The Role of Milestone-Based Contracts for Coordinating R&D Partnerships

(Authors’ names blinded for peer review)

We analyze optimal contractual arrangements in a bilateral 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 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.

Key words: R&D partnerships, options contracts, double-sided moral hazard, holdup, risk preference

1. Introduction

Firms have traditionally relied on internal R&D to maintain their technological competitiveness. However, in recent years, firms are increasingly sourcing new knowledge externally by pursuing R&D and innovation in a collaborative and interactive environment, embedded in their supply, production, and distribution networks. According to the Cooperative Agreements and Technology Indicators (CATI) 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. While in the 1980s most of these were equity alliances, today 96% of these R&D alliances are non-equity 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 (nicholaspiramal.com 2007): Nicholas Piramal will be eligible to receive milestone payments of up to $175 million per target, plus royalties on sales resulting from this collaboration. 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 while 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. Our goal is to investigate contractual structures that can overcome some of the agency issues prevalent in such partnerships. Specifically, we focus on three agency issues motivated mainly by our observations of R&D collaborations across different settings: First, the 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. This may lead to suboptimal investments inducing inefficiencies in these R&D partnerships. In the pharmaceutical industry, a report by the U.S. Congress Office of Technology Assessment\(^1\) (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, non-verifiability of investments in R&D is an important feature of this process leading to double-sided moral hazard.

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

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\(^1\) The Office of Technology Assessment is a division of the Federation of American Scientists, an independent, non-partisan think tank, that provides analysis and practical policy recommendations on issues related to science and technology.
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 under invest (Gilbert and Cvsa 2003, Erat 2006, Edlin and Hermalin 2000).

Third, the contract design problem is further complicated by the fact that small and specialized research organizations (henceforth referred to as providers) with owner-managers are risk-averse relative to publicly owned large firms who contract out parts of their research portfolios (henceforth referred to as clients), and have significant resources and an easy access to liquid capital markets (Eisenhardt 1989). Unlike providers, such as biotech firms in the pharmaceutical industry, clients such as big pharmaceutical firms also have well diversified R&D portfolios. 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.

In this paper, we study the efficacy of milestone payments in designing contracts that resolve the agency issues discussed above. We formulate the problem using a very general model, as a sequential investment game with double-sided moral hazard. The provider performs the initial research stage activities, while the client performs the development, integration and manufacturing activities. We assume that the investments made by the two firms are observable but not verifiable (cf. Noldeke and Schmidt 1998). Based on our observations of contracts in the industry, we compare the efficacy of milestone-based options contracts and buyout options contracts in coordinating the efforts of the two parties. Our setup includes two important practice-driven features of R&D processes: (i) we model the regulatory verification stage that follows the research stage and precedes the development stage and, (ii) we model the risk aversion of the provider. 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 pre-specified value.

Such a sequence of R&D process is valid in a number of industries. For example, in the pharmaceutical industry, biotech firms develop molecules in the early-stage development of a drug, FDA approval is the intermediate regulatory verification stage, and subject to approval, the pharmaceutical firm focuses on the late-stage development, including production, distribution, and marketing of the drug. Another example of regulatory approval is FAA (Federal Aviation Administration) approval for the design of propeller systems, engines and auxiliary power units for aircraft (FAA 2009). The sequence of events in our setting are summarized in Figure 1.

Our results are as follows. When milestone-based options contracts are used, we show that the first-best outcome will be obtained always if the provider has some bargaining power in renegotiation.

\[^2\]Henceforth, the issues of double-sided moral hazard, holdup, and risk aversion will be referred to as the set of relevant agency issues.
Figure 1 Timeline and sequence of events in the model

In contrast, if the provider has no bargaining power in renegotiation, the client may obtain the first-best solution in some restricted situations. 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.

To the best of our knowledge, this paper is the first to show the role of milestone payment-based contracts in overcoming multiple agency issues relevant to R&D partnerships.

To benchmark the performance of the milestone-based options contracts, we compare their efficacy to buyout options contracts that have been studied in the literature (Edlin and Hermalin 2000). As reported in Edlin and Hermalin (2000), if the client uses buyout options contracts, then the first-best solution can always be attained only if the provider has all the bargaining power in renegotiation. If the bargaining power is shared between the provider and the client, then a necessary condition for the first-best outcome to be attained is that the value of the outside option is above a certain threshold. Hence, if the bargaining power in renegotiation is shared between the client and the provider, then milestone-based options contracts dominate buyout options contracts. The driver of this result is that milestone-based options contracts can leverage R&D process levers, like the intermediate regulatory approval, that increases the efficacy of such contracts.

