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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 attaining the first-best outcome is easier for the client when the provider has some bargaining power in renegotiation, and milestone-based options contracts attain the first-best solution in a wider range of cases than buyout options contracts.

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

**History**

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 automobile industry, OEMs rely on their suppliers’ knowledge and R&D capabilities for components, while they perform the integration, assembly, and marketing roles (Moavenzadeh 2006). 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

\(^1\) 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.
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 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 Cvska 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 aversion²) 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

²Henceforth, the issues of double-sided moral hazard, holdup, and risk aversion will be referred to as the set of relevant agency issues.
marketing of the drug. Similarly in the automotive industry, the component supplier first designs the engine (in collaboration with the manufacturer), which is subject to approval by the Environmental Protection Authority and the automaker subsequently manufactures and sells the car. New technologies in water, oil and gas, mining, chemicals sectors are all subject to EPA approval so any contractual or collaborative R&D is also characterized by such intermediate regulatory approval. 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).

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 all the bargaining power in renegotiation, and in many cases where it has some bargaining power. In contrast, if the provider has no bargaining power in renegotiation, the client may obtain the first-best solution in some restricted situations. This result is surprising, as the client can attain the first-best solution in a wider variety of situations when the provider has bargaining power. Specifically, if the provider’s utility function is given by the constant absolute risk aversion (CARA) function, 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, we show that the client can only attain the first-best solution when the degree of absolute risk-aversion of the provider is below a function of the probability of a successful outcome at the research stage. 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 (Demski and Sappington 1991, 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. In the only two cases where the efficacy of milestone-based options contracts and buyout options contracts can be directly compared (either the provider’s bargaining power in renegotiation is zero, or the provider’s utility is given by the CARA model), we show that the efficacy of buyout options contracts is more restricted compared to milestone-based options contracts in attaining the first-best outcome.

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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.
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.

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 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, 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 Hermelin 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.

The sequence of events in our model is shown in Figure 1. 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. The provider then makes an investment of $x$ 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. Similarly, in the auto industry, the Environmental Protection Agency (EPA) certifies the configuration of an engine or engine chassis design, prior to the production of vehicles with that design. The manufacturer has to obtain the certification of the designs of each engine on the vehicle it proposes to manufacture prior to production (EPA 1991). 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 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 $\Phi = [0, M]$, and has a pdf of $f(\phi, x, y)$ and a cdf of $F(\phi, x, y) = \int_{\theta=0}^{\phi} f(\theta, x, y) d\theta$. We make the following assumptions about the model parameters:

Assumption 1: $g(x)$ is concave and non-decreasing in $x$ and $g(0) = 0$. 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.

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: 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 $\tilde{M} \geq 0$).
Assumption 4: $x$ 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 5: We assume that all parameters and functions are such that the first-best system optimal 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 $U(z)$ 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. 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: such an outcome requires the provider and the client to make investment decisions that maximize their joint profits, we call these investments the first-best
investments. Since the investments in the research and development stages are made sequentially, we determine the first-best investments using backward induction:

\[ y^*(x) = \arg\max_{y \geq 0} E[\phi|x, y] - y, \quad (1) \]
\[ x^* = \arg\max_{x \geq 0} [E[\phi|x, y^*(x)] - y^*(x)] g(x) - x. \quad (2) \]

Here \( E[\phi|x, y] = \int_\phi \phi dF(\phi, x, y) \). Equations (1) and (2) determine the first-best investments \( \{x^*, y^*(x^*)\} \) in the coordinated problem that maximize the combined profits of the system. For the client to attain the first-best outcome, another condition is that it extracts the maximum possible profit from the system. The client will attain the maximum possible profit from the system when the expected utility for the provider satisfies its participation constraint and yet, no risk premium is paid to the risk-averse provider. 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. Next, we present the analysis that shows the efficacy of milestone-based options contracts in attaining the first-best outcome for the client.

