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We analyze optimal contractual arrangements in a bilateral research and development (R&D) partnership between a risk-averse provider that conducts early-stage research followed by a regulatory verification stage and a risk-neutral client that performs late-stage development activities, including production, distribution, and marketing. The problem is formulated as a sequential investment game with the client as the principal, where the investments are observable but not verifiable. The model captures the inherent incentive alignment problems of double-sided moral hazard, risk aversion, and holdup. We compare the efficacy of milestone-based options contracts and buyout options contracts from the client's perspective and identify conditions under which they attain the first-best outcome for the client. We find that milestone-based options contracts always attain the first-best outcome for the client when the provider has some bargaining power in renegotiation and identify their applicability to different R&D partnerships.

Keywords: R&D partnerships; options contracts; double-sided moral hazard; holdup; risk preference
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1. Introduction

Firms have traditionally relied on internal research and development (R&D) to maintain their technological competitiveness. However, in recent years, firms are increasingly sourcing new knowledge externally by pursuing R&D in a collaborative environment, embedded in their supply, production, and distribution networks. According to the Cooperative Agreements and Technology Indicators database, in 2006, businesses formed about 900 new business technology alliances. About 60% of these alliances focused on biotechnology, followed by information technology, chemicals, aerospace, and automotive sectors. In the 1980s most of these were equity alliances, but today 96% of these R&D alliances are nonequity alliances based on contracts.

In 2008, Eli Lilly decided to move away from its traditional vertically integrated in-house R&D model to a more "fully integrated pharmaceutical network" that focuses on R&D relationships with partners with complementary assets (Deloitte 2009). Similarly, Merck formed an R&D partnership with Nicholas Piramal for the discovery and development of new oncology drugs (Nicholas Piramal 2007). In the chemicals sector, DuPont recently formed an R&D partnership with Plantic Technologies Limited (DuPont 2007). Plantic will develop biopolymers based on renewably sourced resins and sheet materials based on high-amylose corn starch, and DuPont will market and distribute these products.

Despite this rapid growth in R&D partnerships (e.g., Hagedoorn and Roijakkers 2006, Miller 2007), firms struggle to effectively manage these partnerships: More than 30% of the governing contracts get renegotiated or terminated by mutual consent, and many of them are settled in court (Sahoo 2008). In 1994, Ligand Pharmaceuticals, a biotech firm, sued Pfizer for breach of contract over the research they performed for Pfizer on the compound droloxifene; this case was settled out of court in 1996 (*PR Newswire* 1996). Other recent examples of R&D partnerships that ended in legal proceedings because of contractual issues are Amylin Pharmaceuticals against Eli Lilly on their diabetes collaboration (Krishnan 2011) and Onyx Pharmaceuticals against Bayer on their development agreement for cancer drugs (Jones 2009).

The decentralized nature of R&D partnerships can create several agency issues that pose significant challenges to its effectiveness. This paper investigates contractual structures that can overcome some of the agency issues prevalent in such partnerships. Specifically, we focus on three agency issues motivated by our observations of R&D collaborations across different settings. First, bilateral investments in the R&D process are observable to both parties but not verifiable in a court of law and hence are not directly contractible, creating a double-sided moral hazard problem. In the pharmaceutical industry, for example, a report by the U.S. Congress Office of Technology Assessment (1993) notes that pharmaceutical companies have actively resisted providing R&D cost data to congressional agencies. In the past, an attempt by the U.S. General Accounting Office (GAO) to obtain data on pharmaceutical R&D costs was foiled after many years of effort that involved decisions in the U.S. Supreme Court. The inherent differences in the structure of cost-accounting systems across companies can introduce potential inconsistencies and biases that are difficult to resolve via the legal process. In other words, nonverifiability of investments in R&D is an important feature of this process, leading to double-sided moral hazard. This, in turn, may lead to suboptimal investments, inducing inefficiencies in these R&D partnerships.

Second, the relationship-specific investments are made more complex by the agency structure and sequence of decision making in the R&D process. Contractual inefficiencies are introduced by the classical holdup problem, where the principal may exercise its bargaining power once the agent's relationship-specific investments are sunk to increase its profits, thereby creating incentives for the agent to underinvest (Gilbert and Cvsa 2003, Erat 2006, Edlin and Hermalin 2000).

Third, the contract design problem is further complicated because small and specialized research organizations (henceforth referred to as providers) with owner managers are risk averse compared with publicly owned large firms who contract out parts of their research portfolios (henceforth referred to as clients) and who have significant resources and easy access to liquid capital markets (Eisenhardt 1989). In the pharmaceutical industry, big pharmaceutical firms (the clients) have well-diversified R&D portfolios compared with the biotech firms (the providers). Thus, the design of optimal contracts in the presence of such agency issues (double-sided moral hazard, holdup, and risk aversion) becomes critical for the effective governance of these R&D partnerships.

The economics literature has proposed contracts to resolve these tensions in coordinating bilateral partnerships in a sequential investment setting (Edlin and Hermalin 2000 and references therein). However, the primary focus of this literature has been on the option of transferring ownership (buyout options) of the underlying asset. For example, Edlin and Hermalin (2000) find that buyout options can attain the first-best outcome for the client (the first-best outcome is defined as the outcome in which both firms in the partnership make their first-best or optimal investments as in the coordinated setting, and the client attains its maximum profits) in a limited range of settings.

The aim of this paper is to investigate whether contracts other than buyout options can be designed so that the first-best outcome is attained for the client in a wider range of settings. To study alternative contracts, our setup includes an important practice-driven feature of R&D partnerships. In particular, in the R&D context, the investment made by the provider in the research stage (typically a biotech or contract research organization firm in the first stage) is followed by an intermediate verifiable signal provided by a regulatory authority (e.g., the Food and Drug Administration); subsequently, the client (pharmaceutical firm) makes an investment in the development stage on marketing and manufacturing activities in the next stage. In contrast, the economics literature cited above does not consider the context of bilateral partnerships and such process specific elements in its models.

In this paper, we ask the following questions: Does the inclusion of process specificities of R&D (regulatory approval) result in new levers (milestone payments) that can coordinate the efforts of the two firms to attain the first-best outcome for the client?[1] Is the range of settings in which contracts that include milestone payments attain the first-best outcome larger than the cases where buyout options contracts attain the first-best outcome?

To answer these questions, we formulate a very general model of joint R&D efforts as a sequential investment game with double-sided moral hazard. As stated above, the risk-averse provider performs the initial research stage activities, and the client performs the development, integration, and manufacturing activities. We assume that the investments made by the two firms are observable but not verifiable (see Nöldeke and Schmidt 1998). In addition, if the provider owns the outcome of the R&D partnership such as intellectual property (IP) rights, then the provider has an option to sell the outcome to a third party for a prespecified value.

Before we present the formal mathematical model and our corresponding results, in the following paragraph, we illustrate the R&D setting with an example of a neurological drug being codeveloped between Supernus Pharmaceuticals and Shire plc Supernus is a specialty pharmaceutical company focused on developing and commercializing products for the treatment of central nervous system diseases. Supernus does not own or operate manufacturing facilities for the production of any of its potential products, nor does it have plans to develop its own manufacturing

[1] Such milestone-based payments from the client to the provider that are contingent on approval by the regulatory authority are used widely in practice. For example, in the partnership between Merck and Nicholas Piramal, the latter is eligible to receive milestone payments of up to $175 million per target, plus royalties on sales resulting from this collaboration.

operations for these products in the foreseeable future. Hence, for revenues, it relies on fees for development services and payment for the achievement of specified development and regulatory and sales milestones and royalties of its drugs under development (Supernus 2012). Supernus developed the drug Intuniv in 2006, which is an extended-release formulation of guanfacine and is used in the treatment of ADHD, in collaboration with Shire plc. The contract between the two involved a combination of fixed fees, milestone payments, and royalties. However, this contract was renegotiated later, and ex ante this potential for later renegotiation could give rise to holdup on the part of the client, Shire plc. In May 2009, in exchange for a one-time, lump sum payment of $36.9 million, Shire renegotiated the terms of its contract with Supernus, and Supernus sold its rights for Intuniv to an affiliate of Shire plc on a royalty-free, fully paid-up basis (Supernus 2012). Following this, on September 2, 2009, Shire obtained FDA approval for the manufacturing and marketing of Intuniv to children age 6 to 17 in the United States (Shire 2009, Havrilla 2012). Although our focus is on the pharmaceutical industry, the existence of intermediate verifiable signals in bilateral investment environments in R&D is valid in other industries as well. For example, in the aviation industry, Federal Aviation Administration (FAA) provides regulatory approval for the design of propeller systems, engines, and auxiliary power units for aircraft (FAA 2009). This further underscores the importance of incorporating the context specific elements (milestone payments linked to regulatory approval) of the R&D process in designing contracts.

To summarize, our paper models three relevant agency issues motivated by practice and literature on R&D partnerships. An important contribution of our paper is that by taking into account characteristics of R&D processes such as intermediate verifiable outcomes, we can analyze the attainment of the first-best outcome by simultaneously resolving double-sided moral hazard, holdup, and risk aversion. Thus, the contract structures developed in this paper provide normative guidelines for the optimal design of coordinating contracts to resolve the agency issues in R&D partnerships.

2. Literature Review

The operations literature on contracting has investigated the design of optimal contracts to coordinate investments and resolve agency problems. Plambeck and Taylor (2007) consider bilateral investments where the firm invests in innovation and the supplier invests in capacity. However, since supply quantity is verifiable in their model, a quantity enforcing mechanism can ensure the first-best outcome in the one-buyer, one-supplier case. Related papers by Taylor and Plambeck (2007a, b) are based on unilateral investments in single- and multiperiod games and hence very different from our model. Similarly, Gilbert and Cvsa (2003) consider a manufacturer-supplier relationship, where the supplier invests in innovation, but the manufacturer makes pricing decisions that introduce moral hazard in the supplier's investment decision. They study the trade-off between price commitment strategies that mitigate holdup but also reduce the flexibility to respond to demand fluctuations. Our setting is different from the aforementioned papers because we study the efficacy of options contracts in the context of double-sided moral hazard, holdup and risk aversion.