In sum, our paper models three relevant agency issues motivated by practice and literature on R&D partnerships. We show that the risk aversion of the provider can be overcome and the first-best solution for the client can be achieved without a risk premium. An important contribution of our paper is that by taking into account characteristics of R&D processes such as intermediate verifiable outcomes, we can obtain 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.

3 Buyout options contracts provide the principal with an option of owning the asset and paying the agent a fixed fee, or transferring the ownership to the agent for a fixed fee.
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. Taylor and Plambeck (2007, a and b) are based on unilateral investments in single-period and multi-period games, and hence, very different from our model. Similarly, Gilbert and Cvs (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, as 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) have studied 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 their optimal allocated resources with adverse selection about the capability of the supplier. We contribute to this stream of research by studying milestone-based options contracts that are widely prevalent in healthcare R&D partnerships and identifying their efficacy for optimal contract design.

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. Cost-sharing contracts are better for radically new products with uncertainty in the timing of introduction, whereas effort-sharing contracts are better for symmetric firms working on projects with quality uncertainty. Our paper is different, as investments made by parties are not verifiable, which in turn create agency issues. In a new product co-development setting, Erat (2006) analyzes the impact of market and development uncertainty on the timing of contract negotiation, and show 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 co-production framework (Roels et al. 2010, Corbett et al. 2005). However, in the co-production 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 contrast, R&D partnerships frequently have a sequential investment setting, as the second-stage investments are made after regulatory verification is obtained. Therefore, options-based contracts can be used in our setting to achieve the first-best solution, and contracts not based on options and renegotiation that are used in the above mentioned studies do not attain the first-best solution.

In the economics literature, studies that characterize the use of options-based contracts in the sequential bilateral investment environment with non-verifiable investments are relevant to our setting (Noldeke and Schmidt 1998, Edlin and Hermalin 2000, Demski and Sappington 1991, Lulfesmann 2004). However, none of these studies model the specificity of the R&D process, in particular, intermediate verifiable outcomes, that are commonly observed in practice. For example, automobile engine design has to be approved by the EPA for emissions and ship designs have to be approved by regulatory bodies. We also model the risk-aversion of the provider (Villiger and Bogdan 2005, Schoonhoven et al. 1990). 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 (i) options-based contracts that are driven by milestone payments contingent on the outcome of the regulatory verification stage attain the first-best outcome in most cases if the provider has some bargaining power; and if the provider does not have bargaining power then the necessary condition for the first-best solution to be obtained is that the degree of risk aversion of the provider is below a threshold value. (ii) Buyout options-based contracts studied in these papers attain the first-best outcome only if the provider has all the bargaining power, or the outside option value of the provider is higher than a certain threshold value and the degree of risk aversion of the provider is below another threshold value (Edlin and Hermalin 2000). (iii) Unlike Demski and Sappington (1991), the optimal contracts proposed in this paper also resolve the holdup problem. The holdup issue has been shown to be resolved in games of repeated bargaining; Che and Sakovics (2004) show that the holdup issue can be resolved in a dynamic model of investment if parties renegotiate repeatedly until they obtain agreement in a sufficiently long horizon. In contrast, we adopt a one-stage renegotiation model (after the provider has sunk its investment). Rosenkranz and Schmitz (2003) show that the coordinated systems investments (first-best investments) can also be attained in a sequential move games by other power-sharing contracts like both parties having the right to use the asset from the partnership without the other’s consent, or both parties having veto power.
The main differences between our paper and the economics literature are as follows. Noldeke 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 Noldeke and Schmidt (1998) do not obtain the first-best solution. Further, buyout options contracts with early exercise dates studied in Demski and Sappington (1991) do not solve the holdup problem, as the principal (second mover) can lower the incentive for the agent (first mover) to invest optimally due to the holdup problem (as shown by Edlin and Hermalin 2000). 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 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 highlights (i) 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. At time $t = 0$, the client (principal) offers a contract to the provider (agent) with different incentive structures. 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 $x \in \mathbb{R}^+$ 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 EPA approval in the chemicals and oil and gas industries, and FAA (Federal Aviation Administration) 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 $y \in \mathbb{R}^+$ in the development stage. The final reward $\phi$ from introducing the new product on the market (net profits and IP rights) accrues at time $t = 4$. We assume that $\phi$ has support in the interval $\Phi$, and has a pdf of $f(\phi|x,y)$ and a cdf of $F(\phi|x,y) = \int_0^\phi f(\theta|x,y)d\theta$. We make the following assumptions about the model parameters:

Assumption 1: $g(x)$ 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 and Lieberman 1975).

