contract manufacturer has two prospective customers (buyers 1 and 2). Each buyer $i = 1, 2$ is developing a new product and invests in innovation e_i at a

cost to the buyer of $g_i(e_i)$, where $g_i(\cdot)$ is twice differentiable, increasing, and strictly convex, with $g_i'(0) = 0$, $g_i''(e) > \underline{g} > 0$ and $g_i'(e) \to \infty$ as $e \to 1$. The buyer's innovation investments in product development and marketing stochastically influence the attractiveness of its product in the market.

In an important special case of our innovation model, the price per unit of buyer i's product when q units are sold is $M_i - q$. M_i can be interpreted as the market size. With probability e_i, the product is successful so that $M_i = H$; otherwise, $M_i = L$, where $H \geq L > 0$. When the buyer with q units prices optimally, the resulting revenue is

$$R(M_i, q) = \max_{s \in [0, q]} (M_i - s)s.$$

This innovation model is motivated by drug development, in which incremental spending on research and/or clinical trials increases the likelihood that a drug will prove to be efficacious for the targeted medical condition (market H). Commonly in the biopharmaceutical industry, the developer knows that if the drug is not successful for the targeted medical condition, it will nevertheless be efficacious for a more limited therapeutic range or some veterinary application ($L > 0$). The challenge is to decide how much to spend in the attempt to turn a bioactive protein into a "blockbuster" drug. In the remainder of the paper, we refer to this innovation model with symmetric buyers (e.g., $g_1(e) = g_2(e) = g(e)$) as the *symmetric biopharmaceutical example*.

The symmetric biopharmaceutical example is an important special case of the general revenue functions and market-size distributions considered in this paper. We denote by F_i: $\mathcal{R} \times [0, 1] \to [0, 1]$ the cumulative distribution function for buyer i's market size M_i given his choice of innovation e_i, so $(\partial/\partial m)F_i(m, e) \geq 0$, $F_i(-\infty, e) = 0$, and $F_i(\infty, e) = 1$ for $m \in \mathcal{R}$, $e \in [0, 1]$, $i \in 1, 2$. Innovation stochastically increases the market size in a convex manner:

$$\frac{\partial}{\partial e} F_i(m, e) \leq 0, \qquad \frac{\partial^2}{\partial e^2} F_i(m, e) \geq 0 \quad \text{for } m \in \mathcal{R}, e \in [0, 1], i \in 1, 2. \quad (1)$$

Given e_1 and e_2, the buyers' market sizes M_i are independent random variables. For brevity, we write

$$E_{e_1 e_2}[h(M_1, M_2)] = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} h(m_1, m_2)\, dF_1(m_1, e_1)\, dF_2(m_2, e_2).$$

Furthermore, buyer i's revenue function R_i: $\mathcal{R} \times \mathcal{R}^+ \to \mathcal{R}^+$ satisfies

$$R_i(m, 0) = 0, \qquad \frac{\partial}{\partial q} R_i(m, q) \geq 0, \qquad \frac{\partial}{\partial m} R_i(m, q) \geq 0, \qquad \frac{\partial^2}{\partial m \partial q} R_i(m, q) \geq 0 \quad \text{for } m \in \mathcal{R}, q \in \mathcal{R}^+, i = 1, 2. \quad (2)$$

Assumptions (1) and (2) imply that capacity and innovation are complements:

$$\frac{\partial^2}{\partial e_i \partial q} E_{e_i}[R_i(M_i, q)] \geq 0, \quad (3)$$

$$\frac{\partial^2}{\partial e_i \partial c} E_{e_1 e_2}\Big[\max_{q_1 + q_2 \leq c} \{R_1(M_1, q_1) + R_2(M_2, q_2)\}\Big] \geq 0, \quad (4)$$

$$\frac{\partial}{\partial e_i} E_{e_i}[R_i(M_i, c)] \geq \frac{\partial}{\partial e_i} E_{e_1 e_2}\Big[\max_{q_1 + q_2 \leq c} \{R_1(M_1, q_1) + R_2(M_2, q_2)\}\Big] \quad (5)$$

(see the e-companion).[1] In addition, we assume that for $i = 1, 2$, there exists strictly positive and finite $\bar{Q}_i$ such that $(\partial/\partial q)E_{e_i}[R_i(M_i, q)] = 0$ for $q \geq \bar{Q}_i$ and the inequalities (3)–(5) are strict for $q < \bar{Q}_i$ and $c < \sum_{i=1,2} \bar{Q}_i$. Only our proof of Theorem 3 requires this additional assumption.

The manufacturer builds capacity c at a cost of $k > 0$ per unit, and this capacity can be used to serve either buyer. For simplicity, we will assume that the variable production costs are negligible. Therefore, the total expected profit under innovation (e_1, e_2) and capacity c is

$$\Pi(e_1, e_2, c) = E_{e_1 e_2}\Big[\max_{q_1 + q_2 \leq c} \{R_1(M_1, q_1) + R_2(M_2, q_2)\}\Big] - g_1(e_1) - g_2(e_2) - kc,$$

assuming capacity is allocated optimally after the market sizes are realized. We assume that total expected profit is strictly jointly concave in the decision variables (e_1, e_2, c) for $c \in [0, \bar{c}]$, and strictly decreasing in c for $c \geq \bar{c}$. Hence, the optimization problem for the integrated system

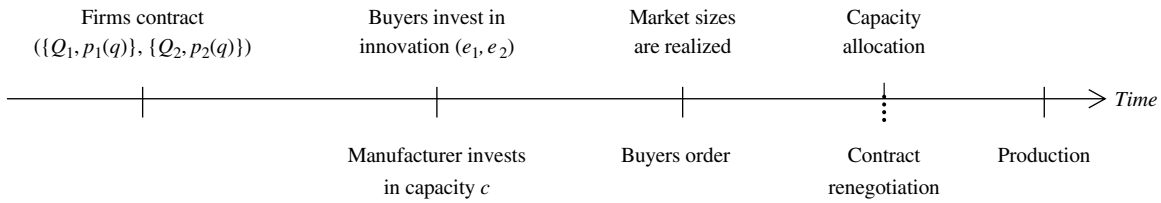
$$\max_{\substack{e_i \in [0, 1], i = 1, 2 \\ c \geq 0}} \Pi(e_1, e_2, c).$$

has a unique optimal solution (e_1^*, e_2^*, c^*) with $c^* \leq \bar{c} < \bar{Q}_1 + \bar{Q}_2$; we assume that $c^* > 0$ and $e_i^* > 0$ for $i = 1, 2$. In the symmetric biopharmaceutical example, imposing a simple lower bound $g_i''(e) > \underline{g}$ ensures that the optimal solution is symmetric in the levels of innovation: $e_1^* = e_2^* = e^*$; see Plambeck and Taylor (2005, Proposition 5).

If the buyers were to innovate before contracting for capacity, each buyer i would face "hold up" by the manufacturer and hence invest less than e_i^* (Plambeck and Taylor 2005). Therefore, the firms contract before investing in capacity and innovation. Specifically, buyer i signs a contract $\{Q_i, p_i(q)\colon 0 \leq q \leq Q_i\}$ with the

[1] An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

Figure 1 Sequence of Events



manufacturer, which gives buyer i the right to choose any order quantity $q_i \in [0, Q_i]$ (after observing his market size M_i) and pay the manufacturer $p_i(q_i)$. The manufacturer must provide that quantity q_i to buyer i unless (ex post) both firms agree to renegotiate the contract. With the contracts in place, the buyers invest in innovation and the manufacturer builds capacity

$$c \geq Q_1 + Q_2. \tag{6}$$

Then, each buyer i observes his own market size and orders some quantity $q_i \in [0, Q_i]$. If the manufacturer has residual capacity, the firms bargain over how to allocate the residual capacity and share the gains from trade. Furthermore, if *contract renegotiation* is allowed, a buyer may negotiate to take less than he ordered, so the capacity allocation is unconstrained. The firms bargain over how to allocate the total capacity and share the gains from trade. Figure 1 depicts the sequence of events.