In the healthcare R&D field, Crama et al. (2008) and Iyer et al. (2005) study the optimal contract design problem within the principal–agent framework. Crama et al. (2008) model the biotech firm as the principal with an information asymmetry on technical characteristics of the drug. The actions of the agent are not contractible, creating a problem of adverse selection and single-sided moral hazard. Iyer et al. (2005) study the bilateral problem where the buyer makes resource commitments to a supplier who in turn decides on its optimal allocated resources with adverse selection about the capability of the supplier. Xiao and Xu (2012) study the effect of royalty revisions in a contract between an innovator and marketer and find that royalty revisions have a tradeoff owing to the better incentive realignment property and the potential for holdup. They identify that royalty contracts contingent on the outcome of the initial R&D stage can manage this trade-off better. We contribute to this stream of research by studying milestone-based (like Xiao and Xu 2012, milestone-based payments are contingent on the R&D outcome) options contracts and identifying their efficacy for optimal contract design. Our paper is different from Xiao and Xu (2012) because our focus is to study options-based contracts. Although the options contracts proposed in this paper are not renegotiation proof, we show that no renegotiation is needed in equilibrium. More importantly, unlike Xiao and Xu (2012), our paper shows the efficacy of milestone-based options contracts in attaining the first-best outcome for the client.

In the context of collaborative new product development, Bhaskaran and Krishnan (2009) assume that the efforts, costs, and revenues are verifiable and find that in the absence of preexisting revenues, cost- and effort-sharing contracts lead to better results. Our paper is different because investments made by parties are not verifiable, which in turn create agency issues. In a new product codevelopment setting, Erat (2006) analyzes the impact of market and development uncertainty on the timing of contract negotiation and shows that contracts should be signed only after uncertainty is partially resolved. We complement this research by studying the affiliated agency issues of double moral hazard, holdup, and risk aversion.

The contract design problem has also been studied in the coproduction framework (Roels et al. 2010, Corbett et al. 2005). However, in the coproduction setting, the two players move simultaneously; these papers show that the first-best solution cannot be achieved in general, and they characterize static revenue-sharing and cost-sharing contracts that are optimal but second best. Roels et al. (2010) also show that if efforts of the players can be verified for a cost, the first-best solution can be achieved. However, the parties make less than their first-best profits since the monitoring cost introduces an inefficiency into the system. In a related vein, Bhattacharyya and Lafontaine (1995) also show that a two-part contract with a variable outcome-based payment and fixed fee is the optimal but second-best solution to the joint production problem with double-sided moral hazard. In a outsourced customer support context, Bhattacharya et al. (2014) study the use of gain-share and cost-plus contracts in incentivizing the support center to participate effectively in the client's product improvement initiative. In contrast, R&D partnerships frequently have a sequential investment setting, as the second-stage investments are made after regulatory verification is obtained; therefore, milestone-based options contracts can be used in this setting.

In the economics literature, studies that characterize the use of options-based contracts in the sequential bilateral investment environment with nonverifiable investments and studies that consider incomplete contracts are relevant to our setting (Nöldeke and Schmidt 1998, Edlin and Hermalin 2000, Demski and Sappington 1991, Lulfesmann 2004, Grossman and Hart 1986). However, none of these studies models the specificity of the R&D process, in particular, intermediate verifiable outcomes, that are commonly observed in practice. In our paper, we show that modeling these process specificities leads us to novel insights that cannot be inferred from previous studies. We show that options-based contracts that are driven by milestone payments contingent on the outcome of the regulatory verification stage attain the first-best outcome in all cases if the provider has some bargaining power; if the provider does not have bargaining power, then we characterize the necessary and sufficient conditions for the first-best solution to be obtained. In contrast, buyout options-based contracts studied in the literature attain the first-best outcome only if the provider has all the bargaining power or the marginal value of the outside option of the provider is higher than a certain threshold (Edlin and Hermalin 2000).

The main differences between our paper and the economics literature are as follows. Nöldeke and Schmidt (1998) and Lulfesmann (2004) study the bilateral investment game with buyout options contracts where both parties are risk neutral and show that late exercise dates help to obtain the first-best solution. In contrast, in this paper, the provider is risk averse; hence, the contract structures in Nöldeke and Schmidt (1998) and Lulfesmann (2004) do not obtain the first-best solution. Edlin and Hermalin (2000) show that buyout options contracts can attain the first-best solution if the provider has an outside option to sell the outcome of its activities and marginal value of this option is higher than a certain threshold. In contrast, the milestone-based options contracts proposed in this paper are able to obtain the first-best solution in a wider variety of cases. Our paper (i) highlights the importance of incorporating intermediate verifiable outcomes while studying the design of optimal contracts in R&D partnerships and (ii) demonstrates the role of milestone payments, which are prevalent in multiple context in alleviating agency issues.

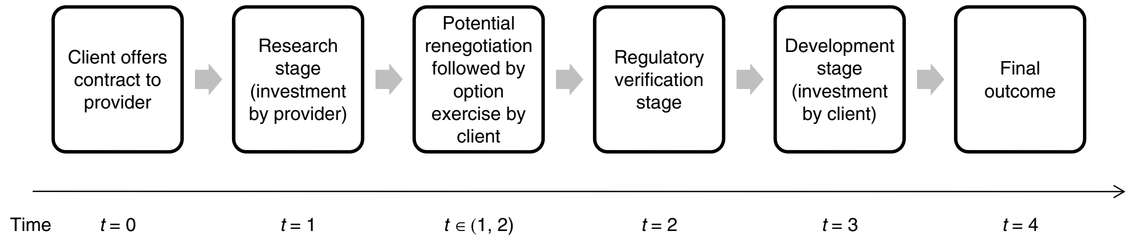
3. Model Description

In this section, we describe the model setting and state our assumptions. Based on the illustrative example of Supernus above, we model the contract design problem for coordinating bilateral investments in an R&D partnership by assuming that the provider (agent) is the first mover who invests in the research stage, and the client (principal) is the second mover who invests in the development stage. The investments made by both parties are observable as the parties collaborate closely but are not verifiable and the agent is assumed to be risk averse (prefers deterministic outcomes to stochastic outcomes). The sequence of events in our setting is summarized in Figure 1.

At time $t = 0$, the client (principal) offers a contract to the provider (agent). The agent accepts the contract provided that it ensures that the agent's expected utility is greater than its reservation value, which is normalized to zero. As shown in Figure 1, the provider then makes an investment of $x \in R^+$ in the research stage at time $t = 1$, and the outcome of the research stage is realized at time $t = 2$. The probability of a successful outcome is dependent on the investment made by the provider and is given by $g(x)$. The outcome of the research stage is given by either regulatory approval or rejection; in the pharmaceutical industry, FDA approval represents the regulatory verification stage. Other examples of regulatory approval include Environmental Protection Agency approval in the chemicals and oil and gas industries, and FAA approval for the design of propeller systems, engines, and auxiliary power units for aircraft (FAA 2009).

If the outcome is successful, then at time $t = 3$, the client makes an investment of $y \in R^+$ in the development stage. The final reward ϕ from introducing the

Figure 1 **Timeline and Sequence of Events in the Model**



new product on the market (net profits and IP rights) accrues at time $t = 4$. We assume that ϕ has support in the interval Φ and has a probability distribution function of $f(\phi \mid x, y)$ and a cumulative distribution function of $F(\phi \mid x, y) = \int_0^{\phi} f(\theta \mid x, y)\, d\theta$. We make the following assumptions about the model parameters (similar to those in Edlin and Hermalin 2000).

Assumption 1. *The probability of a successful outcome ($g(x)$) is concave and increasing in $x \in [0, \infty)$, with $g(0) = 0$, and $g'(\infty) = 0$. This implies that the marginal rewards for the provider will be diminishing in the scale of the investment. This is a standard assumption in the literature on probability success functions in R&D* (Derman et al. 1975).

Assumption 2. *For the final reward ϕ, $\phi = 0$ with probability* 1 *if $y = 0$ $\forall x \in [0, \infty]$. This implies that the impact of the provider's investment alone is not enough to gain a reward from the partnership, or for the product to be launched, and that some minimal investment must be made by the client firm as well. Also, $E[\phi \mid x, y]$ is increasing in x and y.*

Assumption 3. *The investments x and y are observable but not verifiable; hence, they are not directly contractible. The outcome of the provider's research stage investment is binary (success or failure), observable, and verifiable and hence is contractible.*

Assumption 4. *If the provider owns the revenues and IP rights from the new product, as in the buyout options contract, then it has an option to sell the rights to the revenues and IP to a third party (the value accrued is henceforth referred to as the outside option value $M(x) \geq 0$). The option value $M(x)$ is a function of the investment of the provider x that is observable to the third party. The option value $M(x)$ may be stochastic or deterministic. If x is not observable to the third party, then our results can be replicated by assuming $M(x) = \tilde{M}$.*

Assumption 5. *We assume that all parameters and functions are such that the first-best investments, x^* and y^*, are interior points.*

Assumption 6. *We assume that at any decision epoch, if an agent is indifferent between two decisions (e.g., accept/reject the renegotiation offer, exercise one of two options), then that agent will take the decision that maximizes the joint profits. This is a standard assumption and can be ensured without loss of generality by rewarding an arbitrarily small payment, $\epsilon > 0$, to the agent for making such a decision (see Laffont and Martimort* 2001, *p.* 37).

Assumption 7. *After the provider has sunk its investment, any renegotiation by the client and the provider is conducted as follows: the renegotiation bargaining outcome is given by the GNB model, where the bargaining power during renegotiation of the provider is given by β, and the bargaining power of the client is given by $1 - \beta$.*

Assumption 8. *We assume that the provider is risk averse and has a utility of $U(z)$, defined on the real line, from a payoff of z. We also assume $U'(z) > 0$, $U''(z) < 0$, and $U(0) = 0$. The increasing concave assumption about the utility function of the provider is standard in the literature. We also assume that the net surplus from an action x is separable in the revenue and the effort (Edlin and Hermalin* 2000, *Hermalin and Katz* 1991). *In the pharmaceutical industry, biotech firms are small, have less diverse portfolios compared with pharmaceutical firms, and discount potential future risky payments to a larger extent* ($> 20\%$) *compared with pharmaceutical firms* (8%–12%), *the evidence supports their being risk averse with concave utility functions (Eisenhardt* 1989, *Kawasaki and Macmillan* 1987, *Villiger and Bogdan* 2005, *Swinney et al.* 2011).

Assumption 9. *We assume that contract parameters (milestone payments, fixed fees) are unrestricted decision variables that are chosen by the client to maximize its expected profit subject to the individual rationality and incentive compatibility constraints. We discuss the practical implications of this assumption in* §4.2.