**Assumption 2:** \( \phi = 0 \) w.p.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, \( E[\phi|x,y] \) is increasing in \( x \) and \( y \).

**Assumption 3:** \( x \) 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 contractible. As discussed earlier, the observability (but not verifiability) implies that while each party can observe the other’s investments (explicit and tacit), these investments cannot be factually supported in a court of law.

**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 \( M(x) \geq 0 \)). \( M(x) \) is a function of the investment of the provider \( x \), as in the literature, we assume that \( x \) is observable to the third party. \( M(x) \) 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, page 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 Generalized Nash bargaining model, where the bargaining power during renegotiation of the provider is given by \( \beta \), 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 1995). In the pharmaceutical industry, as biotech firms are small, and have less diverse portfolios compared to pharmaceutical firms (Eisenhardt 1989, Kawasaki and Macmillan 1987), the evidence supports their being risk averse with concave utility functions. Data
from the pharmaceutical-biotech industry shows that biotech firms discount potential future risky payments to a larger extent (> 20%) compared to pharmaceutical firms (8-12%) (Villiger and Bogdan 2005); and smaller privately held firms in other industries focus on survival (Schoonhoven et al. 1990, Swinney et al. 2011).

4. Model Analysis
In this section, we study the efficacy of milestone-based options contracts. To analyze the performance of milestone-based 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 to pay the provider any risk-premium. Since 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,

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

Here $E[\phi|x, y] = \int_\phi \phi dF(\phi|x, y)$. 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, $V(x) = E[\phi | x, y^*(x)] - y^*(x)$. Similar to Edlin and Hermalin (2000), the following problem defines the first-best outcome for the client

$$\max_{x \in [0, \infty)} V(x)g(x) - T$$

s.t. $U(T) - x = 0$

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

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

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 $y^*(x^*)$ respective, 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, viz., 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 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, viz., 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 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\(^4\). 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 choose to 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 utilities of the provider from such an options contract are given by (Edlin and Hermalin 2000):

\[
U^A_P = U(T_M + T_A)g(x) + U(T_A)(1 - g(x)) - x \\
U^B_P = U(T_B) - x
\]

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,

\[
G(x) = [V(x)g(x) - \tilde{T}_A + \tilde{T}_A - x] - \\
[(V(x) - T_M)g(x) - T_A + U^{-1}(U(T_M + T_A)g(x) + U(T_A)(1 - g(x))) - x] \\
= T_Mg(x) + T_A - U^{-1}(U(T_M + T_A)g(x) + U(T_A)(1 - g(x))) - x \\
= T_Mg(x) + T_A - U^{-1}(U(T_M + T_A)g(x) + U(T_A)(1 - g(x))) \\
- x.
\]

\(^4\)Milestone-based options contracts may also include royalty terms. Our analysis and results are robust to such cases.
Here, the first term in the right-hand side of the equation above is the joint expected profit post renegotiation, and the second term is the joint expected profit before renegotiation. Let \( \tilde{U}(x) = U(T_M + T_A)g(x) + U(T_A)(1 - g(x)) \). Note that \( U^{-1}(\tilde{U}(x)) \) is the certainty equivalent of the uncertain total payment of the provider under Option A. It is straightforward to check that \( G(x) \geq 0 \) as \( U(T_M g(x) + T_A) \geq U(T_M + T_A)g(x) + U(T_A)(1 - g(x)) \) from Jensen’s inequality. \( G(x) \) has a very 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 \( \beta \), the provider will get \( \beta G(x) \) from the Generalized Nash Bargaining (GNB) result, which is a property of the GNB model. The Generalized Nash bargaining 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 \( \tilde{T}_A = U^{-1}(\tilde{U}(x)) + \beta G(x) \), where \( U^{-1}(\tilde{U}(x)) \) is the certainty equivalent of the uncertain payments to the provider under Option A and \( \beta G(x) \) is the provider’s share of the gains from renegotiation. Therefore, due to 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:

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

The client’s problem can be stated as follows:

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

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

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

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

The client’s problem is characterized by (5) at \( t=0 \) and (6) at \( t=3 \). The provider firm solves (7) at \( t=1 \), and (8) is the provider’s participation constraint. We examine if such a milestone-based options contract can attain the first-best solution, and 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 \( \exists T_M, T_A \) such that \( \forall x \in [0, x^*] \):

\[
U(\beta(T_M g(x) + T_A) + (1 - \beta)U^{-1}(\tilde{U}(x))) - x \leq U(\beta(T_M g(x^*) + T_A) + (1 - \beta)U^{-1}(\tilde{U}(x^*))) - x^* = 0.
\]
Here options A and B are:

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 post 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 2). 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 provides the client with 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 (as 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 while its mechanics require both the 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 as both players know that renegotiation will yield an outcome equivalent to option B.
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 provide the incentive to the provider to increase its investment under Option A to be equal to its first-best investment, while 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:

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

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. Since \( U(\cdot) \) is an increasing function, Equation (9) is always satisfied if \( \exists T_M \) such that \( \frac{d[U^{-1}(U(x)) + \beta G(x)]}{dx} \) 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\(^5\). This is an important result, as 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, as the holdup problem is alleviated. This result shows that the attainment of the first-best solution is reliant on the provider having some bargaining power during renegotiation; if the client has all the bargaining power after renegotiation, it may hinder the client’s ability to attain the first-best outcome.

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\(^5\) The condition on the bargaining power of the provider \( \beta \) ensures that the sufficient conditions for the attainment of the first-best outcome are satisfied, and hence is a conservative condition.
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 $\exists T_H, T_L$ s.t. $U(T_H) \geq x^* + \frac{1-x^*}{g'(x^*)}$ and $U(T_L) \leq x^* - g(x^*)$.

Proposition 3 shows that if the provider does not have any bargaining power, the client can only attain the first-best solution if the conditions in Proposition 3 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 invest 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, as 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 (Demski and Sappington 1991, Edlin and Hermelin 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 intellectual property (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 Hermelin 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 Hermelin 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 $\exists T_1$ such that $\forall x \in [0,x^*)$:

$$U(\beta(V(x)g(x) + T_1) + (1 - \beta)U^{-1}(\kappa(x,T_1))) - x \leq U(\beta(V(x^*)g(x^*) + T_1) + (1 - \beta)U^{-1}(\kappa(x^*,T_1))) - x^* = 0.$$  

(ii) The above condition is always satisfied if $\beta=1$ and $U(V(x)g(x) + T_1) - x$ is ideally quasi-concave in $x$, which implies that the provider has all the bargaining power in renegotiation. If $\beta < 1$, then a necessary condition for the first-best solution to be attained is given by:

$$\left.\frac{dU^{-1}(\kappa(x,T_1))}{dx}\right|_{x^*} \geq \left.\frac{dV(x)g(x)}{dx}\right|_{x^*} = \frac{1}{U'(U^{-1}(x^*))}.$$  

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 an identical condition to Proposition 4 (condition 4) in Edlin and Hermalin (2000)$^6$, which states that the 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 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)$^7$. When $0 < \beta < 1$, milestone options contracts always attain the first-best solution (from Proposition 2), while 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 increases the efficacy of such contracts. We now compare explicitly the efficacy of milestone options contracts and buyout options contracts when $\beta = 0$ explicitly in Proposition 5.

**Proposition 5:** If $\beta = 0$, then milestone 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 options contracts cannot do so.

$^6$Note that there is an added term of $g(x)$ in this expression, all other terms in the necessary condition are the same.

$^7$Note that milestone-based options attain the first-best outcome more generally, as we do not need to impose any other conditions such as ideal quasi-concavity.
Interestingly, it is not possible for milestone 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. While the milestone options contract relies on the shape of the utility function of the provider ($U$) and the shape of the probability of successful outcome function $g(x)$ (Proposition 3), 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 milestone-based options contract provides the client with 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, then 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 options contracts

In this section, we discuss the ease of implementation of the proposed milestone options contracts in practice. First, we note that the fixed fee in the first option for the options contracts ($T_A$ in the milestone options contract) can be negative. Note that is true for buyout options contracts as well, as $T_1$ in the buyout options contract can 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 negatively correlated with the efficacy of the options contract. While milestone options contracts can attain the first-best solution by providing a high 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 same is true for buyout options contracts as well when they attain the first-best solution, if the profit from the external option is high, then a high negative fixed fee has to be set to make the provider’s participation constraint tight.

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. One way to ensure this is by assuming that the provider’s net asset value, $\Omega$, is more than the negative fixed fee (Holmstrom 1982). If however, it is the case that $\Omega$ is less than the negative fixed fee, then the milestone-based options contract discussed in the paper will not attain the first-best outcome for the client. This is a limitation of such an options contract. In this case, to ensure that the provider

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Footnote 8: 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.
exerts the first-best effort, $x^*$, the client will have to leave it with a surplus equal to $-T_A - \Omega$. Note that, if the provider has a positive reservation value ($\omega$), then the surplus paid to the provider reduces to $-T_A - \Omega - \omega$. We chose not to model the positive reservation value in the paper as it has no role to play in the game apart from providing a higher normalizing value for the provider.