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 milestone-based options contracts that consist of milestone payments and a fixed fee. 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:

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

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, \( V(x) = \max_{y \geq 0} E[\phi|x, y] - y \). Note that \( x^* = \arg\max_{x \geq 0} V(x)g(x) - x \).
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 $\tilde{T}_A$. The total surplus of such a renegotiation is,

$$G(x) = [V(x)g(x) - \tilde{T}_A + \tilde{T}_A - x] - [(V(x) - T_M)g(x) - T_A + U^{-1}(U_p^{A}(x))]$$  \hspace{1cm} (3)

$$= T_M g(x) + T_A - x - U^{-1}(U_p^{A}(x))$$  \hspace{1cm} (4)

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. Note that $U^{-1}(U_p^{A}(x))$ is the certainty equivalent of the uncertain profit of the provider under Option A. It is straightforward to check that $G(x) \geq 0$ as $U(T_M g(x) + T_A - x) \geq U(T_M + T_A - x)g(x) + U(T_A - x)(1 - g(x))$ 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 profit 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 $\tilde{T}_A - x = U^{-1}(U_p^{A}(x)) + \beta G(x)$, where $U^{-1}(U_p^{A}(x))$ is the certainty equivalent of the uncertain profit of the provider under Option A and $\beta G(x)$ is the provider’s share of the gains from renegotiation. Therefore, due to the hold-up 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:

$$\max_{x \geq 0} \{U^{-1}(U_p^{A}(x)) + \beta G(x), T_B - x\}.$$  \hspace{1cm} (5)

The client’s problem can be stated as follows:

$$\max_{T_M, T_A, T_B} \{E[\phi|\tilde{x}, \tilde{y}(\tilde{x})] - \tilde{y}(\tilde{x}) \} g(\tilde{x}) - \min\{U^{-1}(U_p^{A}(\tilde{x})) + \beta G(\tilde{x}) + \tilde{x}, T_B\}$$  \hspace{1cm} (6)

s.t. $\tilde{y}(x) = \arg \max_{y \geq 0} \{E[\phi|x, y] - y \} g(x) - \min\{U^{-1}(U_p^{A}(x)) + \beta G(x) + x, T_B\}$  \hspace{1cm} (7)

$$\tilde{x} = \arg \max_{x \geq 0} \min\{U^{-1}(U_p^{A}(x)) + \beta G(x), T_B - x\}$$  \hspace{1cm} (8)

$$\min\{U^{-1}(U_p^{A}(\tilde{x})) + \beta G(\tilde{x}), T_B - \tilde{x}\} \geq 0$$  \hspace{1cm} (9)
The client’s problem is characterized by (6) at \( t=0 \) and (7) at \( t=3 \). The provider firm solves (8) at \( t=1 \), and (9) 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 (with milestone-based payments and fixed payments) 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 the following condition is satisfied:

\[
\exists T_M, T_A \text{ s.t. } \beta (T_M g(x) + T_A - x) + (1 - \beta) U^{-1} (U^A_P(x)) \leq \beta (T_M g(x^*) + T_A - x^*) + (1 - \beta) U^{-1} (U^A_P(x^*)) = 0 \forall x \in [0, x^*)
\]

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 $x^\ast$. If the provider invests more than $x^\ast$, 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 $x^\ast$ 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 $x^\ast$ and gets its reservation value. Observe that no risk-premium is paid to the provider, since after the provider has made its optimal investment, the client is incentivized to choose the fixed-fee contract B, eliminating losses due to risk aversion. All the upside from the partnership is with the client (as it pays only a fixed fee); hence, the client makes its optimal investment, $y^\ast$. 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:

\[
\exists T_M,T_A \text{ s.t. } \beta T_M g'(x) - \beta + (1 - \beta) \frac{\partial}{\partial x} U^A_P(x) \geq 0 \forall x \in [0,x^\ast], \tag{10}
\]