The firms' optimization problem is to derive contract parameters $\{Q_i, p_i(\cdot)\}_{i=1,2}$ and associated Nash equilibrium in investments (e_1, e_2, c) that maximize total expected profit. The firms allocate the total expected profit through transfer payments at the time of contracting (e.g., buyer i makes a transfer payment to the manufacturer in return for the manufacturer's agreement to provide units under the $\{Q_i, p_i(q)\}$ contract). The only role of these up-front transfer payments is to allocate the total system expected profit; they have no effect on the firm's investments or subsequent bargaining. Our model is silent as to how the firms allocate the total system expected profit; we do not model the transfer payments. We characterize the Nash equilibrium investments under a given contract in §§3 and 4, before formalizing the contract-and-investment-equilibrium optimization problem in (18) for the setting with renegotiation and in (23) for the setting without renegotiation.

Within our general class of contracts, we are particularly interested in three simple forms: under a *quantity flexibility contract*

$$p_i(q) = w_i[q - Q_i + \Delta_i]^+,$$

where $[x]^+$ denotes $\max(x, 0)$, w_i is the exercise price per unit, Δ_i is the flexibility in the contract, and $Q_i - \Delta_i$ is the buyer's minimum order quantity; an *options contract* is a quantity flexibility contract with a zero minimum order quantity $Q_i - \Delta_i = 0$; and a *fixed-quantity contract* is a quantity flexibility contract with zero flexibility $\Delta_i = 0$. The payment $p_i(q)$ is in addition to any up-front transfer payment, so that under a quantity flexibility contract, when the buyer comes to choosing his order quantity, he has already paid for the first $Q_i - \Delta_i$ units and hence has no incentive to take less than this. Quantity flexibility contracts are widely used and studied (Bassok and Anupindi 1997, Li and Kouvelis 1999, Tsay 1999, Tsay and Lovejoy 1999, Cachon and Lariviere 2001, Barnes-Schuster et al. 2002, Lariviere 2002).

In the United States, when a buyer has a sole source as in our model, the buyer can sue for specific performance of the contract (Murray 2001), which means that the manufacturer must fill the buyer's order $q_i \in [0, Q_i]$. This forces the manufacturer to build sufficient capacity to meet its obligations (6). In essence, we are focusing on contracts that give flexibility to the buyers but not to the manufacturer. Other recent papers (Tomlin 2003, Erkoc and Wu 2005, Plambeck and Taylor 2007) allow flexibility for the manufacturer to pay a specified financial penalty rather than fill the buyer's order.

An important parameter of our model is the buyer's bargaining confidence index α_i. Buyer i anticipates that he will obtain the fraction α_i of his added value in bargaining over capacity allocation. We will assume that $\alpha_i \in (0, 1/2]$, so that the buyers' beliefs allow for the manufacturer to benefit from the bargaining over capacity allocation. With appropriate choice of $\alpha_i \in (0, 1/2]$, this is remarkably consistent with the kernel or similar to the Shapley value.[2] In the symmetric

[2] In the setting without renegotiation, the kernel corresponds to buyer i receiving $\alpha_i = 1/2$ of her added value. With renegotiation, fixed-quantity contracts, and no capacity speculation (i.e., $c = Q_1 + Q_2$) the kernel corresponds to $\alpha_i = 1/3$. The Shapley value corresponds to buyer i receiving $\alpha_i = 1/3$ of her added value plus $1/6$ of the value buyer i adds for the manufacturer when buyer j does not cooperate. Theorems 1 and 2 continue to hold for the Shapley value, as does Theorem 1 for the kernel. However, with general contracts, the Shapley value and kernel introduce complexity in the interactions between the order quantities of the buyers, which makes verifying the remaining results difficult. The solution concept we employ has the advantage of allowing sensitivity analysis regarding the buyer's bargaining confidence, which is not possible with the kernel or Shapley value.

biopharmaceutical example, we assume that the buyers are symmetric in their bargaining confidence $\alpha_1 = \alpha_2 = \alpha$.

3. Equilibrium Investments in Innovation

In this section, we fix the contract parameters $\{Q_i, p_i(q)\}_{i=1,2}$ and the manufacturer's capacity c, and analyze the buyers' investments in innovation. We first consider the case with no renegotiation. Consider the event that buyer i realizes his market size M_i and orders $q_i \in [0, Q_i]$ units for $i = 1, 2$. Then, the manufacturer and buyers bargain to allocate the remaining $c - q_1 - q_2$ units of capacity. (In the absence of renegotiation, a buyer cannot take less than the q_i that he ordered.) Buyer i's added value is the value buyer i adds by cooperating with the manufacturer and buyer $j \neq i$:

$$V_i^n(M_1, M_2, q_1, q_2) = \max_{\substack{q_1'+q_2' \le c,\\ q_l' \ge q_l,\ l=1,2}} \{R_1(M_1, q_1') + R_2(M_2, q_2')\} - [R_i(M_i, q_i) + R_j(M_j, c - q_i)].$$

The first term is the value created when all the players cooperate, and the second term is the value created when only the manufacturer and buyer j cooperate, in which case buyer i remains with q_i units and any additional capacity is allocated to buyer j. While investing in innovation, buyer i anticipates that his profit from bargaining over this residual capacity allocation will be $\alpha_i V_i^n$. Therefore, if buyer i believes that the other buyer j will invest e_j in innovation and will order $q_j(M_j)$ when facing market size M_j, buyer i's best response is

$$e_i^N = \arg\max_{e_i \in [0,1]} \Big\{ E_{e_i}\Big[\max_{q_i(M_i) \in [0, Q_i]} \{R_i(M_i, q_i(M_i)) - p_i(q_i(M_i)) + \alpha_i E_{e_j}[V_i^n(M_1, M_2, q_1(M_1), q_2(M_2))]\}\Big] - g_i(e_i)\Big\}, \quad (7)$$

where $q_i(M_i)$ denotes buyer i's order when facing market size M_i.