For the implementation of milestone-based options contracts, we make a few important observations. It will never be the case that the client exercise Option A in its original form. Below, we provide a discussion on why the client will not do so for both on- and off-equilibrium outcomes. First, the Option A, with the potential negative fixed fee ($T_A$), is not exercised in equilibrium, as the equilibrium outcome has the client exercising Option B, with a positive fixed fee ($T_B$). It is important to note that the exercise date of the option is before any uncertainty is realized in the system, i.e., the observation of the outcome of the research stage. Hence, Option B is exercised with probability 1, if the provider makes her utility-maximizing decision. Second, if the axiomatic conditions for the game are violated and the provider invests a smaller effort than $x^*$, then even in that case, the client renegotiates with the provider and offers it a fixed fee before the observation of the outcome of the research stage with a probability of 1. In Figure 3, we plot the transfer payment from the client to the provider after renegotiation, the transfer payment made is the lower envelope of the fixed transfer payments under options A and B. From Figure 3, note that (i) the transfer payment is continuous, and (ii) the net transfer payment to the provider are positive for a fairly large deviation from the optimal effort of the provider. We have conducted some sensitivity analyses on the region where the client makes net positive transfer payments to the provider, and find that it is increasing in $\beta$, and decreasing in the range of values of the utility function $U$. Finally, for the milestone options contract, the magnitude of the negative fixed fee is decreasing in the bargaining power of the provider in renegotiation $\beta$ (from Propositions 1 and 2), and if the utility function is bound tightly (Proposition 3).

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 the first-best outcome if some conditions are met, and we characterize those conditions.

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: when buyout options can attain the first-best solution, milestone-based options contracts can also attain the first-best solution. However, the reverse is not true, as there are cases where the milestone-based options contracts attain the first-best solution, however, buyout options contracts do not attain the first-best solution. 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 options contracts and buyout options contracts can attain the first-best solution in restricted domains, and we characterize those domains.

We also have additional insights that are not presented in the paper for brevity. First, for both the milestone-payment based options contract and buyout options contract, 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), as the provider has to be paid a risk premium.
Second, it is easy to see that the options have to be exercised by the client as the second-mover, as if the provider has the right to exercise the option, then the client is exposed to the moral hazard problem, as 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.

It would 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 will involve a more tedious comparison with buyout options contracts.

In sum, the high complexity of the R&D process due to large monetary investments, high uncertainty in outcomes, and increased dependency on niche technologies 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. However, we show that using characteristics of R&D processes in practice such as verifiable intermediate signals, such as FDA approval or EPA certification, options-based contracts can be designed to eliminate such losses.

Another challenge in R&D arises due to co-production, which creates agency issues such as double-sided moral hazard and holdup. We show that contracts that leverage intermediate verifiable outcomes in the form of regulatory approval can simultaneously overcome the issues of holdup, double-sided moral hazard, and risk aversion to attain the first-best solution. 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.

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. While, we have not seen milestone-based options contracts in practice, however, milestone payments and fixed fees are widely prevalent (Cornelli and Yosha 1997, Robinson and Stuart 2007). Putting the two together, we posit that creating options contracts that are based on milestone payments do not pose any additional challenges to client firms. 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. 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.

Appendix

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

C1. The optimal decisions of the provider and the client are \( x^*, y^* \).

C2. The transfer payment made to the provider by the client is \( U - U^{-1}(\beta G(x)) \), 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 Generalized Nash Bargaining (GNB) result, which is a property of the GNB model. To see this, assume that the provider with bargaining power \( \beta \) gets \( P \), and the client with bargaining power \( 1 - \beta \) gets \( G(x) - P \). Then the GNB outcome is given by \( \max_{P \geq 0} P^\beta[G(x) - P]^{1-\beta} \Rightarrow \beta P^\beta[G(x) - P]^{1-\beta} = 0 \Rightarrow P = \beta G(x) \). Therefore, from (4), the provider’s problem is:

\[
\max_{x \geq 0} \min\{U^{-1}(\beta G(x) - x, T_B - x)\}
\]

If the provider invests \( x^* \), then the client’s problem is

\[
\max_{y \geq 0} E[\phi|x^*, y] - y.
\]

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 C2 is satisfied. Our claim is that to attain the first-best outcome we need to show that \( \exists T_M, T_A \) such that \( \forall x \in [0, x^*) \) the following holds,

\[
U[\beta(T_M g(x) + T_A) + (1 - \beta)U^{-1}(\beta G(x)) - x] \leq U[\beta(T_M g(x) + T_A) + (1 - \beta)U^{-1}(U^*(x))] - x^* = 0 \tag{12}
\]