\[
\beta(T_M g(x^\ast) + T_A - x^\ast) + (1 - \beta)U^{-1}_P(U^A_P(x^\ast)) = 0. \tag{11}
\]
While the conditions above may appear restrictive, they are relatively mild and are satisfied by a number of different properties of (i) the bargaining power of the parties after renegotiation, and (ii) the utility function of the provider. Equation (11) 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 (10) is satisfied. Since $\beta T_M g'(x) - \beta$ is always positive for large enough $T_M$ (for example $T_M \geq \frac{1}{\beta g'(x^*)}$) the attainment of the first-best solution depends on the sign of the term $\frac{\beta T_M^A}{U'(T_M + T_A - x)}$. The denominator of this term is always positive (as $U$ is increasing). The numerator can be expanded as follows:

$$\frac{\partial}{\partial x} U^A_p(x) = g'(x)[U(T_M + T_A - x) - U(T_A - x)] + g(x)[U'(T_A - x) - U'(T_M + T_A - x)] - U'(T_A - x).$$

The first two terms in the right-hand side of the equation above are always positive ($U$ is increasing and concave), the third term is negative as $U'(T_A - x)$ is positive. Therefore, to show that the sufficient conditions (10) and (11) hold, we need to check if $\exists$ a large enough $T_M$ such that all the positive terms of the left-hand side of (10) dominate the one negative term $(-U'(T_A - x))$, where $T_A$ is determined by (11). Proposition 2 lists a set of stand-alone conditions under which (10) and (11) are satisfied.

**Proposition 2:** Milestone-based options contracts can always attain the first-best solution ((10) and (11) are satisfied) if any of the following stand-alone conditions hold:

(i) $\beta = 1$,

(ii) $\beta \in (0, 1)$ and $U'(-\infty) = 0$.

(iii)$\beta\in (0, 1)$ and $U''(\cdot) \leq 0$.

(iv) $\beta \in (0, 1)$ and $U(\cdot)$ has the increasing absolute risk aversion (IARA) form.

(v) $\beta \in (0, 1)$ and $U(\cdot)$ is such that $U^{-1}(U(a + b)p + U(a)(1 - p)) = U^{-1}(U(b)p + a)$ for $p \in [0, 1]$.

The set of conditions in Proposition 2 is not exhaustive, and the proposition simply demonstrates that milestone-based options contracts attain the first-best outcome for a wide variety of cases. First, if the provider has all the bargaining power during renegotiation, the client can always achieve the first-best solution with a milestone-based option contract. Second, if the provider has some bargaining power during renegotiation ($\beta \in (0, 1)$), then in many cases, the client can attain the first-best outcome. 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. This result is also counter-intuitive, as it

\footnote{The conditions listed here ensure that the sufficient conditions for the attainment of the first-best outcome are satisfied, and hence are a conservative set of conditions.}
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.

We draw attention to condition (v) above as it models a range of utility functions that are intuitive. \( U^{-1}(U(a+b)p + U(a)(1-p)) \) is the certainty equivalent outcome for a risk-averse agent that is guaranteed a reward of \( a \) and additionally, it may get \( b \) with a probability \( p \). \( U^{-1}(U(b)p) \) is the certainty equivalent outcome for a risk-averse agent that earns \( b \) with a probability \( p \). Therefore condition (v) states that the certainty equivalent outcome for a risk-averse agent that earns \( b \) with a probability \( p \) and \( a \) with probability 1 is \( U^{-1}(U(b)p) + a \). The intuition behind this condition is that the agent conducts risk-adjusted discounting (with a discount rate that includes an additional risk-premium) only for its stochastic earnings. This property is consistent with the constant absolute risk aversion (CARA) model. We note that for the CARA function, \( U''(\cdot) > 0 \).

While we have shown that milestone-based options contracts attain the first-best outcome for a variety of cases\(^5\), the necessary and sufficient condition in Proposition 1 is hard to interpret in the general form. To obtain deeper managerial insights into situations where the first-best solution can be attained, we analyze the special case where the utility function of the provider is given by the CARA form \( U(z) = \eta(1-e^{-\zeta z}) \). The CARA functional form is the most widely used risk-averse utility functional form in the literature and in practice (Kirkwood 2004); Corner and Corner (1995) find that when modeling risk aversion, 80% of the applications of utility functions used the CARA model, while 20% used all other functions combined.