Now let us allow contract renegotiation. Renegotiation will occur only in the event that the profit for the system as a whole can be increased by allocating fewer units to a buyer than he ordered. By increasing system profit, renegotiation increases each of the buyer's added value. In particular, in the capacity allocation, buyer i has an added value of

$$V_i(M_1, M_2, q_1, q_2) = V_i^n(M_1, M_2, q_1, q_2) + \Gamma(M_1, M_2, q_1, q_2), \quad (8)$$

where

$$\Gamma(M_1, M_2, q_1, q_2) = \max_{q_1'+q_2' \le c} \{R_1(M_1, q_1') + R_2(M_2, q_2')\} - \max_{\substack{q_1'+q_2' \le c,\\ q_i' \ge q_i,\ i=1,2}} \{R_1(M_1, q_1') + R_2(M_2, q_2')\}. \quad (9)$$

Γ is the gain to the total system that arises from relaxing the constraints on how capacity is allocated between the two buyers. If buyer i believes that the other buyer j will invest e_j in innovation and will order $q_j(M_j)$ when facing market size M_j, buyer i's best response is

$$e_i^R = \arg\max_{e_i \in [0,1]} \Big\{ E_{e_i}\Big[\max_{q_i(M_i) \in [0, Q_i]} \{R_i(M_i, q_i(M_i)) - p_i(q_i(M_i)) + \alpha_i E_{e_j}[V_i(M_1, M_2, q_1(M_1), q_2(M_2))]\}\Big] - g_i(e_i)\Big\}. \quad (10)$$

How does the possibility of renegotiation impact a buyer's incentive for innovation? To develop intuition, assume that the firms have fixed-quantity contracts: $q_i(M_i) = Q_i$ for $i = 1, 2$. Then, the difference between the buyer's objective function with renegotiation (10) and without (7) is $\alpha_i E_{e_1 e_2}[\Gamma(M_1, M_2, Q_1, Q_2)]$; therefore, the possibility of renegotiation increases buyer i's incentive for innovation if and only if

$$\frac{\partial}{\partial e_i} E_{e_1 e_2}[\Gamma(M_1, M_2, Q_1, Q_2)] \ge 0. \quad (11)$$

Suppose that the manufacturer does not build speculative capacity: $c = Q_1 + Q_2$. Then, (11) simplifies to

$$\frac{\partial}{\partial e_i} E_{e_1 e_2}[R_i(M_i, q_i^*(M_1, M_2, c))] \ge \frac{\partial}{\partial e_i} E_{e_i}[R_i(M_i, Q_i)],$$

where $(q_1^*(M_1, M_2, c), q_2^*(M_1, M_2, c))$ denotes the optimal unconstrained capacity allocation, the solution to $\max_{q_1+q_2 \le c}\{R_1(M_1, q_1) + R_2(M_2, q_2)\}$. Because capacity and innovation investment are complements (3), if the event $q_i^*(M_1, M_2, c) > Q_i$ (buyer i gains capacity in the renegotiation) has sufficiently high probability, renegotiation increases buyer i's incentive for innovation. Alternatively, if the event $q_i^*(M_1, M_2, c) < Q_i$ (buyer i gives up capacity in the renegotiation) is likely, then renegotiation decreases buyer i's incentive for innovation. Therefore, renegotiation tends to increase buyer i's incentive for innovation when his contractual quantity Q_i is small and the other buyer's investment in innovation e_j is small. It follows that, in equilibrium, buyer i's innovation investment is greater with renegotiation if and only if buyer j's

innovation investment is below the threshold

$$\bar{e}_j = \inf\Bigg\{ e_j \in (0,1]: (\partial/\partial e_i) E_{e_1 e_2}\Bigg[\sum_{l=1,2} R_l(M_l, q_l^*(M_1, M_2, c))\Bigg]\Bigg|_{e_i = e_i^n} \geq (\partial/\partial e_i) E_{e_i}[R_i(M_i, Q_i)]|_{e_i = e_i^n}\Bigg\},$$

which decreases with Q_i. All proofs, with the exception of that of Theorem 2, are provided in the e-companion.

Theorem 1. *Suppose that the buyers have fixed-quantity contracts and the manufacturer does not build speculative capacity, i.e., $c = Q_1 + Q_2$. There exists a unique Nash equilibrium in innovation in the setting with no renegotiation (e_1^n, e_2^n) and at least one Nash equilibrium in innovation in the setting with renegotiation. Any Nash equilibrium in innovation (e_1^r, e_2^r) in the setting with renegotiation satisfies, for $i = 1, 2$ and $j \neq i$,*

$$e_i^r > e_i^n \quad \text{if and only if} \quad e_j^r < \bar{e}_j. \tag{12}$$

If the buyers and contracts are symmetric, then $e_1^n = e_2^n = e^n$, the symmetric equilibrium in the setting with renegotiation is unique $e_1^r = e_2^r = e^r$, and

$$e^r > e^n \quad \text{if and only if} \quad e^n < \bar{e}_1. \tag{13}$$

The basic managerial insight underlying Theorem 1 is that when a buyer is likely to gain capacity through renegotiation—notably when his reserved capacity and the rival firm's innovation investment are small—the prospect of renegotiation makes investing in innovation more attractive. With more general contracts, a buyer's optimal order quantity depends upon his market size and whether or not renegotiation is allowed. The effect of renegotiation on equilibrium innovation becomes more complex. Nevertheless, the next theorem establishes that the basic managerial insight underlying Theorem 1 extends to a setting with quantity flexibility contracts. Theorem 2 focuses on the case where the buyer with low market size orders the minimum quantity $Q - \Delta$ and the buyer with high market size orders the maximum quantity Q; this is equivalent to imposing a lower bound and an upper bound on the exercise price w.

Theorem 2. *Consider the symmetric biopharmaceutical example, and assume that the buyers have identical quantity flexibility contracts with exercise price w set so a buyer with market size L optimally orders the minimum quantity $Q-\Delta$ and a buyer with market size H orders the maximum quantity Q. There exists a unique symmetric Nash equilibrium in innovation in the setting with no renegotiation $e_1^n = e_2^n = e^n$ and a unique symmetric Nash equilibrium in innovation in the setting with renegotiation $e_1^r = e_2^r = e^r$. If $q_1^*(L, H, c) \geq Q - \Delta$ (the contract results in efficient capacity allocation), then $e^r = e^n$. Otherwise,*

$$\begin{aligned} &\text{if } e^n < 1/2, \quad \text{then } e^r \in (e^n, 1/2),\\ &\text{if } e^n = 1/2, \quad \text{then } e^r = e^n,\\ &\text{if } e^n > 1/2, \quad \text{then } e^r \in (1/2, e^n). \end{aligned}$$

Before discussing the implications of the theorem, we provide the proof to build intuition. The symmetric Nash equilibrium innovation with no renegotiation e^n is the unique solution to

$$\begin{aligned} g'(e) = {} & \big[R(H,Q) - wQ + \alpha e V_1^n(H,H,Q,Q) \\ & + \alpha(1-e)V_1^n(H,L,Q,Q-\Delta)\big] \\ & - \big[R(L,Q-\Delta) - w(Q-\Delta) \\ & + \alpha e V_1^n(L,H,Q-\Delta,Q) \\ & + \alpha(1-e)V_1^n(L,L,Q-\Delta,Q-\Delta)\big] \end{aligned} \tag{14}$$

(the first-order optimality condition in (7)), and the symmetric Nash equilibrium innovation with renegotiation e^r is the unique solution to

$$\begin{aligned} g'(e) = {} & \big[R(H,Q) - wQ + \alpha e V_1(H,H,Q,Q) \\ & + \alpha(1-e)V_1(H,L,Q,Q-\Delta)\big] \\ & - \big[R(L,Q-\Delta) - w(Q-\Delta) \\ & + \alpha e V_1(L,H,Q-\Delta,Q) \\ & + \alpha(1-e)V_1(L,L,Q-\Delta,Q-\Delta)\big] \end{aligned} \tag{15}$$