4. Model Analysis

In this section, we study the efficacy of milestone-based options contracts. To analyze the performance of milestone-based options contracts, we compare their ability to attain the first-best outcome with that of buyout options contracts that have been previously studied in the literature. We begin by defining the first-best outcome. The first-best outcome is defined by an outcome that maximizes the client's profit, subject to the provider's expected utility being its reservation value (normalized to zero). In addition, such an outcome should not require paying the provider any risk premium. Because the investments in the research and development stages are made sequentially, we first define $y^*(x)$ as the optimal investment in the development stage, given an investment level x during the research stage. Therefore, we have

$$y^*(x) = \arg\max_{y\geq 0}\{E[\phi \mid x, y] - y\}. \tag{1}$$

Here $E[\phi \mid x, y] = \int_\Phi \phi \, dF(\phi \mid x, y)$. Let $V(x)$ be the optimal value of the outcome after the research stage, if the outcome of the research stage is successful. That is, $V(x) = E[\phi \mid x, y^*(x)] - y^*(x)$. Similar to Edlin and Hermalin (2000), the following problem defines the first-best outcome for the client:

$$\max_{T,\, x\in[0,\infty)} \{V(x)g(x) - T\}$$
$$\text{s.t. } U(T) - x = 0.$$

Since x^* is assumed to be an interior point, we have the following first-order condition:

$$\left.\frac{dV(x)g(x)}{dx}\right|_{x=x^*} = \frac{1}{U'(U^{-1}(x^*))}. \tag{2}$$

Equations (1) and (2) determine the first-best investments $\{x^*, y^*(x^*)\}$. To summarize, for the client to attain the first-best outcome, a contract should ensure that the provider and the client make investments equal to x^* and $y^*(x^*)$, respectively, and the net transfer payment from the client to the provider is $U^{-1}(x^*)$. Note that for the provider's participation constraint to be satisfied while no risk premium is paid to the provider, it implies (from Jensen's inequality) that the provider's realized compensation is not linked to uncertain elements in the system. Also note that if the contract terms only contain fixed fees, then the provider has no incentive to exert a positive investment. Therefore, any contract form that attains the first-best outcome must have some contingent elements in the form of options (or renegotiation) with fixed fees (deterministic) as one option and performance-linked (stochastic) compensation as another.

The extant literature has shown the role of one type of options contracts, namely, buyout options contracts, in attaining the first-best outcome for the client. However, as noted in that literature, buyout options contracts have a limited ability of attaining the first-best outcome. In the absence of guidelines from the existing literature, it is unclear if any other type of options contracts can attain the first-best outcome. Our analysis below shows that exploiting the specificity of R&D processes, namely, regulatory approval, allows the client to create options contracts that are linked to milestone-based terms, and such contracts are able to attain the first-best outcome for a wider range of conditions.

4.1. Milestone-Based Options Contracts

In this section, we analyze the case where milestone-based options contracts are offered by the client to the provider. Milestone-based options contracts are very widely used in practice in R&D partnerships in general and in the healthcare industry in particular (Crama et al. 2008, Robinson and Stuart 2007). We focus on pure milestone-based options contracts that consist of milestone payments and a fixed fee.[2] Let the client offer the provider an options-based contract to be exercised at time $t \in (1, 2)$ such that the client could either pay the provider a milestone payment T_M if the intermediate verifiable signal is successful with a fixed fee T_A (option A) or it could pay the provider a fixed fee T_B (option B). The exercise date of such an options contract is observed in the Intuniv illustrative example, where the milestone and royalty payments were replaced with a fixed fee before FDA approval. The utilities of the provider from such an options contract are given by Edlin and Hermalin (2000):

$$U_P^A = U(T_M + T_A)g(x) + U(T_A)(1 - g(x)) - x,$$
$$U_P^B = U(T_B) - x.$$

Since the provider moves first, it is exposed to a potential holdup by the client, wherein the client may renegotiate the terms of the contract. A potential holdup may take place in this case if the client does not exercise option B—which exposes the risk-averse provider to a stochastic milestone payment, in which case both the provider and the client are mutually better off by renegotiating option A to a fixed-fee contract $\tilde{T}_A$ at time $t \in (1, 2)$. The total surplus of such a renegotiation is

$$\begin{aligned}G(x) &= \big[V(x)g(x) - \tilde{T}_A + \tilde{T}_A - x\big]\\ &\quad - \big[(V(x) - T_M)g(x) - T_A\\ &\qquad + U^{-1}\big(U(T_M + T_A)g(x) + U(T_A)(1 - g(x))\big) - x\big]\\ &= T_M g(x) + T_A\\ &\quad - U^{-1}\big(U(T_M + T_A)g(x) + U(T_A)(1 - g(x))\big). \end{aligned} \tag{3}$$

Here, the first term on the right-hand side of the above equation ($[V(x)g(x) - \tilde{T}_A + \tilde{T}_A - x]$) is the joint expected profit after renegotiation, and the second term ($[(V(x) - T_M)g(x) - T_A + U^{-1}(U(T_M + T_A)g(x) + U(T_A)\cdot(1 - g(x))) - x]$) is the joint expected profit before renegotiation. Let $\bar{U}(x) = U(T_M + T_A)g(x) + U(T_A)(1 - g(x))$. Note that $U^{-1}(\bar{U}(x))$ is the certainty equivalent of the uncertain total payment of the provider under option A. It is straightforward to check that $G(x) \geq 0$ because $U(T_M g(x) + T_A) \geq U(T_M + T_A)g(x) + U(T_A)(1 - g(x))$

[2] Milestone-based options contracts may also include royalty terms. Our analysis and results are robust to such cases.

from Jensen's inequality. The surplus of renegotiation $G(x)$ has an intuitive interpretation: it is the risk premium for the provider; that is, $G(x)$ is the amount that a risk-averse provider is willing to pay to convert its stochastic payment to a deterministic amount. The gains from such renegotiation may be split between the provider and the client based on their relative bargaining power during the renegotiation stage. As stated in Assumption 7, since the bargaining power of the provider is given by β, the provider will get $\beta G(x)$ from the generalized Nash bargaining (GNB) result, which is a property of the GNB model. The GNB model has been used extensively in the literature (Lovejoy 2010, Iyer and Villas-Boas 2003). Hence, if the client does not exercise option B, then option A will be renegotiated to a fixed-fee contract ($\tilde{T}_A$) such that $\tilde{T}_A = U^{-1}(\bar{U}(x)) + \beta G(x)$. Such a renegotiation is observed in the Intuniv illustrative example, where the payment components linked to stochastic outcomes were renegotiated to a fixed fee. Therefore, because of the holdup problem, which leads to renegotiation, the client will choose to transfer a payment equal to $\min\{\tilde{T}_A, T_B\}$ to the provider. Hence, the provider's problem can be stated as

$$\max_{x\geq 0} \min\{U(U^{-1}(\bar{U}(x)) + \beta G(x)) - x,\, U(T_B) - x\}. \tag{4}$$

The client's problem can be stated as

$$\max_{T_M,\, T_A,\, T_B} \; [E[\phi \mid \tilde{x}, \tilde{y}(\tilde{x})] - \tilde{y}(\tilde{x})]g(\tilde{x}) - \min\{U^{-1}(\bar{U}(\tilde{x})) + \beta G(\tilde{x}),\, T_B\} \tag{5}$$

s.t.

$$\tilde{y}(x) = \arg\max_{y\geq 0}[E[\phi \mid x, y] - y]g(x) - \min\{U^{-1}(\bar{U}(x)) + \beta G(x), T_B\}, \tag{6}$$

$$\tilde{x} = \arg\max_{x\geq 0}\min\{U(U^{-1}(\bar{U}(x)) + \beta G(x)) - x,\, U(T_B) - x\}, \tag{7}$$

$$\min\{U(U^{-1}(\bar{U}(\tilde{x})) + \beta G(\tilde{x})) - \tilde{x}, U(T_B) - \tilde{x}\} \geq 0. \tag{8}$$

The client's problem is characterized by (5) at $t = 0$ and by (6) at $t = 3$. The provider firm solves (7) at $t = 1$, and (8) is the provider's participation constraint. We examine whether such a milestone-based options contract can attain the first-best solution, and we state the result formally in Proposition 1.

Proposition 1. *A milestone-based options contract that gives the client the right at time $t \in (1, 2)$ to choose between options A and B can attain the first-best solution for the client if and only if there exists a T_M, T_A such that $\forall\, x \in [0, x^*)$:*

$$U(\beta(T_M g(x) + T_A) + (1-\beta)U^{-1}(\bar{U}(x))) - x \leq U(\beta(T_M g(x^*) + T_A) + (1-\beta)U^{-1}(\bar{U}(x^*))) - x^* = 0.$$

Here options A and B are the following:

Option A. *Pay the provider a fixed payment T_A and a milestone payment T_M if the intermediate verifiable signal is successful.*

Option B. *Pay the provider a fixed payment T_B.*

The compensation to the provider under the milestone-based options contract after renegotiation is shown in Figure 2. (All the numerical values used for the parameters are stated in the appendix.) The mechanics of the options contract based on milestone payments are as follows. The client sets the terms of the contract such that if the provider invests lower than x^*, then the client will exercise option A (Figure 3). In this case, the condition in Proposition 1 states that the provider will not earn its reservation utility and hence stands to gain by investing x^*. If the provider invests more than x^*, then T_B is set in such a manner that the client will exercise option B, which will also result in a lower utility for the provider. Hence, the provider invests x^* as illustrated in Figure 2. The necessary and sufficient condition stated in Proposition 1 gives the client the range of contractual parameters such that the provider makes an investment of x^* and gets its reservation value. After the provider's investment, all the upside from the partnership is with the client (because it pays only a fixed fee); hence, the client makes its optimal investment, y^*. Therefore, this options contract resolves the holdup and risk aversion issues simultaneously. An important detail of such an options contract is that although its mechanics require both players to anticipate the potential renegotiation due to holdup when choosing their actions prior to the potential renegotiation ($\{T_M, T_A, T_B\}$ for the client and x for the provider are actions prior to the potential renegotiation), no renegotiation will take place in equilibrium because both players know that renegotiation will yield an outcome equivalent to option B.