**Proposition 3:** If the utility to the provider has the CARA functional form:

(i) If \( \beta \in (0,1) \), then milestone-based options contracts always attain the first-best outcome.

(ii) If \( \beta = 0 \), a necessary condition for the client to attain the first-best solution is that the provider’s absolute degree of risk aversion \( \zeta \) satisfies \( \zeta < \frac{g'(x^*)}{1-g(x^*)} \).

Proposition 3 shows that if the provider has the CARA functional form for its utility, the client always achieves the first-best solution if the provider has some bargaining power after renegotiation (conditions 10 and 11 can always be satisfied). However, if the client has all the bargaining power during renegotiation, then the client can only attain the first-best solution if the provider’s degree

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\(^5\)Note that other utility functions such as the logarithm or polynomial functions are not defined for the entire real line. However, we can create smooth utility functions defined on the entire real line by using logarithm or polynomial functions along with linear functions. For example utility functions of the form \( U(z) = \theta(ln z + 1) \forall z \geq 1 \) and \( U(z) = \theta z \forall z \leq 1 \); or \( U(z) = \theta(z^\gamma - 1) + \theta \gamma z \forall z \geq 1 \) and \( U(z) = \theta \gamma z \forall z \leq 1 \), where \( \theta > 0, \gamma \in (0,1) \) are smooth utility functions that satisfy all the axioms of risk-averse expected utility models. Any such smooth utility function that takes the linear form in the negative domain is consistent with case (ii) of Proposition 2, and hence will attain the first-best outcome when \( \beta > 0 \) with milestone-based options contracts.
of risk aversion is below a certain threshold. This is again an interesting result, as 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). Therefore, when the provider has some bargaining power during renegotiation, the first-best outcome is always attained.

If $\beta = 0$, an important condition for the attainment of the first-best solution is that $\zeta < g'(x^*) \frac{1}{1-g(x^*)}$. This implies that a function of the probability of a successful outcome at the research stage has to be greater than the degree of absolute risk aversion of the provider. As a special case, we use $g(x) = 1 - e^{-\alpha x}$ to provide some additional insights.

**Corollary 1:** If $\beta = 0$ and the utility to the provider has the CARA functional form, and $g(x)$ is given by $g(x) = 1 - e^{-\alpha x}$, the necessary condition for the client to attain the first-best solution ($\zeta < g'(x^*) \frac{1}{1-g(x^*)} = \alpha$) is also a sufficient condition. The milestone payment $T_M$ to implement the first-best solution satisfies:

$$T_M = \frac{1}{\zeta} \ln \left( \frac{\zeta e^{\alpha x^*} + \alpha - \zeta}{\alpha - \zeta} \right).$$

If the probability of a successful outcome is given by the function $g(x) = 1 - e^{-\alpha x}$, then the function $g'(x^*) \frac{1}{1-g(x^*)}$ simplifies to the rate parameter $\alpha$. Hence, the difference between the rate parameter of the probability of a successful outcome and the degree of risk aversion of the provider has to be positive for the client to attain the first-best solution. If the provider is very risk-averse ($\alpha \leq \zeta$), then the client will not be able to incentivize the provider to invest in non-zero investment, as the expected utility of the provider from a positive investment is strictly non-increasing in the investment. Hence, only a moderately risk-averse provider will invest the first-best investment in the partnership.

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

### 4.2. Buyout options contracts

In this section, we analyze the case where buyout options contracts are offered by the client to the provider, buyout contracts have been studied in the literature (Edlin and Hermalin 2000). 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 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 for a fixed fee $T_1$ (option 1). We also assume (Assumption 3) that if the provider has the ownership of the IP after the research stage (in the case the client uses option 1) then the provider has an external option to sell its output at the research stage for a payment $\tilde{M} \geq 0$, if the outcome of the intermediate verifiable signal is successful. In the context of R&D partnerships, the investment of the provider will be observable to the client, but not to the external partner. Hence, we model the external option as having a value of $\tilde{M}$, since the intermediate verifiable signal (0 or 1) is observable and verifiable to all parties.