(the first-order optimality condition in (10)). If both buyers experience the same market size, the efficient allocation of capacity is achieved without renegotiation; therefore, $V_1^n(H,H,Q,Q) = V_1(H,H,Q,Q)$ and $V_1^n(L,L,Q-\Delta,Q-\Delta) = V_1(L,L,Q-\Delta,Q-\Delta)$. Renegotiation will only occur in the event that buyer i has L demand and buyer j has H demand, and the profit for the system as a whole can be increased by allocating fewer than $Q-\Delta$ units to buyer i. By increasing system profit, renegotiation increases each buyer's added value. In particular, without renegotiation, buyer i's added value is

$$\begin{aligned} V_i^n(L,H,Q-\Delta,Q) = {} & \max_{\substack{q_L+q_H\leq c,\\ q_L\geq Q-\Delta,\, q_H\geq Q}} \{R(L,q_L)+R(H,q_H)\} \\ & -[R(L,Q-\Delta)+R(H,c-Q+\Delta)], \end{aligned}$$

and with renegotiation, buyer i's added value is given by (8), where the gain from renegotiation is

$$\begin{aligned} \Gamma(L,H,Q-\Delta,Q) = {} & \max_{q_L+q_H\leq c} \{R(L,q_L)+R(H,q_H)\} \\ & - \max_{\substack{q_L+q_H\leq c,\\ q_L\geq Q-\Delta,\, q_H\geq Q}} \{R(L,q_L)+R(H,q_H)\}. \end{aligned}$$

Because the cost of innovation g is strictly convex, renegotiation increases the equilibrium innovation if and only if, at $e = e^n$, the right-hand side of (15) is greater than the right-hand side of (14). Subtracting the right-hand side of (14) from the right-hand side of (15), we find that renegotiation increases the equilibrium innovation investments if and only if

$$\alpha(1-2e^n)\Gamma(L, H, Q-\Delta, Q) \geq 0,$$

or equivalently, $e^n \leq 1/2$.

Theorem 2 describes how renegotiation affects innovation in terms of the equilibrium success probability in the setting without renegotiation e^n. That equilibrium success probability decreases with the cost of innovation and exercise price w, and increases with the maximum order quantity Q. Therefore, if innovation is inexpensive and the contractual terms are sufficiently attractive such that choosing a large success probability is cost effective, renegotiation decreases innovation. Conversely, if innovation is sufficiently costly, then renegotiation increases innovation. Because the development of biopharmaceuticals involves less traditional, well-tested approaches, the cost of innovation may be particularly high relative to more traditional pharmaceuticals. As a result, buyers' success probabilities are well under 50% (only 30% of biologic drugs are anticipated to pass Phase 2 clinical trials) (Sinclair 2001). Consequently, Theorem 2 suggests that the anticipation of future renegotiation leads biopharmaceutical developers to invest more in innovation: A developer anticipates that the drug of his rival for capacity will fail, freeing up capacity that can be obtained by renegotiation and making product success more attractive. This logic applies more generally to developers of risky, but potentially "breakthrough" products (i.e., products that have large potential market sizes but are likely to fail) that contract with a common manufacturer.

The basic managerial insight underlying Theorems 1 and 2 generalizes to settings with multiple buyers and alternative innovation-revenue models; the minimal essential assumption is that capacity and innovation are complements. Under this assumption, if a buyer's gain from renegotiation arises primarily from obtaining additional capacity when his realized market size is large, then renegotiation increases his incentive for innovation to increase the market size. Conversely, if a buyer gains from renegotiation primarily by selling his capacity, then renegotiation decreases his incentive for innovation.

4. Capacity Investment

Now consider the manufacturer who invests in capacity simultaneously as the buyers invest in innovation. The manufacturer's beliefs regarding the ex post bargaining stage shape how he invests in capacity. The manufacturer expects to obtain $\alpha_m \in [0, 1)$ of his added value in the cooperative game of capacity allocation. In the setting without renegotiation, given the buyers' market sizes and order quantities $(M_i, q_i)_{i=1,2}$, the manufacturer's added value from allocating the residual capacity $c - q_1 - q_2$ is

$$\mathcal{V}^n(M_1, M_2, q_1, q_2) = \max_{\substack{q_1'+q_2' \leq c,\\ q_i' \geq q_i,\ i=1,2}} \{R_1(M_1, q_1') + R_2(M_2, q_2')\} - [R_1(M_1, q_1) + R_2(M_2, q_2)].$$

Therefore, if the manufacturer believes that buyer i will invest e_i in innovation and order $q_i(M_i)$ upon realizing market size M_i, the manufacturer's best response is

$$c^N = \arg\max_{c \geq Q_1+Q_2} \{\alpha_m E_{e_1 e_2}[\mathcal{V}^n(M_1, M_2, q_1(M_1), q_2(M_2))] - kc\}. \tag{16}$$

Similarly, in the setting with renegotiation, the manufacturer's best response is

$$c^R = \arg\max_{c \geq Q_1+Q_2} \{\alpha_m E_{e_1 e_2}[\mathcal{V}(M_1, M_2, q_1(M_1), q_2(M_2))] - kc\}, \tag{17}$$

where $\mathcal{V} = \mathcal{V}^n + \Gamma$, Recall that Γ, defined in (9), is the incremental profit from allowing the buyer with relatively low market size to take less than he ordered.

A limitation of the biform model is that the firms' beliefs about the outcome of bargaining over the capacity allocation might be inconsistent.[3] An alternate formulation that overcomes this weakness is to assume that the manufacturer anticipates capturing the total value that is created in the cooperative game less the portion that the buyers anticipate capturing. We have verified that our results extend with minor modifications to this alternate formulation for the symmetric biopharmaceutical example, but we have not established this for the more general setting.

The next section establishes that under optimal contracts and the associated Nash equilibrium in capacity, innovation, and order quantities, the manufacturer does not speculate, that is, $c = Q_1 + Q_2$.

5. Optimal Contracts

In our model, the potential for renegotiation simplifies the derivation and analysis of the optimal contracts.

[3] For example, in the case without renegotiation, it may be that for some M_1, M_2,

$$\alpha V_1^n(M_1, M_2, q_1(M_1), q_2(M_2)) + \alpha V_2^n(M_1, M_2, q_1(M_1), q_2(M_2)) + \alpha_m \mathcal{V}^n(M_1, M_2, q_1(M_1), q_2(M_2)) \neq \max_{\substack{q_1'+q_2' \leq c,\\ q_i' \geq q_i(M_i),\ i=1,2}} \{R_1(M_1, q_1') + R_2(M_2, q_2')\} - R_1(M_1, q_1(M_1)) - R_2(M_2, q_2(M_2)).$$

Therefore, we begin by characterizing the optimal contracts in the setting with renegotiation. In particular, we show that among all contracts of the form $\{Q_i, p_i(q)\}$, quantity flexibility contracts are optimal. Then, we explain how the optimal quantity flexibility contracts differ in the setting without renegotiation. We complement our analytical results with an extensive numerical study of the symmetric biopharmaceutical example: For 1,920 different parameter settings (all possible combinations of $k \in \{4, 8, 12, 16, 20, 24\}$, $\alpha \in \{0.05, 0.15, 0.25, 0.35, 0.45\}$, $H \in \{70, 80, 90, 100\}$, $L = \{10, 20, 30, 40\}$, and $A \in \{2{,}000, 3{,}000, 4{,}000, 5{,}000\}$, where $g(e) = A(\log[1/(1-e)] - e)$), we computed the optimal symmetric quantity flexibility contract and associated symmetric equilibrium, and total expected profit in the setting with renegotiation and in the setting without renegotiation.