Figure 2 **Utility of Provider Under Milestone-Based Options Contract After Renegotiation with $\beta = 0.5$**

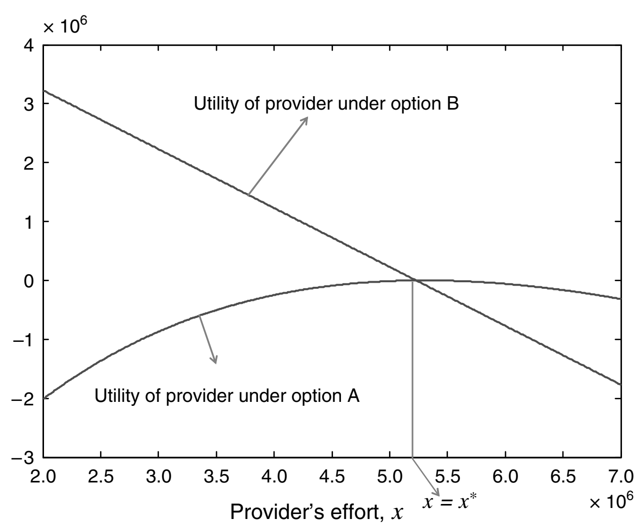
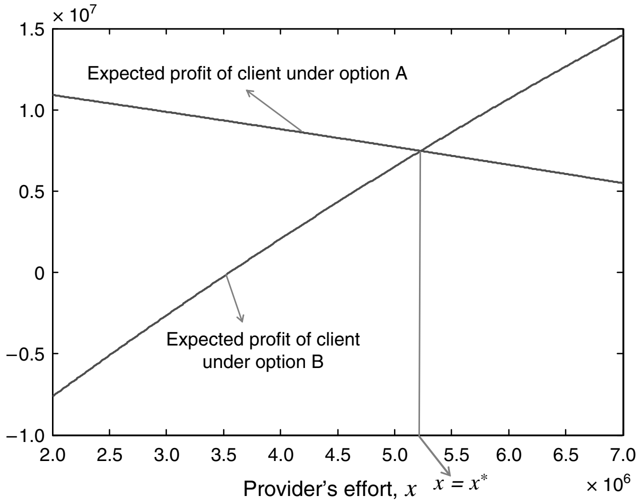


Figure 3 **Client's Expected Profit (with Endogenous Optimal Client Effort) as a Function of Provider's Effort**



A key observation in such contracts is the important role played by the milestone payments (option A). The milestone payment in this contract drives the investment of the provider to the first-best investment and gives the incentive to the provider to increase its investment under option A to be equal to its first-best investment, whereas the fixed fee is used to make the participation constraint of the provider tight. This finding has important implications for the use of milestone payments in the design of optimal contracts. In the operations literature, milestones have been recognized for their role in monitoring and coordinating the product and supply chain development investment (Joglekar et al. 2001, Graves and Willems 2005, Mihm 2010, Crama et al. 2008), and they are observed widely in practice as well (Robinson and Stuart 2007). We complement this stream of literature by demonstrating the criticality of milestone payments in options-based contracts to coordinate bilateral investments in R&D partnerships to overcome agency issues such as double-sided moral hazard, holdup, and risk aversion simultaneously.

The following conditions are sufficient to satisfy the condition in Proposition 1 and hence enable milestone-based options contracts to attain the first-best outcome:

$$\exists T_M, T_A \quad \text{s.t.} \quad U'\big(U^{-1}(\bar{U}(x)) + \beta G(x)\big) \cdot \frac{d[U^{-1}(\bar{U}(x)) + \beta G(x)]}{dx} \geq 1, \quad \forall x \in [0, x^*], \tag{9}$$

$$U\big(\beta(T_M g(x^*) + T_A) + (1-\beta)U^{-1}(\bar{U}(x^*))\big) - x^* = 0. \tag{10}$$

Equation (10) gives the client the value of the fixed fee T_A to attain the first-best solution and is dependent on T_M. Hence, milestone-based options contracts can attain the first-best solution if Equation (9) is satisfied. Because $U(\cdot)$ is an increasing function, Equation (9) is always satisfied if there exists a T_M such that $d[U^{-1}(\bar{U}(x)) + \beta G(x)]/dx$ can be made sufficiently large. Proposition 2 describes the domain of conditions under which milestone-based options contracts always attain the first-best solution.

Proposition 2. *Milestone-based options contracts can always attain the first-best solution if* $\beta \in (0, 1]$.

Proposition 2 demonstrates that milestone-based options contracts always attain the first-best outcome if the provider has some bargaining power during renegotiation.[3] This is an important result because it shows that irrespective of other parameters like the reward and degree of risk aversion, the client can attain the first-best outcome when the provider has some bargaining power in renegotiation because the holdup problem is alleviated. Hence, although first-order intuition may suggest that if the client has all the bargaining power in renegotiation, the client may perform better, Proposition 2 shows that having all the bargaining power in renegotiation may hinder the client's ability to attain the first-best outcome.

The milestone-based options contracts are able to attain the first-best outcome if $\beta > 0$ because the regulatory approval depends on the efforts of the provider, and hence, the milestone-based options contract is able to alleviate the holdup problem. The attainment of the first-best outcome also requires that the provider does not earn any risk premium which is ensured by the fixed-fee option embedded in the contracts proposed above. In a single-sided moral hazard setting with a risk-averse agent, Hermalin and Katz (1991) show that the first-best outcome may be attained via a renegotiation mechanism. (Edlin and Hermalin 2001 provide a correction for a proof presented in Hermalin and Katz 1991.) Our results are different from this literature because the contracts presented above do not require renegotiation in equilibrium to attain the first-best outcome. More importantly, the milestone-based options contract is more robust in attaining the first-best outcome, in that any renegotiation-based mechanism can be replicated by an options contract by setting one option equal to the initial contract and another option equal to the renegotiated contract. However, the other way round is not always true. For example, the condition used in Edlin and Hermalin (2001) to show the attainment of the first-best outcome using a renegotiation mechanism in our context would imply that $g(x) < g(x^*)$ $\forall x \neq x^*$. This implies that $g(x) < g(x^*)$ $\forall x > x^*$, which violates the context specificity of our model wherein the probability of a successful outcome

[3] The condition on the bargaining power of the provider β ensures that the sufficient conditions for the attainment of the first-best outcome are satisfied and hence is a conservative condition.

from the regulatory approval stage is increasing in x $\forall x \in [0, \infty)$. Thus, the milestone-based options contract presented in this paper provides normative guidelines for the optimal design of coordinating contracts to resolve the agency issues in R&D partnerships.

Proposition 3. *If $\beta = 0$, then milestone-based options contracts may or may not attain the first-best solution. The necessary and sufficient conditions for milestone-based options contracts to attain the first-best solution when $\beta = 0$ are given by there exists a* finite *T_H, T_L such that $U(T_H) \geq x^* + (1 - g(x^*))/g'(x^*)$ and $U(T_L) \leq x^* - g(x^*)/g'(x^*)$.*

Proposition 3 shows that if the provider does not have any bargaining power, the client can only attain the first-best solution if the stated conditions in the proposition are satisfied. This result shows that the client cannot always attain the first-best solution if it has all the bargaining power during renegotiation. The driver of this result is the ability of the client to incentivize the provider to make its first-best investment: if the provider does not have some bargaining power during renegotiation, the client is not able to give it sufficient incentives to overcome the holdup problem because the risk-averse provider may heavily discount the stochastic milestone payments. However, when the provider has some bargaining power during renegotiation ($\beta > 0$), it is partly compensated by the certainty equivalent of the original option A and partly by the gains of the renegotiation. In this case it is possible to set a milestone payment, even if highly discounted by the provider, such that the total transfer payment to the provider (from the discounted certainty equivalent of option A and the shared gains from renegotiation) is large enough to overcome the holdup problem (making options A and B equivalent).

We now analyze the efficacy of buyout options contracts in attaining the first-best solution.

4.1.1. Comparison with Buyout Options Contracts. We now compare the efficacy of milestone-based options contracts in attaining the first-best solution with that of buyout options contracts, which have been the main contracts that have been studied in ameliorating the effect of the holdup issue in double moral hazard applications in the literature (Edlin and Hermalin 2000). Buyout options contracts are structured as follows. The client offers the provider an options-based contract to be exercised at time $t \in (1, 2)$ such that the client could either own the entire value of the IP from the research stage and pay the provider a fixed fee T_2 (option 2) or give the provider the entire value of the IP and a fixed fee T_1 (option 1). If the client uses option 1, the provider has the ownership of the IP after the research stage, and it then has an external option to sell its output at the research stage for a payment $M(x) \geq 0$, where $M(x)$ could be stochastic or deterministic.

The analysis of buyout options contracts closely follows the literature (Edlin and Hermalin 2000); hence, we only summarize the results for the efficacy of buyout contracts. Let $\kappa(x, T_1) = E[U(M(x) + T_1)]$, where $\kappa(x, T_1)$ denotes the expected revenues to the provider from option 1. Note that if $M(x)$ is deterministic, then $\kappa(x, T_1) = U(M(x) + T_1)$.

Proposition 4 (Edlin and Hermalin 2000). (i) *Buyout options contracts where the client has the option to choose at time $t \in (1, 2)$ to either give the IP rights to the provider and a fixed fee T_1 (option 1) or retain the IP rights and pay the provider a fixed fee T_2 (option 2) can attain the first-best solution for the client if and only if there exists a T_1 such that for all $x \in [0, x^*)$:*

$$\begin{aligned} &U\big(\beta(V(x)g(x) + T_1) + (1-\beta)U^{-1}(\kappa(x, T_1))\big) - x \\ &\quad \leq U\big(\beta(V(x^*)g(x^*) + T_1) + (1-\beta)U^{-1}(\kappa(x^*, T_1))\big) - x^* \\ &\quad = 0. \end{aligned}$$

(ii) *The above condition is always satisfied if $\beta = 1$ (the provider has all the bargaining power in renegotiation) and $U(V(x)g(x) + T_1) - x$ is ideally quasiconcave*[4] *in x. If $\beta < 1$, then a necessary condition for the first-best solution to be attained is given by $(dU^{-1}(\kappa(x, T_1))/dx)|_{x^*} \geq (dV(x)g(x)/dx)|_{x^*} = 1/(U'(U^{-1}(x^*)))$.*

As before, $V(x)$ is the optimal value of the outcome after the research stage, if the outcome of the research stage is successful. The second condition in Proposition 4 yields a condition identical to Proposition 4 (condition 4) in Edlin and Hermalin (2000),[5] which states that the marginal profit for the provider of investing x^* from its outside option is weakly greater than the marginal profit for the centralized system (when provider and client act as one firm).

Hence, for buyout options contracts to attain the first-best solution when the bargaining power in renegotiation is shared between the parties, the marginal profit from the external option has to be sufficiently high. The only case where buyout options contracts always attain the first-best solution is the case where all the bargaining power in the partnership is with the provider ($\beta = 1$), which implies that the holdup problem does not exist (Edlin and Hermalin 2000).

We now compare the efficacy of milestone-based options contracts and buyout options contracts in attaining the first-best solution for the client. When the provider has all the bargaining power in renegotiation ($\beta = 1$), both contracts attain the first-best solution (from Propositions 2 and 4).[6] When $0 < \beta < 1$,

[4] Edlin and Hermalin (2000) provide the definition of ideally quasiconcave in their Definition 1 (p. 407).

[5] Note that there is an added term of $g(x)$ in this expression; all other terms in the necessary condition are the same.