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, \( \min\{U(U^{-1}(\bar{U}(x)) + \beta G(x)) - x, U(T_B) - x\} = U(U^{-1}(\bar{U}(x)) + \beta G(x)) - x \leq 0 \) (from 12). Assume that the provider invests \( x > x^* \). In this case the provider’s utility is, \( \min\{U(U^{-1}(\bar{U}(x)) + \beta G(x)) - x, U(T_B) - x\} \leq U(T_B) - x < 0 \) (from 13). Hence the provider will invest \( x = x^* \), as 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 \( \exists \{T_M, T_A, T_B\} \) such that the first-best outcome is attained and \( \exists \tilde{x} \in [0,x^*] \) 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 C2 we have that \( \min\{U(U^{-1}(\bar{U}(\tilde{x})) + \beta G(\tilde{x})) - \tilde{x}, U(\tau_B) - x^*\} = 0 \). 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 \( \tilde{x} < x^* \), its utility is \( \min\{U(U^{-1}(\bar{U}(\tilde{x})) + \beta G(\tilde{x})) - \tilde{x}, U(\tau_B) - \tilde{x}\} > \min\{U(U^{-1}(\bar{U}(x^*)) + \beta G(x^*)) - x^*, U(\tau_B) - x^*\} = 0 \); and hence the client cannot attain the first-best outcome. Finally, let us assume that \( \exists \{T_M, T_A, T_B\} \) 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 \( U(U^{-1}(\bar{U}(x^*)) + \beta G(x^*)) - x^* < 0 \), as 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 \( \exists x \rightarrow 0^+ \) such that \( U(U^{-1}(\bar{U}(x^* - \epsilon)) + \beta G(x^* - \epsilon)) - (x^* - \epsilon) > 0 \), due to 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 C2 we have that \( \min\{U(U^{-1}(\bar{U}(x^* - \epsilon)) + \beta G(x^* - \epsilon)) - x^* - \epsilon, U(\tilde{\tau}_B) - x^*\} = 0 \). 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 \( \tilde{x} < x^* \), its utility is \( \min\{U(U^{-1}(\bar{U}(x^* - \epsilon)) + \beta G(x^* - \epsilon)) - (x^* - \epsilon) > 0, U(\tilde{\tau}_B) - x^* + \epsilon\} > \min\{0, U(\tilde{\tau}_B) - x^*\} = 0 \); and hence the client cannot attain the first-best outcome as the condition C2 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

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

(14)

(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 \( T_M = \frac{1}{U'(U^{-1}(x^*)) g'(x^*)} \).

(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, \exists \text{ a finite } T_A \text{ that ensures that (10) is satisfied. The inequality in condition (9) can be expanded as}

\[
U'(\bar{T}_A) [\beta T_M g'(x) + (1 - \beta) \frac{d}{dx} U^{-1}(\bar{U}(x))] \geq 1 \forall x \in [0,x^*].
\]  

(15)
This expression can be further expanded as,

$$U'(\tilde{T}_A)[\beta T_M g'(x) + (1 - \beta)\frac{g'(x)[U(T_M + T_A) - U(T_A)]}{U'(U^{-1}(U(x))} \geq 1 \forall x \in [0, x^*)$$

Note that as $U(\cdot)$ is concave and increasing, we have $U'(\tilde{T}_A) > 0$. Also, since $T_M > 0$, $U(T_M + T_A) > U(T_A)$, and by assumption, $g'(x) > 0$ and $g(\cdot)$ is concave. Therefore, it is easy to see that there exists a finite $T_M$ such that $\beta T_M + (1 - \beta)\Lambda(T_M) = \frac{1}{U'(U^{-1}(x^*))}g(x^*)$, where $\Lambda(T_M) = \frac{d}{dx}U^{-1}(U(x)) > 0$, and this satisfies the sufficient conditions. Note that setting $T_M$ such that $T_M = \frac{1}{U'(U^{-1}(x^*))}g(x^*)$ 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:

$$U(x) - x \leq 0 \forall x \in [0, x^*)$$

(16)

$$U(x^*) = x^*$$

(17)

From the second equation in (17), we have:

$$U(T_M + T_A) = \frac{x^*}{g(x^*)} - U(T_A)(\frac{1}{g(x^*)} - 1)$$

(18)

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

$$\forall x \leq x^*, \frac{d}{dx}U(x) \geq 1 \implies U(T_M + T_A) - U(T_A) \geq \frac{1}{g(x^*)}$$