5.1. Optimal Contract with Renegotiation

As discussed in §2, the firms choose contracts and coordinate on an equilibrium to maximize total expected profit (they can allocate this profit in any way by transfer payments). In the setting with renegotiation, the optimal contracts and associated equilibrium (in capacity, innovation, and order quantities) solve the optimization problem

$$\max_{\substack{e_i \in [0,1],\ \{Q_i,\, p_i(q)\},\, q_i(M_i)\, i=1,2,\\ c \geq 0}} \Pi(e_1, e_2, c) \quad \text{subject to (10) for } i = 1, 2 \text{ and (17).} \tag{18}$$

Theorem 3 characterizes the structure of optimal contracts (within the class $\{Q_i, p_i(q)\}$) and associated Nash equilibrium investments. Let $\hat{Q}_i$ denote the unique value of Q_i that satisfies

$$(\partial/\partial e_i) E_{e_i^*}[R_i(M_i, Q_i)] = (\partial/\partial e_i) E_{e_1^* e_2^*}\left[\sum_{l=1,2} R_l(M_l, q_l^*(M_1, M_2, c^*))\right]. \tag{19}$$

Let $e_i^*(c, e_j)$ denote the integrated-optimal innovation for buyer i given capacity c and innovation by the other buyer of e_j; i.e.,

$$e_i^*(c, e_j) = \arg\max_{e_i \in [0,1]} \left\{ E_{e_1 e_2}\left[\sum_{l=1,2} R_l(M_l, q_l^*(M_1, M_2, c))\right] - g_i(e_i) \right\}.$$

Theorem 3. *Quantity flexibility contracts are optimal. They induce the first-best investments* (e_1^*, e_2^*, c^*) *if and only if*

$$\sum_{i=1,2} \hat{Q}_i \leq c^*. \tag{20}$$

If $\sum_{i=1,2} \hat{Q}_i \geq c^*$, *fixed-quantity contracts are optimal* $(\Delta_i^r = 0$ *for* $i = 1, 2)$, *the manufacturer does not speculate* $c^r = Q_1^r + Q_2^r$, *the buyers weakly underinvest in innovation* $e_i^r \leq e_i^*(c^r, e_j^r)$, $i \neq j$, $i = 1, 2$, *and total expected profit increases with each buyer's bargaining confidence* α_i. *If* $\sum_{i=1,2} \hat{Q}_i < c^*$, *the optimal contract is flexible* $(\Delta_i^r > 0$ *for at least one buyer*) *and the manufacturer does not speculate* $c^r = Q_1^r + Q_2^r$. *In the symmetric biopharmaceutical example*, (20) *holds if and only if*

$$e^* \geq 1/2, \quad \text{or equivalently,} \quad k \leq \tilde{k}, \tag{21}$$

where $\tilde{k} < H$ *and* $\tilde{k} > 0$ *if and only if* $g'(1/2) < (H^2 - L^2)/4$. $\tilde{k}$ *is increasing in* H *and decreasing in* L.

The first part of Theorem 3 (optimality of quantity flexibility contracts) holds for systems with $N > 2$ buyers.

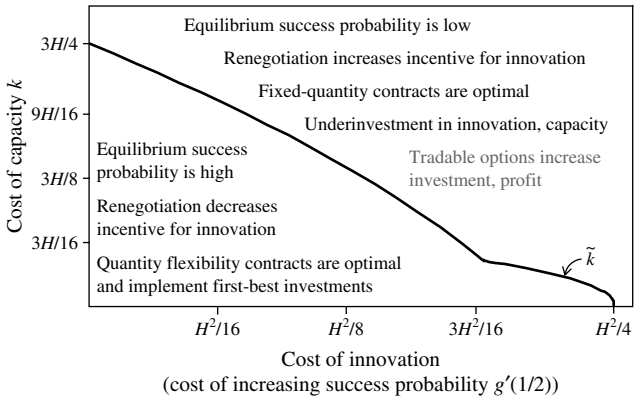
Flexibility is *not* necessary to achieve efficient capacity allocation; the firms will renegotiate to an efficient capacity allocation. Instead, the role of flexibility in the contract is to fine-tune the firms' incentives for investment. This fine-tuning can be accomplished with simple quantity flexibility contracts. Further, for a wide range of parameters (which correspond to expensive capacity in the symmetric biopharmaceutical example), simpler fixed-quantity contracts are optimal.

To grasp the basis of the proof of Theorem 3, suppose that the buyers are symmetric and have symmetric contracts with quantity $Q = c^*/2$. With fixed-quantity contracts ($\Delta = 0$), the manufacturer effectively "sells the plant" to the buyers in advance, which maximizes the incentives for innovation. Suppose that $\Delta = 0$, the manufacturer will build the first-best capacity c^*, and buyer 1 will choose the first-best innovation $e_1 = e^*$. Should buyer 2 choose e_2 greater than (or less than) e^*? If $\sum_{i=1,2} \hat{Q}_i > c^*$, then $\hat{Q}_2 > Q$ and

$$(\partial/\partial e_2) E_{e_2^*}[R_2(M_2, Q)] < (\partial/\partial e_2) E_{e_1^* e_2^*}\left[\sum_{i=1,2} R_i(M_i, q_i^*(M_1, M_2, c^*))\right]. \tag{22}$$

In solving (10), buyer 2 places weight $(1 - \alpha)$ on the left-hand side of (22), his marginal expected revenue if he refuses to renegotiate his contract, and places weight α on the right-hand side of (22), the marginal total expected revenue with renegotiation. Therefore, buyer 2 should choose e_2 less than e^*. Fixed-quantity contracts are optimal because flexibility (to purchase less than Q) would make a buyer with low market size better off, and thus worsen the problem of underinvestment. Alternatively, if $\sum_{i=1,2} \hat{Q}_i < c^*$, then $\hat{Q}_2 < Q$ and the inequality in (22) is reversed, so buyer 2 should choose e_2 greater than e^*. Substituting a quantity flexibility contract with sufficiently large Δ and w weakens buyer 2's incentive for innovation, so he chooses the first-best innovation e^*. Therefore, quantity flexibility contracts (with $\Delta > 0$) induce

Figure 2 Summary of Results



Notes. The capacity threshold $\tilde{k}$ is depicted for the specific case $L = 0$. In general, $\tilde{k}$ is a continuous, decreasing function of $g'(1/2)$.

the first-best innovation.[4] In either case, the manufacturer should build no more capacity than his contractual requirement ($c^* = 2Q$) because the buyers weakly underinvest, capacity is complementary to innovation, and the manufacturer would share any marginal revenue generated by additional capacity with the buyers.

For the symmetric biopharmaceutical example, the pooling of capacity via renegotiation increases the marginal value of innovation only when innovation is low (Plambeck and Taylor 2005). Consequently, when capacity is expensive, $k > \tilde{k}$, which makes low innovation attractive (i.e., (21) is violated), the buyers underinvest in innovation even when fixed-quantity contracts are employed. When capacity is cheap, $k \le \tilde{k}$, innovation-damping quantity flexibility contracts induce the first-best investments. The capacity cost threshold $\tilde{k}$ increases as the reward for innovation increases and the cost of innovation decreases.