[6] Note that milestone-based options contracts attain the first-best outcome more generally because we do not need to impose any other conditions. such as ideal quasiconcavity.

milestone-based options contracts always attain the first-best solution (from Proposition 2), whereas buyout options contracts can only attain the first-best solution if the second condition in Proposition 4 (the marginal profit from the external option of the provider is high) is satisfied. The driver of this result is that unlike buyout options contracts, milestone-based options contracts can leverage R&D process levers, like the intermediate regulatory approval, that increase the efficacy of such contracts. We now compare explicitly the efficacy of milestone-based options contracts and buyout options contracts when $\beta = 0$ in Proposition 5.

Proposition 5. *If $\beta = 0$, then milestone-based options contracts may attain the first-best solution when buyout options contracts cannot do so, and buyout options contracts may attain the first-best solution when milestone-based options contracts cannot do so.*

Interestingly, it is not possible for milestone-based options contracts to always dominate buyout options contracts. When $\beta = 0$, the necessary and sufficient conditions for buyout options contracts and milestone-based options contracts are different. The intuition behind Proposition 5 is as follows. When $\beta = 0$, the milestone-based options contract relies on the initial contract only to attain the first-best outcome because the provider does not obtain any additional gains from renegotiation. Although the milestone payment in the initial contract can be modified, the shape of the utility function and the probability of a successful outcome determine if the first-best outcome can be attained. If the shape of the utility function and the probability of a successful outcome do not satisfy two conditions that are necessary for the attainment of the first-best outcome (see Proposition 3), then no initial milestone-based option contract can attain the first-best solution. The intuition behind these two conditions is that the range of the provider's utility function has to be higher than a threshold value to induce it to make its first-best investment (x^*). In contrast, buyout options contracts rely on the marginal value of the outside option, which has to be sufficiently high. Hence, whereas the milestone-based options contract relies on the shape of the utility function of the provider (U) and the shape of the probability of successful outcome function $g(x)$, buyout options contracts rely on the marginal profit of the provider from the outside option and the shape of $V(x)g(x)$. Hence, when $\beta = 0$, each contract can attain the first-best solution in a set of conditions that do not influence the efficacy of the other contract.

To conclude, we show that the milestone-based options contract gives the client a greater ability to attain the first-best outcome when the provider has some bargaining power during renegotiation. However, when all the bargaining power is with the client, managers have to contextually evaluate the two types of options contracts to infer which contract type performs better than the other. Our results, along with results from Edlin and Hermalin (2000), provide managers with guidelines in designing R&D outsourcing contracts.

4.2. Implementation of Milestone-Based Options Contracts

In this section, we discuss the practical implementation of the proposed milestone-based options contracts. First, we note that the fixed fee in the first option for the options contracts (T_A in the milestone-based options contract) may be negative. Note that this is true for buyout options contracts as well because T_1 in the buyout options contract may be negative. An important element of the negative fixed fee is as follows: owing to the mechanics of the options contract, the fixed fee is necessary for the efficacy of the options contract. Although milestone-based options contracts can attain the first-best solution by providing a positive milestone payment, attaining the first-best solution dictates that the client have a negative fixed fee to extract the surplus from the provider to make its participation constraint tight. (The fixed fee T_A is linked to $T_M g(x)$, and hence its magnitude is significantly lower than T_M.)[7]

Second, the results presented in §4.1 assume that the milestone payment (T_M) and the fixed fee (T_A) are unrestricted. For the milestone-based options contract to attain the first-best outcome, an implicit requirement is that option A of the milestone-based options contract can be enforced, if exercised. This assumption is key to the attainment of the first-best solution. In practice, the ability of the client to pay a high milestone payment and that of the provider to pay a high fixed fee to the client may be limited by their respective net asset values (cash, physical, and IP; see Holmstrom 1982). In such a case, there may be exogenous bounds that need to be enforced on the contractual parameters: an upper bound on the milestone payment and a lower (negative) bound on the fixed fee. When $\beta \in (0, 1]$, we show that there exists a finite T_M and T_A that ensure that the first-best solution is always attained.

We note that the values of T_M and T_A (negative) may be high, which may impede the practical implementation of the proposed milestone-based options contracts. It follows from the proof of Proposition 2 that the first-best outcome is attainable by setting T_M and T_A such that $\bar{T}_M \le T_M < \infty$ and $-\infty < U^{-1}(x^*) - T_M g(x^*) \le T_A \le U^{-1}(x^*) - T_M g(x^*)\beta$, where $\bar{T}_M$ ($< \infty$) has been defined in the proof of Proposition 2. The value of $T_M = 1/(U'(U^{-1}(x^*))g'(x^*)\beta) < \infty$ ensures that the first-best solution can be attained with finite values of the

[7] If the provider has a positive reservation value, then the magnitude of the negative fixed fee is smaller for both kinds of options contracts and may also be positive depending on the reservation value.

milestone payment and the fixed fee. Note that the above inequalities provide conservative bounds because they satisfy sufficient conditions for the attainment of the first-best outcome. This implies that if T_M is exogenously restricted to be lower than $\bar{T}_M$ and T_A is restricted to be higher than $U^{-1}(x^*) - \bar{T}_M g(x^*)$, then the sufficient conditions (Proposition 2) to attain the first-best solution are not satisfied. Therefore, in such cases, the implementation of the proposed milestone-based options contracts may be unrealistic in the motivating context. When $\beta = 0$, attainment of the first-best solution requires that $U^{-1}(x^* + (1 - g(x^*))/g'(x^*))$ and $U^{-1}(x^* - g(x^*)/g'(x^*))$ should exist and be finite, and by setting $T_A \le U^{-1}(x^* - g(x^*)/g'(x^*))$ and $T_M \ge U^{-1}(x^* + (1 - g(x^*))/g'(x^*)) - T_A$. Finally, for all $\beta \in [0, 1]$ T_B is always set equal to $U^{-1}(x^*)$. Note that $U^{-1}(x^*)$ is the minimum transfer payment needed to satisfy the provider's participation constraint.

With respect to the magnitude of the milestone payment, note that there are other mitigating factors to moderate the magnitude of the milestone payment. If royalty payments are used along with the milestone payments, then the magnitude of the milestone payment to achieve the first-best outcome is lower. We have not included this factor in the paper since its focus is on the role of milestone payments as the driving force behind the achievement of the first-best outcome. In addition, the magnitude of the negative fixed fee (T_A) can be lower if the reservation value of the provider is positive. We chose not to model the positive reservation value in the paper because it has no role to play in the game apart from providing a higher normalizing value for the provider.

5. Conclusions and Discussion

In this paper, we study the efficacy of milestone-based options contracts and buyout options contracts in coordinating the client's and provider's investments in an R&D partnership. We assume that the risk-averse provider is the first mover that invests in the research stage, and a risk-neutral client invests in the development stage if the research stage is successful. The outcome of the research stage is verifiable to all parties. We model the problem as a sequential bilateral investment problem using a principal–agent framework with double-sided moral hazard, with the client as the principal.

Our results can be summarized as follows. When milestone-based options contracts are used, interestingly, the client can always attain the first-best solution if the provider has some bargaining power in renegotiation. If the provider has no bargaining power in renegotiation, the client can attain the first-best outcome if some conditions are met, and we characterize those conditions. In this case, we show that the client can only attain the first-best solution when the utility of the provider has a range that incorporates two threshold values.

In contrast, as the literature has shown, if buyout options contracts are used, the first-best outcome can be achieved unconditionally by the client only if all the bargaining power in renegotiation is with the provider. If the bargaining power is shared between the client and the provider, then a necessary condition for buyout options contracts to attain the first-best solution is that the marginal value of the external option has to be high. Hence, we show that milestone-based options contracts Pareto dominate buyout options contracts if the provider has some bargaining power in renegotiation. The driver of this result is that unlike buyout options contracts, milestone-based options contracts can leverage R&D process levers, like the intermediate regulatory approval, that increases the efficacy of such contracts. When the provider has no bargaining power in renegotiation, then both milestone-based options contracts and buyout options contracts may attain the first-best solution in restricted domains, and we characterize those domains.

We illustrated the questions being addressed in the paper with an example of a drug for the treatment of ADHD being codeveloped between Supernus Pharmaceuticals and Shire plc. Note the following: (i) If royalty payments are part of option A in the milestone-based options contract as in the illustrative example, then the milestone payment and the corresponding fixed fee offered by the client for the first-best outcome to be attained are lower than those described in the paper, and we did not include royalty payments to make the model parsimonious. (ii) The renegotiation between the parties was conducted in May 2009, before Shire plc obtained FDA approval in September 2009. This is an important condition for both the milestone-payment-based options contract and buyout options contract to attain the first-best solution; it is easy to see that they cannot attain the first-best solution with an exercise time $t > 2$ (after the outcome of the intermediate verifiable signal) because the provider has to be paid a risk premium. (iii) Supernus accepted a fixed fee of \$36.9 million in renegotiation rather than the risky milestone payments and royalties. The milestone-based options contract presented in this paper can replicate the mechanism (and outcome) of the illustrated renegotiation by setting the fixed fee of option B equal to the fixed transfer payment that is expected from the renegotiation. Finally, it is easy to see that in the options-based contracts, the options have to be exercised by the client as the second mover, and if the provider has the right to exercise the option, then the client is exposed to the moral hazard problem because the provider can choose to invest zero and then pay itself with the fixed-fee contract.

We have also conducted robustness checks on the probability of successful outcome ($g(x)$) being a noisy measure and the provider being risk neutral. In the first case (noisy probability of a successful outcome), we find that the options contracts have the same domain of attaining the first-best outcome (by taking the expected value of the probability of the successful outcome conditional on the investment x). If the provider is risk neutral, we find that the options contracts in the paper always attain the first-best solution; in addition, a simple milestone payment with fixed-fee contract can also attain the first-best outcome.

We also outline a number of interesting avenues for future research. Note that our results rely on the assumption that the investments are fully observable. It would be interesting to analyze the performance of the contracts studied here when the investments are only partially observable. It would also be interesting to compare the efficacy of milestone-based options contracts and buyout options contracts when both contract types fail to attain the first-best outcome (when $\beta = 0$). In this case, managers are faced with designing optimal (second-best) contracts and it is unclear which of these contract types would dominate. Another area of potential future research is to study settings that incorporate more process details such as multiple steps in the research phase with multiple regulatory approval stages. Such settings will closely capture the pharmaceutical industry; however, they will involve a more tedious comparison with buyout options contracts.

Finally, the implementation of the contracts studied in this paper is widely observed in R&D partnerships. Buyout options contracts are observed in practice, suggesting that options-based contracts are considered viable in such partnerships. Although we have not seen milestone-based options contracts in practice, milestone payments and fixed fees are widely prevalent (Cornelli and Yosha 2003, Robinson and Stuart 2007). Putting the two together, we posit that creating options contracts that are based on milestone payments does not pose any additional challenges to client firms. Moreover, as discussed above in the Intuniv illustrative example, initial contracts linked to stochastic payments are often renegotiated to fixed payments in practice. The options contracts studied in this paper have an added advantage that there is no renegotiation in equilibrium under such contracts. In addition, our results suggest that options based on milestone payments and fixed fees are capable of eliminating the agency issues in R&D outsourcing.