Observe that if the client chooses Option 1, then it will not make any investment in the development stage as it earns a fixed fee under that option. Therefore, the utilities of the provider from such an options contract are given by:

$$U_P^1(x) = U[\tilde{M} - T_1 - x]g(x) + U[-T_1 - x](1 - g(x))$$
$$U_P^2(x) = U[T_2 - x]$$

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 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,

$$G(x) = [V(x)g(x) - x] - [T_1 + U^{-1}(U_P^1(x))]$$
$$= V(x)g(x) - x - T_1 - U^{-1}(U_P^1(x)).$$

Similar to Edlin and Hermalin (2000) we assume that the R&D partnership is valuable or $V(x)g(x) - x \geq T_1 + U^{-1}(U_P^1(x))$. 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 $\tilde{T}_1 - x = U^{-1}(U_P^1(x)) + \beta G(x)$, 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:

$$\max_{x \geq 0} \min \{U^{-1}(U_P^1(x)) + \beta G(x), T_2 - x\}. \quad (12)$$
The client’s problem can be stated as follows:

\[
\begin{align*}
\max_{T_1, T_2} & \quad [E[\phi(\tilde{x}, \tilde{y}(\tilde{x})) - \tilde{y}(\tilde{x})] g(\tilde{x}) - \min\{U^{-1}(U_p(\tilde{x})) + \beta G(\tilde{x}) + \tilde{x}, T_2\}] \\
\text{s.t.} & \quad \tilde{y}(x) = \arg\max_{y \geq 0} [E[\phi|x, y] - y] g(x) - \min\{U^{-1}(U_p(x)) + \beta G(x) + x, T_2\} \\
& \quad \tilde{x} = \arg\max_{x \geq 0} \min\{U^{-1}(U_p(\tilde{x})) + \beta G(\tilde{x}), T_2 - \tilde{x}\} \\
& \quad \min\{U^{-1}(U_p(\tilde{x})) + \beta G(\tilde{x}), T_2 - \tilde{x}\} \geq 0
\end{align*}
\]

The client’s problem is characterized by (13) at \(t=0\) and (14) at \(t=3\). The provider solves (15) at \(t=1\), and (16) is the provider’s participation constraint. We examine if such a buyout options contract can attain the first-best solution, and state the result formally in Proposition 4.

**Proposition 4:** (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 for 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 the following condition is satisfied: \(\exists T_1\) s.t. 

\[
\beta(V(x^*) g(x^*) - T_1 - x^*) + (1 - \beta) U^{-1}(U_p(x^*)) \leq \beta(V(x^*) g(x^*) - T_1 - x^*) + (1 - \beta) U^{-1}(U_p(x^*)) = 0 \forall x \in [0, x^*).
\]

(ii) The above condition is always satisfied if \(\beta=1\), which implies that the provider has all the bargaining power in renegotiation.

The mechanics of the buyout options contracts are similar to options contracts based on milestone payments. The client sets the terms of the contract such that if the provider invests lower than \(x^*\), then the client will exercise Option 1. In this case, the condition in Proposition 4 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 \(T_2\) is set in such a manner that the client will exercise Option 2, which will also result in a lower utility for the provider. Hence, the provider invests \(x^*\). The necessary and sufficient condition stated in Proposition 4 provides the client with the range of contractual parameters such that the provider makes an investment of \(x^*\) and gets its reservation value. Observe that no risk-premium is paid to the provider, since after the provider has made its optimal investment, the client is incentivized to choose the fixed-fee contract 2, eliminating losses due to risk aversion. All the upside from the partnership is with the client (as it pays only a fixed fee); hence, the client makes its optimal investment, \(y^*\). Similar to milestone-based options contracts no renegotiation will take place in equilibrium as both players know that renegotiation will yield an outcome equivalent to option 2. There is however one important distinction between the buyout and milestone-based options contracts — the outside option \(M\) is exogenous in buyout based options contracts whereas the milestone payment \(T_M\) is the client’s decision. Therefore, it is intuitive to see that it is easier to satisfy the necessary and sufficient conditions to attain the
first-best outcome with milestone-based options contracts than with buyout options contracts. Corollary 2 illustrates the restricted ability of buyout options contracts in attaining the first-best outcome.