Figure 2 summarizes our main analytical results in the context of the symmetric biopharmaceutical example. The figure depicts the capacity cost threshold $\tilde{k}$ as a function of the cost of innovation (as measured by the marginal cost of increasing the success probability above 1/2); $\tilde{k}$ divides the parameter space into two regions, and a different set of results holds in each region. When the capacity and innovation costs are low ($k < \tilde{k}$), quantity flexibility contracts are optimal and implement the first-best investments $e^r = e^* > 1/2$, which correspond to a high success probability. Thus, under the optimal contracts, renegotiation decreases the incentive for innovation $e^r < e^n$ (by Theorem 2). When the capacity and innovation costs are high ($k > \tilde{k}$), fixed-quantity contracts are optimal, but result in underinvestment in capacity $c^r < c^*$ (as can be shown by direction extension of Theorem 3) and innovation $e^r < e^* < 1/2$, which corresponds to a low success probability. Thus, under the optimal contracts, renegotiation increases the incentive for innovation $e^r > e^n$ (by Theorem 2). Finally, the gray text in Figure 2 foreshadows our last main analytical result, Theorem 4, which shows that tradable options improve performance in the high-cost region.

[4] Reducing the buyer's incentive for innovation could be accomplished by reducing $Q < c^*/2$, but then the manufacturer would underinvest in capacity $c < c^*$. Plambeck and Taylor (2007, Theorem 3) show that this need for flexibility is eliminated when the manufacturer captures all the gain in the renegotiation ($\alpha_m = 1$ and $\alpha_1 = \alpha_2 = 0$) because the manufacturer has efficient incentives for investment even when $Q < c^*/2$.

5.2. Impact of Renegotiation on the Optimal Contract

In the setting without renegotiation, the optimal contracts and associated equilibrium solve the optimization problem

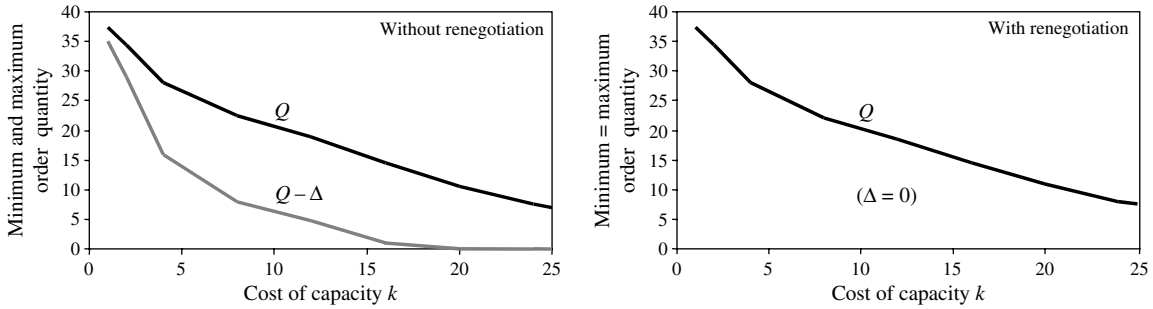
$$\max_{\substack{e_i \in [0,1],\ \{Q_i, p_i(q)\},\ q_i(M_i) i=1,2,\\ c \ge 0}} \{\Pi(e_1, e_2, c) - E_{e_1 e_2}[\Gamma(M_1, M_2, q_1(M_1), q_2(M_2))]\} \quad (23)$$

$$\text{subject to } (7) \text{ for } i = 1, 2 \text{ and } (16).$$

The objective function reflects the loss in profit due to the constrained allocation. The optimization problem is more complex than (18) because buyer i's order quantity $q_i(\cdot)$ depends on buyer's j's order quantity $q_j(\cdot)$. Even in the symmetric biopharmaceutical example with symmetric quantity flexibility contracts, the derivation of an optimal contract is much more difficult than in the setting with renegotiation because one faces a trade-off between incentives for innovation and allocative efficiency: Typically, increasing the minimum order quantity, $Q - \Delta$, increases the buyers' equilibrium investment in innovation. However, a large $Q - \Delta$ constrains the allocation of capacity.

In our numerical study, we observed that the primary impact of excluding the possibility of renegotiation is that it increases the flexibility in the optimal contract, often substantially. In the setting with renegotiation, the relative flexibility Δ/Q is typically small, if not zero (it is significant only when the cost of innovation is very low, H is much greater than L, and the cost of capacity is moderate). In contrast, in the setting without renegotiation, the optimal contract always has flexibility $\Delta > 0$ and the relative flexibility Δ/Q is often quite large. Although the potential for renegotiation reduces the flexibility Δ in the optimal contract, it has little effect on the maximum order quantity Q. This is illustrated in Figure 3. In both settings, the manufacturer does not speculate, so the maximum order quantity is the capacity per buyer.

Figure 3 Minimum and Maximum Order Quantity in the Optimal Contract for the Setting Without Renegotiation (Left) and With Renegotiation (Right)



Notes. System parameters are $H = 80, L = 20, \alpha = 0.25$, and $g(e) = 2{,}000(\log[1/(1-e)] - e)$. In the setting with renegotiation, the optimal contract has zero flexibility.

5.3. Impact of Failing to Account for Renegotiation in Contract Design

Figure 4 shows that renegotiation can greatly improve system performance, but only if the contract is designed to anticipate renegotiation. We computed the total expected profit under the optimal contract in the setting without renegotiation and in the setting with renegotiation. On the left, Figure 4 shows that renegotiation greatly improves system performance when the cost of capacity is high and the buyers have low to moderate bargaining confidence. In the setting without renegotiation, the buyers' incentive for innovation (the right-hand side of (14)) is increasing with α. To provide greater incentives for innovation, the optimal contract's minimum order quantity increases, causing the allocation of capacity to be less efficient. Thus, renegotiation, by increasing the incentive for innovation and allocating capacity optimally, adds the most value when α is small and k is large. We also computed the expected profit with renegotiation under the "naïve" contract that is optimal for the setting without renegotiation (i.e., the naïve contract fails to account for the potential for renegotiation). We assume that the buyers anticipate renegotiation. On the right, Figure 4 shows that renegotiation of the naïve contract scarcely improves expected profit. The naïve contract, anticipating that renegotiation will not occur, is very flexible; consequently, there is little to gain from renegotiation in terms of allocative efficiency and hence, expected profit. In contrast, the optimal contract, anticipating renegotiation, is inflexible; this inflexibility provides stronger incentives for innovation which leads to significant performance improvement.

The insights obtained for the specific system in Figure 4 hold in the larger study. Table 1 reports the increase in expected profit due to renegotiation under the naïve and optimal contracts. All figures are expressed as a percentage of the first best expected profit.[5] The key insights discussed in the specific example above hold in this larger study. First, renegotiation can greatly improve system performance, but only if the contract is designed to anticipate renegotiation. Indeed, both the overall maximum and mean increase in expected profit are an order of magnitude larger when the contract is designed to anticipate renegotiation (43.8% versus 3.8% and 2.7% versus 0.15%). Second, the relative gain from renegotiation and optimal contract design is greatest when capacity is expensive.