To summarize, the high complexity of the R&D process due to large monetary investments and high uncertainty in outcomes is leading to a growth in R&D partnerships. In this context, firms are faced with the challenge of overcoming different agency issues that may limit the effectiveness of such partnerships. Our paper provides managerial insights for the existence of optimal contracts that can overcome potential inefficiencies in R&D partnerships due to the different agency issues. For example, one might expect that in a partnership with an inherently uncertain outcome, the risk aversion of one party would lead to a loss in efficiency in the system in the form of a risk-premium. We show that by using characteristics of R&D processes in practice that are verifiable intermediate signals, such as FDA approval or EPA certification, options-based contracts can be designed to eliminate such losses. Milestones have been recognized in the operations literature on new product development for their role in monitoring the product and supply chain development effort (Joglekar et al. 2001, Graves and Willems 2005); for risk sharing in new product development (Mihm 2010); and for coordinating unilateral efforts (single-sided moral hazard) in the R&D supply chain with asymmetric information on exogenous probability of successful outcomes (Crama et al. 2008). This paper demonstrates that milestones are critical in coordinating bilateral investments in R&D partnerships as they simultaneously overcome relevant agency issues. Our results provide normative recommendations to alleviate agency issues in R&D partnerships. Based on our findings, we propose that partners in the joint development effort can make better decisions on the contractual elements used, and the framework proposed in the paper can act as a prescriptive model in this regard.

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Appendix

Proof of Proposition 1. Recall that for first-best we need the following conditions to be true:

Condition 1. *The optimal decisions of the provider and the client are* x^*, y^*.

Condition 2. *The transfer payment made to the provider by the client is* $U^{-1}(x^*)$ *and is not linked to any stochastic outcome.*

As mentioned in the body of the paper, the provider will get $\beta G(x)$ from the GNB result, which is a property of the GNB model. To see this, assume that the provider with bargaining power β gets P, and the client with bargaining power $1-\beta$ gets $G(x) - P$. Then the GNB outcome is given by

$$\max_{P\geq 0} P^{\beta}[G(x)-P]^{1-\beta}$$

$$\Rightarrow \beta P^{\beta-1}[G(x)-P]^{1-\beta} - (1-\beta)P^{\beta}[G(x)-P]^{-\beta} = 0$$

$$\Rightarrow P = \beta G(x).$$

Therefore, from (4), the provider's problem is

$$\max_{x\geq 0} \min\{U^{-1}(\bar{U}(x)) + \beta G(x) - x,\, T_B - x\}.$$

If the provider invests x^*, then the client's problem is

$$\max_{y\geq 0}\{E[\phi \mid x^*, y]-y\}. \tag{11}$$

Comparing (11) and (1) confirms that the client makes the first-best investment y^*. Therefore, we need to derive conditions such that the provider invests x^* and that Condition 2 is satisfied. Our claim is that to attain the first-best outcome we need to show that there exists a T_M, T_A, such that $\forall\, x\in[0,x^*)$, the following holds:

$$\begin{aligned} &U[\beta(T_M g(x)+T_A)+(1-\beta)U^{-1}(\bar U(x))]-x\\ &\quad\leq U[\beta(T_M g(x^*)+T_A)+(1-\beta)U^{-1}(\bar U(x^*))]-x^*=0. \end{aligned} \tag{12}$$

To show sufficiency, let us assume that (12) is satisfied for some T_M and T_A. Set T_B such that

$$U(T_B)-x^*=0. \tag{13}$$

Equations (12) and (13) ensure that the provider will not invest $x\neq x^*$. Assume that the provider invests $x<x^*$. In this case the provider's utility is

$$\begin{aligned} &\min\{U(U^{-1}(\bar U(x))+\beta G(x))-x,\, U(T_B)-x\}\\ &\quad= U(U^{-1}(\bar U(x))+\beta G(x))-x\leq 0 \quad \text{(from (12))}. \end{aligned}$$

Assume that the provider invests $x>x^*$. In this case the provider's utility is

$$\begin{aligned} &\min\{U(U^{-1}(\bar U(x))+\beta G(x))-x,\, U(T_B)-x\}\\ &\quad\leq U(T_B)-x<0 \quad \text{(from (13))}. \end{aligned}$$

Hence, the provider will invest $x=x^*$ because deviating is not beneficial.

Next we will show that (12) is also necessary for the attainment of the first-best outcome. Let us assume that there exists a $\{T_M, T_A, T_B\}=\{\tau_M,\tau_A,\tau_B\}$ such that the first-best outcome is attained and there exists a $\tilde x\in[0,x^*)$ such that $U(U^{-1}(\bar U(\tilde x))+\beta G(\tilde x))-\tilde x > U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*$. Since first-best is assumed to exist, from Condition 2 we have that $\min\{U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*,\, U(\tau_B)-x^*\}=0$. This implies that $U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*\geq 0$ and $U(\tau_B)-x^*\geq 0$. Since $U(U^{-1}(\bar U(\tilde x))+\beta G(\tilde x))-\tilde x > U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*$ and $\tilde x<x^*$, if the provider invests $\tilde x<x^*$, its utility is $\min\{U(U^{-1}(\bar U(\tilde x))+\beta G(\tilde x))-\tilde x,\, U(\tau_B)-\tilde x\} > \min\{U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*,\, U(\tau_B)-x^*\}=0$; hence, the client cannot attain the first-best outcome. Finally, let us assume that there exists a $\{T_M, T_A, T_B\}=\{\tilde\tau_M,\tilde\tau_A,\tilde\tau_B\}$ such that the first-best outcome is attained and $U(U^{-1}(\bar U(x))+\beta G(x))-x\leq U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*$ $\forall\, x\in[0,x^*)$. We need to show that it must be that $U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*=0$. Clearly it cannot be the case that $U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*<0$, because then $\min\{U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*, U(T_B)-x^*\}<0$, which violates the participation constraint of the provider. If $U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*>0$, then there exists a $\epsilon\to 0^+$ such that $U(U^{-1}(\bar U(x^*-\epsilon))+\beta G(x^*-\epsilon))-(x^*-\epsilon)>0$ because of the continuity of the function $h(x)=U(U^{-1}(\bar U(x))+\beta G(x))-x$. Since first-best is assumed to exist, from Condition 2 we have that $\min\{U(U^{-1}(\bar U(x^*))+\beta G(x^*))-x^*,\, U(\tilde\tau_B)-x^*\}=0$. This implies that $U(\tilde\tau_B)-x^*\geq 0$. Since $U(U^{-1}(\bar U(x^*-\epsilon))+\beta G(x^*-\epsilon))-(x^*-\epsilon)>0$ and $\tilde x<x^*$, if the provider invests $x^*-\epsilon$, its utility is $\min\{U(U^{-1}(\bar U(x^*-\epsilon))+\beta G(x^*-\epsilon))-(x^*-\epsilon)>0,\, U(\tilde\tau_B)-x^*+\epsilon\}>\min\{0, U(\tilde\tau_B)-x^*\}=0$; hence the client cannot attain the first-best outcome as the Condition 2 is violated. Therefore, (12) gives the necessary and sufficient condition for the attainment of the first-best outcome. Substituting $G(x)$ in (12) yields the necessary and sufficient condition stated in the proposition. □

Proof of Proposition 2. (i) When $\beta=1$, (9) reduces to

$$\exists T_M, T_A \quad \text{s.t.}\ \frac{dU(T_M g(x)+T_A)}{dx}-1\geq 0, \quad \forall\, x\in[0,x^*], \tag{14}$$

and (10) is satisfied by setting $T_A=U^{-1}(x^*)-T_M g(x^*)$. Since $U(\cdot)$ and $g(\cdot)$ are strictly increasing and concave, (14) is satisfied if $U'(U^{-1}(x^*))T_M g'(x^*)\geq 1$. This is always satisfied by setting $T_M=1/(U'(U^{-1}(x^*))g'(x^*))$.

(ii) When $0<\beta<1$, from Jensen's inequality, we have that $\bar U(x)\leq U(T_M g(x)+T_A)$. For $T_M\geq 0$, $U(T_M+T_A)g(x)+U(T_A)(1-g(x))\geq U(T_A)$ since $U(\cdot)$ is increasing. Therefore, we have $T_A\leq U^{-1}(\bar U(x))\leq T_M g(x)+T_A$. Substituting this in (10) yields

$$U^{-1}(x^*)-T_M g(x^*)\leq T_A\leq U^{-1}(x^*)-T_M g(x^*)\beta.$$

Therefore, given a finite $T_M\geq 0$, there exists a finite T_A that ensures that (10) is satisfied. The inequality in condition (9) can be expanded as

$$U'(\tilde T_A)\left[\beta T_M g'(x)+(1-\beta)\frac{d}{dx}U^{-1}(\bar U(x))\right]\geq 1, \quad \forall\, x\in[0,x^*]. \tag{15}$$

This expression can be further expanded as

$$U'(\tilde T_A)\left[\beta T_M g'(x)+(1-\beta)\frac{g'(x)[U(T_M+T_A)-U(T_A)]}{U'(U^{-1}(\bar U(x)))}\right]\geq 1, \quad \forall\, x\in[0,x^*].$$

Note that because $U(\cdot)$ is concave and increasing, we have $U'(\tilde T_A)\geq U'(U^{-1}(x^*))>0$. Also, since $T_M>0$, $U(T_M+T_A)>U(T_A)$, and by assumption, $g'(x)>0$ $\forall\, x\in[0,\infty)$ and $g(\cdot)$ is concave. Therefore, it is easy to see that there exists a finite $T_M=\bar T_M$ such that $\beta\bar T_M+(1-\beta)\Lambda(\bar T_M)=1/(U'(U^{-1}(x^*))g'(x^*))$, where $\Lambda(\bar T_M)=[U(\bar T_M+U^{-1}(x^*))-x^*]/(U'(U^{-1}(x^*)-\bar T_M g(x^*)))>0$, and this satisfies the sufficient conditions. Note that setting T_M such that $T_M=1/(U'(U^{-1}(x^*))g'(x^*)\beta)$ is also a (conservative) sufficient condition to show that (15) can be satisfied. □