**Corollary 2:** (i) If the provider and the client operate in a niche market \( \tilde{M} = 0 \), then buyout options contracts cannot attain the first-best solution.

(ii) If the marginal profit for the provider of investing \( x^* \) from its outside option is lower than the marginal profit for the centralized system (when provider and client act as one firm), then buyout options contracts cannot attain the first-best solution. Hence, a necessary condition to attain the first-best solution is:

\[
\begin{align*}
\frac{\partial U^{-1}[U^1_P(x)\big]}{\partial x} |_{x^*} &\geq \frac{\partial [V(x)g(x) - x]}{\partial x} |_{x^*} = 0
\end{align*}
\]

Hence, for buyout options contracts to attain the first-best solution when the bargaining power in renegotiation is shared between the parties, the external option \( \tilde{M} \) 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 client having some bargaining power in renegotiation restricts its ability to always attain the first-best solution when using buyout options contracts.

We now examine the efficacy of buyout contracts in attaining the first-best solution when the provider has no bargaining power in renegotiation.

**Proposition 5:** If the provider has no bargaining power in renegotiation \((\beta = 0)\), and if buyout options contracts attain the first-best outcome then milestone-based options contracts also attain the first-best outcome. However, if milestone-based options contracts attain the first-best outcome, buyout options may not attain the first-best outcome.

Since the necessary and sufficient conditions for buyout options contracts and milestone-based options contracts are different (as the two kinds of contracts have different structures), it is only possible to directly compare the two contracts when the provider has no bargaining power in renegotiation, or the conditions for the existence of the first-best solution can be found explicitly (as with the CARA functional form). In both cases, we find that milestone-based options contracts dominate buyout options contracts in their efficacy to attain the first-best outcome. In the first

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6 This result is the same as Proposition 3 in Edlin and Hermalin (2000). Additionally, if we assume that \( U^{-1}[U^1_P(x)] \) is ideally quasi-concave, then this is also a sufficient condition (Edlin and Hermalin 2000, Proposition 4).
case, when the provider does not have any bargaining power in renegotiation, Proposition 5 illustrates the restricted ability of buyout options contracts in attaining the first-best outcome. Unlike milestone-based options contracts, buyout options contracts do not enable the client to incentivize the provider to make the first-best investment as the upside of making such investments is determined exogenously. Milestone-based options contracts in contrast enable the client to design a high enough milestone payment $T_M$ such that the provider finds it optimal to make an investment equal to $x^*$. Hence, if the buyout options contract can attain the first-best solution, then a milestone-based options contract can also attain the first-best solution by setting $T_M = \tilde{M}$.

**Proposition 6:** If $\beta < 1$ and $U(\cdot)$ has the CARA functional form, attaining the first-best outcome using buyout options contracts requires the following necessary conditions: $\zeta < \frac{g'(x^*)}{1 - g(x^*)}$, and $\tilde{M} \geq 1 \ln \frac{g'(x^*) + \zeta g(x^*)}{g'(x^*) - \zeta}.$

Comparing Proposition 6 to Proposition 3 (where the provider’s utility has the CARA form) enables us to compare the efficacy of milestone-based options contracts and buyout options contracts for all values of bargaining power sharing in renegotiation between the two parties. Recall that if $U(\cdot)$ has the CARA functional form, Proposition 3 shows that milestone-based options contracts always attain the first-best solution if $\beta \in (0, 1)$. The necessary condition for milestone-based options contracts to attain the first-best solution if $\beta = 0$ is that $\zeta < \frac{g'(x^*)}{1 - g(x^*)}$.