(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:

$$U^1_1(x) = \kappa(x, T_1) - x$$

$$U^2_2(x) = U(T_2) - x$$

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, $V(x) = \max_{y \geq 0} E[\phi | x, y] - y$. Similar to the case in Section 4.1, a potential hold-up 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,

$$G(x) = [V(x)g(x) - x] - [U^{-1}(\kappa(x, T_1)) - T_1 - x]$$

$$= V(x)g(x) + T_1 - U^{-1}(\kappa(x, T_1)) - V(x)g(x) - x$$

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, $G(x) > 0$. 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, due to the
hold-up problem which may lead to potential renegotiation, the provider solves the following problem:

$$\max_{x \geq 0} \min_x \{ U \left( U^{-1}(\kappa(x, T_1)) + \beta G(x) \right) - x, U(T_2) - x \}. \quad (20)$$

The client’s problem can be stated as follows:

$$\max_{x, T_1, T_2} \left\{ \mathbb{E}[\phi(\tilde{x}, \tilde{y}(\tilde{x})) - \tilde{g}(\tilde{x})] g(\tilde{x}) - \min_x \{ U^{-1}(\kappa(\tilde{x}, T_1)) + \beta G(\tilde{x}), T_2 \} \right\} \quad (21)$$

subject to:

$$\tilde{g}(x) = \operatorname{arg\,max}_{y \geq 0} \mathbb{E}[\phi(x, y) - y] g(x) - \min_x \{ U^{-1}(\kappa(x, T_1)) + \beta G(x), T_2 \} \quad (22)$$

$$\tilde{x} = \operatorname{arg\,max}_x \{ U \left( U^{-1}(\kappa(x, T_1)) + \beta G(x) \right) - x, U(T_2) - x \} \quad (23)$$

$$\min_x \{ U \left( U^{-1}(\kappa(\tilde{x}, T_1)) + \beta G(\tilde{x}) \right) - \tilde{x}, U(T_2) - \tilde{x} \} \geq 0 \quad (24)$$

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

$$\max_{y \geq 0} \mathbb{E}[\phi(x^*, y)] - y. \quad (25)$$

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 C2 (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:

$$\exists T_1 \text{ s.t. } U \left( U^{-1}(\kappa(x, T_1)) + \beta G(x) \right) - x \leq U \left( U^{-1}(\kappa(x^*, T_1)) + \beta G(x^*) \right) - x^* = 0 \ \forall x \in [0, x^*]. \quad (26)$$