Proof of Proposition 3. When $\beta=0$, from Proposition 1, the necessary and sufficient conditions for attaining the first-best solution are given by

$$\bar U(x)-x\leq 0 \quad \forall\, x\in[0,x^*), \tag{16}$$

$$\bar U(x^*)=x^*. \tag{17}$$

From Equation (17), we have

$$U(T_M+T_A)=\frac{x^*}{g(x^*)}-U(T_A)\left(\frac{1}{g(x^*)}-1\right). \tag{18}$$

Since $g(\cdot)$ is an increasing and concave function, Equation (16) can then be rewritten as

$$\frac{d}{dx}\bar{U}(x)\geq 1 \;\Rightarrow\; U(T_M+T_A)-U(T_A)\geq \frac{1}{g'(x^*)} \quad \forall\, x\leq x^*. \tag{19}$$

Substituting the terms for $U(T_M+T_A)$ and $U(T_A)$ from (18) in (19), $T_H=T_M+T_A$, and $T_A=T_L$ gives us the desired bounds for the utility values. □

Proof of Proposition 4. The utilities of the provider from a buyout options contract are given by

$$U_P^1(x)=\kappa(x,T_1)-x,$$
$$U_P^2(x)=U(T_2)-x.$$

As before, let $V(x)$ be the optimal value of the outcome after the research stage, if the outcome of the research stage is successful. That is, $V(x)=\max_{y\geq 0}E[\phi\mid x,y]-y$. Similar to the case in §4.1, a potential holdup may take place in this case if the client does not exercise option 2—which exposes the risk-averse provider to a stochastic reward from the outside option, in which case both the provider and the client are mutually better off by renegotiating option 1 to a fixed-fee contract $\tilde{T}_1$. The total surplus of such a renegotiation is

$$\begin{aligned} G(x) &= [V(x)g(x)-x]-[U^{-1}(\kappa(x,T_1))-T_1-x] \\ &= V(x)g(x)+T_1-U^{-1}(\kappa(x,T_1)). \end{aligned}$$

Similar to Edlin and Hermalin (2000), we assume that the R&D partnership is valuable or $V(x)g(x)\geq U^{-1}(\kappa(x,T_1))-T_1$. Therefore, $G(x)\geq 0$. Similar to Proposition 1, if the client does not exercise option 2, then option 1 will be renegotiated to a fixed-fee contract ($\tilde{T}_1$) such that $\tilde{T}_1=U^{-1}(\kappa(x,T_1))+\beta G(x)$, where the client buys back the IP of the research stage from the provider by paying it $\tilde{T}_1$. Therefore, because of the holdup problem, which may lead to potential renegotiation, the provider solves the following problem:

$$\max_{x\geq 0}\min\big\{U(U^{-1}(\kappa(x,T_1))+\beta G(x))-x,\,U(T_2)-x\big\}. \tag{20}$$

The client's problem can be stated as follows:

$$\max_{T_1,T_2}\ \big\{\big[E[\phi\mid\tilde{x},\tilde{y}(\tilde{x})]-\tilde{y}(\tilde{x})\big]g(\tilde{x}) - \min\big\{U^{-1}(\kappa(\tilde{x},T_1))+\beta G(\tilde{x}),T_2\big\}\big\} \tag{21}$$

$$\text{s.t.}\quad \tilde{y}(x)=\arg\max_{y\geq 0}[E[\phi\mid x,y]-y]g(x) - \min\big\{U^{-1}(\kappa(x,T_1))+\beta G(x),T_2\big\}, \tag{22}$$

$$\tilde{x}=\arg\max_{x\geq 0}\min\big\{U(U^{-1}(\kappa(x,T_1))+\beta G(x))-x,\ U(T_2)-x\big\}, \tag{23}$$

$$\min\big\{U(U^{-1}(\kappa(\tilde{x},T_1))+\beta G(\tilde{x}))-\tilde{x},U(T_2)-\tilde{x}\big\}\geq 0. \tag{24}$$

If the provider invests x^*, then the client's problem is

$$\max_{y\geq 0}\big\{E[\phi\mid x^*,y]-y\big\}. \tag{25}$$

Comparing (25) and (1) confirms that the client makes the first-best investment y^*. Therefore, we need to derive conditions such that the provider invests x^* and that Condition 2 (above) is satisfied. Our claim is that to attain the first-best outcome we need to show that for a given $M(x)$, the following condition is necessary and sufficient:

$$\begin{aligned} \exists\, T_1 \quad \text{s.t. } & U\big(U^{-1}(\kappa(x,T_1))+\beta G(x)\big)-x \\ & \leq U\big(U^{-1}(\kappa(x^*,T_1))+\beta G(x^*)\big)-x^*=0, \\ & \forall\, x\in[0,x^*). \end{aligned} \tag{26}$$

To show sufficiency, let us assume that (26) is satisfied for some T_1. Set T_2 such that

$$U(T_2)-x^*=0. \tag{27}$$

Equations (26) and (27) ensure that the provider will not invest $x\neq x^*$. Assume that the provider invests $x<x^*$. In this case the provider's utility is

$$\begin{aligned} &\min\big\{U(U^{-1}(\kappa(x,T_1))+\beta G(x))-x,\,U(T_2)-x\big\} \\ &\quad = U(U^{-1}(\kappa(x,T_1))+\beta G(x))-x\leq 0 \quad \text{(from (26))}. \end{aligned}$$

Assume that the provider invests $x>x^*$. In this case the provider's utility is

$$\begin{aligned} &\min\big\{U(U^{-1}(\kappa(x,T_1))+\beta G(x))-x,\,U(T_2)-x\big\} \\ &\quad \leq U(T_2)-x<0 \quad \text{(from (27))}. \end{aligned}$$

Hence, the provider will invest $x=x^*$ because deviating is not beneficial.

Next we will show that (26) is also necessary for the attainment of the first-best outcome. Let us assume that there exists a $\{T_1,T_2\}=\{\tau_1,\tau_2\}$ such that the first-best outcome is attained and there exists a $\tilde{x}\in[0,x^*)$ such that $U(U^{-1}(\kappa(\tilde{x},\tau_1))+\beta G(\tilde{x}))-\tilde{x}>U(U^{-1}(\kappa(x^*,\tau_1))+\beta G(x^*))-x^*$. Since first-best is assumed to exist, we have that $\min\{U(U^{-1}(\kappa(x^*,\tau_1))+\beta G(x^*))-x^*,\ U(\tau_2)-x^*\}=0$. This implies that $U(U^{-1}(\kappa(x,\tau_1))+\beta G(x^*))-x^*\geq 0$ and $U(\tau_2)-x^*\geq 0$. Since $U(U^{-1}(\kappa(\tilde{x},\tau_1))+\beta G(\tilde{x}))-\tilde{x}>U(U^{-1}(\kappa(x^*,\tau_1))+\beta G(x^*))-x^*$ and $\tilde{x}<x^*$, if the provider invests $\tilde{x}<x^*$, its utility is $\min\{U(U^{-1}(\kappa(\tilde{x},\tau_1))+\beta G(\tilde{x}))-\tilde{x},U(\tau_2)-\tilde{x}\}>\min\{U(U^{-1}(\kappa(x^*,\tau_1))+\beta G(x^*))-x^*,\,U(\tau_2)-x^*\}=0$; hence the client cannot attain the first-best outcome. Finally, Let us assume that there exists a $\{T_1,T_2\}=\{\tilde{\tau}_1,\tilde{\tau}_2\}$ such that the first-best outcome is attained and $U(U^{-1}(\kappa(x,\tilde{\tau}_1))+\beta G(x))-x\leq U(U^{-1}(\kappa(x^*,\tilde{\tau}_1))+\beta G(x^*))-x^*\ \forall\, x\in[0,x^*)$. We need to show that it must be that $U(U^{-1}(\kappa(x^*,\tilde{\tau}_1))+\beta G(x^*))-x^*=0$. Clearly it cannot be the case that $U(U^{-1}(\kappa(x^*,\tilde{\tau}_1))+\beta G(x^*))-x^*<0$ because then $\min\{U(U^{-1}(\kappa(x^*,\tilde{\tau}_1))+\beta G(x^*))-x^*,U(\tilde{\tau}_2)-x^*\}<0$, which violates the participation constraint of the provider. If $U(U^{-1}(\kappa(x^*,\tilde{\tau}_1))+\beta G(x^*))-x^*>0$, then there exists a $\epsilon\to 0^+$ such that $U(U^{-1}(\kappa(x^*-\epsilon,\tilde{\tau}_1))+\beta G(x^*-\epsilon))-(x^*-\epsilon)>0$ because of the continuity of the function $h(x)=U(U^{-1}(\kappa(x,\tilde{\tau}_1))+\beta G(x))-x$. Since first-best is assumed to exist, from Condition 2 we have that $\min\{U(U^{-1}(\kappa(x^*,\tilde{\tau}_1))+\beta G(x^*))-x^*,U(\tilde{\tau}_2)-x^*\}=0$. This implies that $U(\tilde{\tau}_2)-x^*\geq 0$. Since $U(U^{-1}(\kappa(x^*-\epsilon,\tilde{\tau}_1))+\beta G(x^*-\epsilon))-(x^*-\epsilon)>0$ and $\tilde{x}<x^*$, if the provider invests $x^*-\epsilon$, its utility is $\min\{U(U^{-1}(\kappa(x^*-\epsilon,\tilde{\tau}_1))+\beta G(x^*-\epsilon))-(x^*-\epsilon),U(\tilde{\tau}_2)-x^*+\epsilon\}>\min\{0,U(\tilde{\tau}_2)-x^*\}=0$; hence the client cannot attain the first-best outcome. Therefore, (26) gives the necessary and sufficient condition for the attainment of the first-best outcome. Substituting $G(x)$ in (26) yields the necessary and sufficient condition stated in the proposition.

When $\beta = 1$, (26) reduces to

$$\exists\, T_1 \quad \text{s.t. } U(V(x)g(x)+T_1)-x \le U(V(x^*)g(x^*)+T_1)-x^* = 0 \quad \forall\, x \in [0, x^*). \tag{28}$$

Set $T_1 = U^{-1}(x^*) - V(x^*)g(x^*)$. Taking the derivative of $U(V(x)g(x)+T_1)-x$ at x^* yields

$$U'(U^{-1}(x^*))\frac{dV(x)g(x))}{dx}\bigg|_{x=x^*} - 1.$$

From (2) it follows that the derivative of $U(V(x)g(x)+T_1)-x$ is zero at x^*. Therefore, condition (28) follows from the ideally quasiconcavity of $U(V(x)g(x)+T_1)-x$.