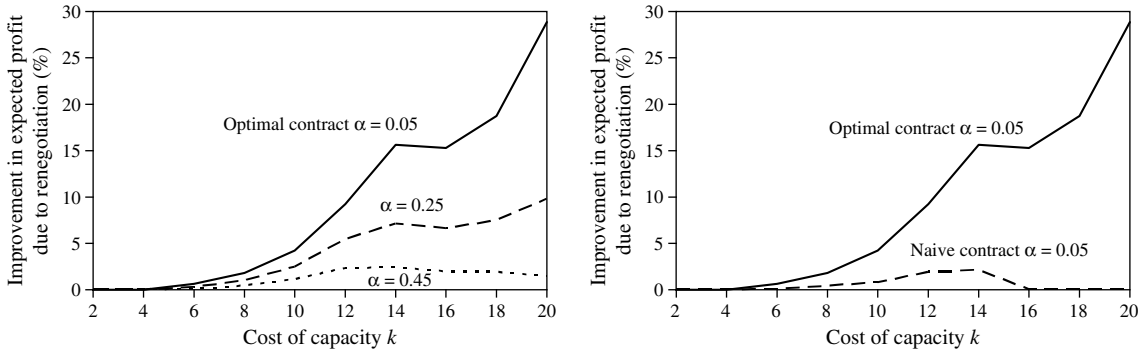
One would expect the firms to renegotiate because, ex post, this increases the profit for every firm. However, under limited circumstances, the firms are better off ex ante if they *cannot* renegotiate ex post. This happens when the prospect of renegotiation undermines the provision of incentives for investment. Supply chain partners might commit not to renegotiate in the context of a long-term relationship. However, our results suggest that, under most circumstances, firms should plan for renegotiation. In the remainder of the paper, we assume that the firms will renegotiate to an efficient allocation.

6. Tradable Options

In this section, we focus on the parameter region where quantity flexibility contracts (coupled with renegotiation) fail to coordinate the system and simple fixed-quantity contracts are optimal. In this region, increasing a buyer's bargaining confidence α_i increases the incentive for innovation and thus increases expected profit. Therefore, the firms should

[5] Table 1 provides summary statistics for 1,715 out of the 1,920 data points; 205 data points with zero expected profit for the integrated system are excluded. For 13 data points, expected profit is zero without renegotiation and is positive with renegotiation under the optimal contract. Hence, the maximum and the mean increase in expected profit with renegotiation under the optimal contract, expressed as a percentage of expected profit in the setting without renegotiation as in Figure 4, would be infinite; the median over all 1,920 data points would be 0.6%.

Figure 4 **On the Left, the Increase in Total Expected Profit Due to Renegotiation When the Optimal Contracts Are Used, as a Function of Capacity Cost k and Buyers' Bargaining Strength α; On the Right, the Improvement in Expected Profit Due to Renegotiation With the Optimal Contract and With a "Naive" Contract That is Optimal Without Renegotiation**



Notes. The increase in expected profit is expressed as a percentage of total expected profit in the setting without renegotiation. System parameters are $H = 80$, $L = 20$, and $g(e) = 3{,}000(\log[1/(1-e)] - e)$.

design the fixed-quantity contracts for renegotiation, by inserting a clause that increases each buyer's bargaining confidence. Taiwan Semiconductor Manufacturing Corporation (TSMC), the world's largest semiconductor contract manufacturer, is a pioneer in using *tradable* capacity options (LaPedus 1995, *The Economist* 1996). Tradable options give the buyers the right to trade their capacity amongst themselves, with varying degrees of involvement by the manufacturer. TSMC usually retains "first rights" to purchase the options at whatever price a buyer contracts to sell those options to a secondary buyer. We consider the more extreme case in which tradable options give the buyers the legal right to trade their capacity without interference from the manufacturer, so the manufacturer cannot extract revenue in the renegotiation of capacity allocation. We show that shifting the gain from renegotiation to the buyers increases expected profit, but not necessarily to the first best.

Table 1 **Increase in Expected Profit Due to Renegotiation With the Naive Contract That Is Optimal in the Setting Without Renegotiation, and the Optimal Contract**

		Increase in expected profit due to renegotiation (%)	
Cost of capacity k	Statistic	Naive contract	Optimal contract
{4, 8}	Mean	0.1	0.7
	Median	0.0	0.1
	Max	3.0	22.9
	Min	−0.2	−0.2
{12, 16}	Mean	0.2	3.0
	Median	0.1	1.5
	Max	3.0	48.6
	Min	−2.1	−0.2
{20, 24}	Mean	0.1	3.8
	Median	0.0	2.3
	Max	2.9	35.3
	Min	−3.7	−2.3

Notes. Each row reports the statistics for the 640 parameter combinations that correspond to the two capacity costs. All figures are expressed as a percentage of the first best expected profit.

The manufacturer sells Q_i tradable options to each buyer $i = 1, 2$. Buyer i is guaranteed Q_i units of production capacity at an exercise price of zero, and the right to trade these units with buyer j. The manufacturer makes a capacity investment of $c \geq Q_1 + Q_2$, and the buyers invest in innovation which determines the distribution of market sizes, as discussed in §2. Then, the market sizes (M_1, M_2) are realized. The value the buyers can create together, by trading capacity options among themselves, is

$$V^t(M_1, M_2, Q_1, Q_2) = \max_{q_1+q_2 \leq Q_1+Q_2} \{R_1(M_1, q_1) + R_2(M_2, q_2)\} - [R_1(M_1, Q_1) + R_2(M_2, Q_2)].$$

The buyers can create this value without cooperation from the manufacturer. Therefore, the manufacturer's added value in the bargaining game is only from selling speculative capacity $c - (Q_1 + Q_2)$:

$$\mathcal{V}(c) = \max_{q_1+q_2 \leq c} \{R_1(M_1, q_1) + R_2(M_2, q_2)\} - \max_{q_1+q_2 \leq Q_1+Q_2} \{R_1(M_1, q_1) + R_2(M_2, q_2)\}. \quad (24)$$

Note that (24) is smaller than the added value for the manufacturer under any set of contracts $\{Q_i, p_i(q)\}_{i=1,2}$ with the same maximum order quantities Q_i. The essential function of tradable options is to constrain the added value of the manufacturer, so that the buyers can extract greater profit in bargaining over capacity allocation.

For simplicity, we will focus on equilibria in which the manufacturer does not speculate: $c = Q_1 + Q_2$. (We

will construct tradable options contracts and a corresponding Nash equilibrium that yield strictly greater expected profit than the optimal fixed-quantity contracts and associated Nash equilibrium. Considering equilibria with capacity speculation could only strengthen the case for using tradable options.) It is important to note that

$$\mathcal{V}(Q_1 + Q_2) = 0.$$

If the manufacturer does not speculate, then his added value is zero, so he is effectively excluded from the bargaining game. Therefore, the most plausible outcome of the bargaining game is that the buyers will split the gain from trade 50:50. Specifically, buyer i purchases $q_i^*(M_1, M_2, Q_1 + Q_2) - Q_i$ units of production capacity from buyer j and pays $R_i(M_i, q_i^*(M_1, M_2, Q_1 + Q_2)) - R_i(M_i, Q_i) - \frac{1}{2}V^t(M_1, M_2, Q_1, Q_2)$. The buyers are symmetric in their added value, and each gains exactly half of his added value in the bargaining game. If buyer i believes that the other buyer j will invest e_j in innovation, he chooses e_i to

$$\max_{e_i \in [0,1]} \{E_{e_1 e_2}[R_i(M_i, Q_i) + \tfrac{1}{2}V^t(M_1, M_2, Q_1, Q_2)] - g_i(e_i)\}.$$

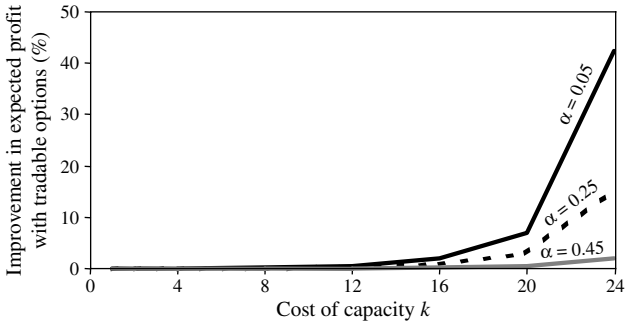
This is identical to buyer i's optimization problem (10) with fixed-quantity contracts $\{Q_i\}_{i=1,2}$ and $\alpha_i = 1/2$. That is, making the options tradable has the effect of increasing each buyer's bargaining confidence to $\alpha = 1/2$.