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

$$U(T_2) - x^* = 0. \quad (27)$$

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, $\min_x \{ U \left( U^{-1}(\kappa(x, T_1)) + \beta G(x) \right) - x, U(T_2) - x \} = U \left( U^{-1}(\kappa(x, T_1)) + \beta G(x) \right) - x \leq 0$ (from 26). Assume that the provider invests $x > x^*$. In this case the
provider’s utility is, $\min_x \{ U \left( U^{-1}(\kappa(x, T_1)) + \beta G(x) \right) - x, U(T_2) - x \} \leq U(T_2) - x < 0$ (from 27). Hence the
provider will invest $x = x^*$, as 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 $\exists \{T_1, T_2\} = \{\tau_1, \tau_2\}$ such that the first-best outcome is attained and $\exists \tilde{x} \in [0, x^*]$ such that
$U \left( U^{-1}(\kappa(\tilde{x}, \tau_1)) + \beta G(\tilde{x}) \right) - \tilde{x} > U \left( U^{-1}(\kappa(x^*, \tau_1)) + \beta G(x^*) \right) - x^*$. Since first-best is assumed to exist, we have that $\min_x \{ U \left( U^{-1}(\kappa(x^*, \tau_1)) + \beta G(x^*) \right) - x^*, U(\tau_2) - x^* \} = 0$. This implies that,
$U \left( U^{-1}(\kappa(x, \tau_1)) + \beta G(x) \right) - x^* = 0$ and $U(\tau_2) - x^* = 0$. Since $U \left( U^{-1}(\kappa(\tilde{x}, \tau_1)) + \beta G(\tilde{x}) \right) - \tilde{x} > U \left( U^{-1}(\kappa(x^*, \tau_1)) + \beta G(x^*) \right) - x^*$ and $\tilde{x} < x^*$, if the provider invests $\tilde{x} < x^*$, its utility is
$\min_x \{ U \left( U^{-1}(\kappa(\tilde{x}, \tau_1)) + \beta G(\tilde{x}) \right) - \tilde{x}, U(\tau_2) - \tilde{x} \} > \min_x \{ U \left( U^{-1}(\kappa(x^*, \tau_1)) + \beta G(x^*) \right) - x^*, U(\tau_2) - x^* \} = 0$; and hence the client cannot attain the first-best outcome. Finally, let us assume that $\exists \{T_1, T_2\} = \{\tilde{\tau}_1, \tilde{\tau}_2\}$ such that the first-best outcome is attained and $U \left( U^{-1}(\kappa(x, \tilde{\tau}_1)) + \beta G(x) \right) - x \leq U \left( U^{-1}(\kappa(x^*, \tilde{\tau}_1)) + \beta G(x^*) \right) - x^* \ \forall x \in [0, x^*]$. We need to show that it must be that $U \left( U^{-1}(\kappa(x^*, \tilde{\tau}_1)) + \beta G(x^*) \right) - x^* = 0$. Clearly it cannot be the case that $U \left( U^{-1}(\kappa(x^*, \tilde{\tau}_1)) + \beta G(x^*) \right) - x^* < 0$, as then $\min_x \{ U \left( U^{-1}(\kappa(x^*, \tilde{\tau}_1)) + \beta G(x^*) \right) - x^*, U(\tau_2) - x^* \} = 0$. Therefore, deviating to $x^*$ is not beneficial.
$x^* < 0$ which violates the participation constraint of the provider. If $U \left( U^{-1}(\kappa(x^*, \tilde{\tau}_1)) + \beta G(x^*) - x^* > 0 \right)$, then $\exists \epsilon > 0$ such that $U \left( U^{-1}(\kappa(x^* - \epsilon, \tilde{\tau}_1)) + \beta G(x^* - \epsilon) - (x^* - \epsilon) > 0 \right)$, due to the continuity of the function $h(x) = U \left( U^{-1}(\kappa(x, \tilde{\tau}_1)) + \beta G(x) \right) - x$. Since first-best is assumed to exist, from condition C2 we have that $\min\left\{ U \left( U^{-1}(\kappa(x^* - \epsilon, \tilde{\tau}_1)) + \beta G(x^*) \right) - x^*, U(\tilde{\tau}_2) - x^* \right\} = 0$. This implies that $U(\tilde{\tau}_2) - x^* \geq 0$. Since $U \left( U^{-1}(\kappa(x^* - \epsilon, \tilde{\tau}_1)) + \beta G(x^* - \epsilon) \right) - (x^* - \epsilon) > 0$ and $\tilde{x} < x^*$, if the provider invests $x^* - \epsilon$, its utility is $\min\left\{ U \left( U^{-1}(\kappa(x^* - \epsilon, \tilde{\tau}_1)) + \beta G(x^* - \epsilon) \right) - (x^* - \epsilon), U(\tilde{\tau}_2) - x^* + \epsilon \right\} > \min\{0, U(\tilde{\tau}_2) - x^* \} = 0$; and 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.

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

$$3T_1 \text{s.t. } U(V(x)g(x) + T_1) - x \leq U(V(x^*)g(x^*) + T_1) - x^* = 0 \forall x \in [0, x^*]. \tag{28}$$

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, $U'(U^{-1}(x^*)) \frac{dV(x)g(x)}{dx} |_{x=x^*} - 1$. 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-quasi concavity of $U(V(x)g(x) + T_1) - x$.

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

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

Simplifying (29) yields,

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

Using (2), (30) simplifies further as

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

**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)).

$$3T_1, 3T_2 \text{s.t. } U(\tilde{T}_1) \geq x^* + \frac{1 - g(x^*)}{g(x^*)}. \tag{32}$$

$$U(\tilde{T}_2) \leq x^* - \frac{g(x^*)}{g(x^*)}. \tag{33}$$

Therefore, when $\beta = 0$, (32) and (33) are not satisfied, and $3T_1 \text{s.t. } \{ \kappa(x^*, T_1) = x^*, \left. \frac{dx(x, T_1)}{dx} \right|_{x=x^*} \geq 1 \forall x \in [0, x^*] \}$, then milestone-based options contracts do not attain the first-best outcome, whereas buyout options contracts do so. Similarly, when $\beta = 0$, (32) and (33) are satisfied, and $3T_1 \text{s.t. } \left. \frac{dx(x, T_1)}{dx} \right|_{x=x^*} \geq 1$, then milestone-based options contracts attain the first-best outcome, whereas buyout options contracts do not do so.

**Functions and parameters values for numerical example**

We assume the following functional forms for all the numerical examples presented in the paper:

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

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

References