When $\beta < 1$, for (26) to be satisfied, it is necessary that the slope of $U(U^{-1}(\kappa(x, T_1))+\beta G(x))-x$ be positive at x^*. Therefore, the necessary condition for (26) to hold is

$$\frac{dU(U^{-1}(\kappa(x, T_1))+\beta G(x))}{dx}\bigg|_{x=x^*} \ge 1. \tag{29}$$

Simplifying (29) yields

$$U'(U^{-1}(x^*))\left(\beta\frac{dV(x)g(x)}{dx}\bigg|_{x=x^*} + (1-\beta)\frac{dU^{-1}(\kappa(x, T_1))}{dx}\bigg|_{x=x^*}\right) \ge 1. \tag{30}$$

Using (2), (30) simplifies further as

$$\frac{dU^{-1}(\kappa(x, T_1))}{dx}\bigg|_{x=x^*} \ge \frac{1}{U'(U^{-1}(x^*))} = \frac{dV(x)g(x)}{dx}\bigg|_{x=x^*}. \quad \square \tag{31}$$

Proof of Proposition 5. From Proposition 3, milestone-based options contracts do not attain the first-best solution when $\beta = 0$, and the two conditions in Proposition 3 are not satisfied ((32) and (33)).

$$\exists\, \tilde{T}_1, \tilde{T}_2 \quad \text{s.t.}$$

$$U(\tilde{T}_1) \ge x^* + \frac{1-g(x^*)}{g'(x^*)}, \tag{32}$$

$$U(\tilde{T}_2) \le x^* - \frac{g(x^*)}{g'(x^*)}. \tag{33}$$

Therefore, when $\beta = 0$, (32) and (33) are not satisfied, and there exists a T_1 such that $\{\kappa(x^*, T_1) = x^*, d\kappa(x, T_1)/dx \ge 1\ \forall\, x \in [0, x^*)\}$, then milestone-based options contracts do not attain the first-best outcome, whereas buyout options contracts do. Similarly, when $\beta = 0$, (32) and (33) are satisfied, and there does not exist a T_1 such that $(d\kappa(x, T_1)/dx)|_{x=x^*} \ge 1$, then milestone-based options contracts attain the first-best outcome, whereas buyout options contracts do not do so. $\square$

Functions and Parameters Values for Numerical Example. We assume the following functional forms for all the numerical examples presented in the paper:

$$g(x) = 1 - e^{-\alpha x}, \qquad f(\phi, x, y) = \lambda(x, y)e^{-\lambda(x, y)\phi},$$
$$1/\lambda(x, y) = \mu x^\gamma y^\theta, \qquad U(z) = \eta(1 - e^{\zeta z}).$$

The parameter values assumed are $\gamma = 9 \times 10^{-4}$, $\theta = 0.7$, $\mu = 500$, $\alpha = 5.0 \times 10^{-8}$, $\zeta = 4 \times 10^{-8}$, and $\eta = 10^7$. With these functions and parameters, we have $x^* = 5.23 \times 10^6$, $y^* = 3.16 \times 10^8$, $g(x^*) = 0.23$, and $E[\phi] = \mu(x^*)^\gamma(y^*)^\theta = 4.52 \times 10^8$.

References

Bhaskaran SR, Krishnan V (2009) Effort, revenue and cost sharing mechanisms for collaborative new product development. *Management Sci.* 55(7):1152–1169.

Bhattacharyya S, Lafontaine F (1995) Double-sided moral hazard and the nature of share contracts. *RAND J. Econom.* 26(4):761–781.

Bhattacharya S, Gupta A, Hasija S (2014) Joint product improvement by client and customer support center: The role of gain-share contracts in coordination. *Inform. Systems Res.* 25(1):137–151.

Corbett CJ, Decroix GA, Ha AY (2005) Optimal shared-savings contracts in supply chains: Linear contracts and double moral hazard. *Eur. J. Oper. Res.* 163(3):653–667.

Cornelli F, Yosha O (2003) Stage financing and the role of convertible securities. *Rev. Econom. Stud.* 70(1):1–32.

Crama P, De Reyck B, Degraeve Z (2008) Milestone payments or royalties? Contract design for R&D licensing. *Oper. Res.* 56(6):1539–1552.

Deloitte (2009) Partnering strategies in life sciences R&D. Research report. http://www.deloitte.com/assets/Dcom-Luxembourg Local%20Assets/Documents/Whitepapers/2009/dtt_wp_partneringstrategieslsrd_2009.pdf.

Demski JS, Sappington DEM (1991) Resolving double moral hazard problems with buyout agreements. *RAND J. Econom.* 22(2):232–240.

Derman C, Lieberman GJ, Ross SM (1975) A stochastic sequential allocation model. *Oper. Res.* 23(6):1120–1130.

DuPont (2007) DuPont and Plantic announce starch-based biomaterials alliance. Press release, September 26, http://www2.dupont.com/Biomax/en_US/plantic_pr.html.

Edlin A, Hermalin BE (2000) Contract renegotiation and options in agency problems. *J. Law, Econom., Organ.* 16(2):395–423.

Edlin A, Hermalin BE (2001) Implementing the first best in an agency relationship with renegotiation: A corrigendum. *Econometrica* 69(5):1391–1395.

Eisenhardt KM (1989) Agency theory: An assessment and review. *Acad. Management Rev.* 14(1):57–74.

Erat S (2006) Joint product development and inter-firm innovation. Unpublished doctoral dissertation, Georgia Institute of Technology, Atlanta.

Federal Aviation Administration (FAA) (2009) Design approvals. Accessed June 2013, http://www.faa.gov/aircraft/air_cert/design_approvals/.

Gilbert SM, Cvsa V (2003) Strategic commitment to price to stimulate downstream innovation in a supply chain. *Eur. J. Oper. Res.* 150(3):617–639.

Graves SC, Willems SP (2005) Optimizing the supply chain configuration for new products. *Management Sci.* 51(8):1165–1180.

Grossman SJ, Hart OD (1986) The costs and benefits of ownership: A theory of vertical and lateral integration. *J. Political Econom.* 94(4):691–719.

Hagedoorn J, Roijakkers N (2006) Inter-firm R&D partnering in pharmaceutical biotechnology since 1975: Trends, patterns, and networks. *Res. Policy* 35(3):431–446.

Havrilla M (2012) Supernus Pharma: A recent IPO awaiting pair of FDA decisions. *Seeking Alpha* (June 12), http://seekingalpha.com/article/653671-supernus-pharma-a-recent-ipo-awaiting-pair-of-fda-decisions.

Hermalin BE, Katz ML (1991) Moral hazard and verifiability: The effects of renegotiation in agency. *Econometrica* 59(6):1735–1753.

Holmstrom B (1982) Moral hazard in teams. *Bell J. Econom.* 13(2):324–340.

Iyer AV, Schwartz LB, Zenios SA (2005) A principal-agent model for product specification and production. *Management Sci.* 51(1):106–119.

Iyer G, Villas-Boas JM (2003) A bargaining theory of distribution channels. *J. Marketing Res.* 40(1):80–100.

Joglekar NR, Yassine AA, Eppinger SD, Whitney DE (2001) Performance of coupled product development activities with a deadline. *Management Sci.* 47(12):1607–1620.

Jones E (2009) Onyx claims breach of contract against Bayer. *Drug Industry Daily* 8(97):15–17.

Kawasaki, S, Macmillan J (1987) The design of contracts: Evidence from Japanese subcontracting. *J. Japanese Internat. Econom.* 1(3):327–349.

Krishnan A (2011) Amylin secures "restraining order" against Eli Lilly. *IHS Global Insight Daily Anal.* 205.

Laffont JJ, Martimort D (2001) *The Theory of Incentives* (Princeton Publishing House, Princeton, NJ).

Lovejoy WS (2010) Bargaining chains. *Management Sci.* 56(12): 2282–2301.

Lulfesmann C (2004) Research collaborations with sequential investments. *Economica* 71(282):241–259.

Mihm J (2010) Incentives in new product development projects and the role of target costing. *Management Sci.* 56(8):1324–1344.

Miller J (2007) Stall out in R&D outsourcing. *Pharma Tech* (July 2), http://www.pharmtech.com/pharmtech/Outsourcing,+contract+services/Stall-Out-in-RampD-Outsourcing/ArticleStandard/Article/detail/437496.

Nicholas Piramal (2007) Nicholas Piramal announces drug discovery and development agreement with Merck. Press release, November 19, http://www.fiercebiotech.com/press-releases/press-release-nicholas-piramal-announces-drug-discovery-and-development-agreement-mer.

Nöldeke G, Schmidt KM (1998) Sequential investments and options to own. *RAND J. Econom.* 29(4):633–653.

Plambeck EL, Taylor TA (2007) Implications of breach remedy and renegotiation for innovation and capacity. *Management Sci.* 53(12):1859–1871.

PR Newswire (1996) Ligand elects to receive milestone payments from Pfizer in Ligand common stock; Ligand could retire over 101,000 shares. (May 7), http://www.thefreelibrary.com/LIGAND+ELECTS+TO+RECEIVE+MILESTONE+PAYMENTS+FROM+PFIZER+IN+LIGAND...-a018266631.

Robinson DT, Stuart TE (2007) Financial contracting in biotech strategic alliances. *J. Law Econom.* 50(3):559–595.

Roels G, Karmarkar US, Carr S (2010) Contracting for collaborative services. *Management Sci.* 56(5):849–863.

Sahoo A (2008) *Successful Pharmabiotech Alliance Strategies: Driving Synergies, Avoiding Failure and Managing Relationships* (Business Insights, London).

Shire (2009) FDA approves Intuniv. Accessed June 2013, http://www.drugs.com/history/intuniv.html.

Supernus (2012) Supernus Pharmaceuticals IPO prospectus. SEC Registration 333-171375, pursuant to Rule 424(b)(4). Last accessed May 26, 2014, http://www.sec.gov/Archives/edgar/data/1356576/000104746912005169/a2209285z424b4.htm.

Swinney R, Cachon GP, Netessine S (2011) Capacity investment timing by startups and established firms in new markets. *Management Sci.* 57(4):763–777.

Taylor TA, Plambeck EL (2007a) Simple relational contracts to motivate capacity investment: Price only vs. price and quantity. *Manufacturing Services Oper. Management* 9(1):94–113.

Taylor TA, Plambeck EL (2007b) Supply chain relationships and contracts: The impact of repeated interaction on capacity investment and procurement. *Management Sci.* 53(10):1577–1593.

U.S. Congress, Office of Technology Assessment (1993) *Pharmaceutical R&D: Costs, Risks and Rewards, OTA-H-522*, (U.S. Government Printing Office, Washington, DC).

Villiger R, Bogdan B (2005) Getting real about valuations in biotech. *Nature Biotechnology* 23(4):423–428.

Xiao W, Xu Y (2012) The impact of royalty contract revision in a multistage strategic R&D alliance. *Management Sci.* 58(12): 2251–2271.