THEOREM 4. *Suppose that* $\sum_{i=1,2} \hat{Q}_i > c^*$. *The firms achieve greater expected profit with tradable options than contracts of the form* $\{Q_i, p_i(q)\colon 0 \le q \le Q_i\}_{i=1,2}$.

Both tradable options and quantity flexibility contracts achieve allocative efficiency through renegotiation. However, tradable options, by increasing each buyer's bargaining confidence to $\alpha = 1/2$, strengthen incentives for innovation, which in turn, in the parameter region $\sum_{i=1,2} \hat{Q}_i > c^*$, increases total system profit. Because options increase total system profit and because the total system profit can be allocated via transfer payments at the contracting stage, there exist transfer payments which ensure that all firms (including the manufacturer) are better off under tradable options than under quantity flexibility contracts. In the symmetric biopharmaceutical example, the parameter region $\sum_{i=1,2} \hat{Q}_i > c^*$ corresponds to the high innovation and capacity-cost region $k > \tilde{k}$ depicted in Figure 2. Further support for tradable options is provided by Plambeck and Taylor (2007), which establishes a result parallel to Theorem 4 when the manufacturer captures all the gain in the renegotiation ($\alpha_m = 1$ and $\alpha_1 = \alpha_2 = 0$).

In our numerical study of the symmetric biopharmaceutical example, within the subset of the 1,920 parameter settings in which quantity flexibility contracts fail to achieve the first best (i.e., $\sum_{i=1,2} \hat{Q}_i > c^*$), the percentage increase in expected profit from adopting tradable options increases with the cost of capacity k and decreases with the buyers' bargaining confidence index α. Under the optimal contracts of the form $\{Q_i, p_i(q)\colon 0 \le q \le Q_i\}_{i=1,2}$, when the buyers' bargaining confidence index is small, the buyers substantially underinvest in innovation which leads to low expected profit. Consequently, adopting tradable options, which is equivalent to increasing the buyers' bargaining confidence index from α to 1/2, has the greatest positive effect when α is small. The increase in profit can be substantial. Figure 5 is representative.

Figure 5 **Increase in Expected Profit from Adopting the Optimal Tradable Options Contracts Rather Than the Optimal Contracts of the Form $\{Q_i, p_i(q)\colon 0 \le q \le Q_i\}_{i=1,2}$ for the System with Renegotiation**



Note. System parameters are $H = 80$, $L = 20$, and $g(e) = 2{,}000(\log[1/(1-e)] - e)$.

7. Discussion

We have proven that with renegotiation, quantity flexibility contracts are optimal (among supply contracts that specify each buyer's payment as a general function of his order quantity). In our biopharmaceutical example, we find that when the cost of capacity is low, quantity flexibility contracts with renegotiation induce the first-best investments and capacity allocation. Otherwise, when capacity is expensive, underinvestment occurs and the optimal contracts have zero flexibility to maximize the incentives for investment. Giving buyers the right to trade capacity increases expected profit, but not necessarily to the first-best level.

Under any given quantity flexibility contract, the potential for renegotiation may strengthen or weaken the buyer's incentive to invest in demand-stimulating innovation. If a buyer is likely to gain capacity through renegotiation, the potential for renegotiation increases his incentive for innovation. Conversely, if a buyer is likely to release capacity (take less than the minimum specified in his quantity flexibility contract)

through renegotiation, then the potential for renegotiation reduces his incentive for innovation. Therefore, the prospect of renegotiation can reduce expected profit by weakening incentives for investment, even though renegotiation increases profit ex post by efficient capacity allocation.

In a numerical study, we observed that renegotiation typically increases expected profit. The increase in expected profit is large when capacity is expensive, provided that the contract parameters are chosen correctly. Intuitively, anticipating renegotiation leads to a contract with much less flexibility. The degree of flexibility in the optimal contract in the setting without renegotiation reflects the trade-off between providing incentives for innovation ex ante and maximizing revenues ex post. Specifically, decreasing a buyer's minimum order quantity (increasing flexibility) improves the ex post allocation of capacity, but may interfere with creating proper incentives for innovation.

Motivated by biopharmaceutical contract manufacturing, we have assumed that variable production costs are negligible compared to the initial cost of capacity (this is consistent with the approach taken by other researchers addressing capacity allocation (e.g., Cachon and Lariviere 1999a, Van Mieghem 1999, Chod and Rudi 2006)). However, with variable production costs, when both buyers have low demand, the profit-maximizing production quantity for each buyer may be less than the minimum order quantity, and then the firms will renegotiate the contracts to allow both buyers to take less than the minimum order quantity. If renegotiation is not allowed, incorporating a variable production cost would tend to increase the amount of flexibility in an optimal contract (to allow the buyer to order less and avoid inefficient variable production costs). Hence, the presence of variable production costs would reinforce our observation that the optimal quantity flexibility contract has less flexibility in the setting with renegotiation.

We have assumed that the manufacturer must fill the buyer's order, unless both firms agree to renegotiate the contract. This is motivated by the recent trend in U.S. courts to enforce specific performance of procurement contracts when the buyer has a sole source (Murray 2001). An alternative would be to give the manufacturer the option to supply less than the buyer orders, and pay a contractually stipulated penalty per unit of shortage (Tomlin 2003, Erkoc and Wu 2005). Under fixed-quantity contracts, it is optimal to set the penalty sufficiently high so that the manufacturer chooses not to short the buyers. Therefore, the optimal quantities, investments, and profits are identical to our base case with specific performance. Extending our analysis to general contracts with a linear shortage penalty appears intractable. A further complication is that courts in the United States and some other jurisdictions will not enforce a contractually stipulated penalty for breach of contract that exceeds the injured party's actual damages (Farnsworth 1999). The case where the manufacturer may short the buyer and pay precisely the buyer's value for the units is analyzed in Plambeck and Taylor (2007).

By highlighting the importance of renegotiation in practice and demonstrating that the optimal quantity flexibility contract is substantially different in a setting with renegotiation than in a setting without renegotiation, we hope to encourage supply chain researchers and practitioners to consider renegotiation in the design of all sorts of supply contracts. In settings with common information and contracting to create incentives for investment (as in biopharmaceutical contract manufacturing considered in this paper), the potential for renegotiation tends to simplify the structure of an optimal contract and thus facilitate analysis. In settings with asymmetric information, incorporating renegotiation makes the analysis more complex, but produces new and different managerial insights, as in Beaudry and Poitevin (1993).

8. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

Acknowledgments

The authors thank Larry Thomas, Contract Manager at Lonza and Jim Doran, Vice President of Memory Technology Development at AMD, for helpful discussions about the renegotiation of quantity flexibility contracts. They also thank the referees, the associate editor, and the participants in the Kellogg Operations Workshop for helpful comments, and Wenqiang Xiao and Kaijie Zhu for assistance with the numerical analysis. An earlier version of this paper was titled "Renegotiation of Supply Contracts."

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