In contrast, the necessary conditions for the client to attain the first-best solution with buyout options contracts are twofold: (i) $\zeta$ satisfies $\zeta < \frac{g'(x^*)}{1 - g(x^*)}$, which implies that the provider’s degree of risk aversion is limited. We note that the efficacy of buyout options contracts in attaining the first-best outcome is not enhanced by the bargaining power of the provider in renegotiation; even if the provider has non-zero bargaining power, the degree of risk aversion of the provider has to be limited for buyout options contracts to attain the first-best solution. In contrast, milestone-based options contracts attain the first-best solution always if $\beta > 0$ and $U(\cdot)$ has the CARA form. (ii) Buyout options contracts have the additional limitation that they attain the first-best outcome only if the external option payment $\tilde{M}$ satisfies: $\tilde{M} \geq 1 \ln \frac{g'(x^*) + \zeta g(x^*)}{g'(x^*) - \zeta}$. Hence, in this case as well, milestone-based options contracts have a higher efficacy in attaining the first-best solution compared to buyout options contracts.

Figure 3 summarizes the domains where the first-best solutions are obtained with milestone-based options contracts and buyout options contracts when the utility of the provider has the CARA functional form, and the probability of a successful outcome at the research stage is given by $g(x) = 1 - e^{-\alpha x}$. The outside option value ($\tilde{M}$) is plotted on the vertical axis, and the degree
of risk aversion of the provider ($\zeta$) is plotted on the horizontal axis. As can be seen from Figure 3, when the bargaining power of the provider in renegotiation is non-zero, milestone-based options contracts can always attain the first-best solution (Proposition 3). However, if the bargaining power of the provider is zero (all the bargaining power is with the client), then milestone-based options contracts only attain the first-best solution if the degree of risk aversion of the provider is below $\alpha$, the rate parameter of $g(x)$ (Proposition 3 and Corollary 1). In contrast, buyout options contracts always attain the first-best outcome if the provider has all the bargaining power ($\beta = 1$, Proposition 4(i)), or if $\tilde{M}$ is above a threshold, and the provider’s degree of risk aversion ($\zeta$) is below a threshold (Proposition 5). If the provider has no bargaining power and the provider has a high degree of risk aversion, then the first-best solution cannot be attained.

Figure 3  Efficacy of Milestone-based and Buyout Options Contracts (BO = buyout, MS = milestone, FB = first-best)

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 all the bargaining power in renegotiation, and in many cases where the bargaining power in renegotiation is shared between the parties. 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.

As a special case, we use the constant absolute risk aversion (CARA) utility function to model the risk-aversion of the provider, and show that: (i) the client can always attain the first-best outcome if the provider has some bargaining power in renegotiation; and (ii) if the bargaining power of the provider in renegotiation is zero, a necessary condition for milestone-based options contracts to attain the first-best solution is that the degree of risk aversion is below a certain threshold value, that is based on the probability of a successful outcome at the research stage. If the probability of a successful outcome is given by an exponential function, then this necessary condition is sufficient as well, and reduces to the degree of risk aversion being lower than the rate parameter of the exponential function.

In contrast, 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.

If the utility of the provider is given by the CARA function, then for all cases where the bargaining power in renegotiation is shared between the client and the provider (irrespective of the degree of sharing), there are two necessary conditions for buyout options contracts to attain the first-best outcome: the degree of risk aversion should be below a certain threshold value (the same threshold value as milestone-based options contracts), and the value of the external option should be above a certain threshold value.

When a direct comparison of milestone-based options contracts and buyout options contracts is possible ((i) the provider’s bargaining power in renegotiation is zero, and (ii) the provider’s utility functional form is given by the CARA model), we show that milestone-based options contracts Pareto-dominate buyout options contracts: 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.

Table 1 summarizes our findings when the provider’s utility is given by the CARA function.

<table>
<thead>
<tr>
<th>Contract:</th>
<th>Milestone-based options contract</th>
<th>Buyout options contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provider has all the bargaining power ($\beta = 1$)</td>
<td>Always attains first-best solution</td>
<td>Always attains first-best solution</td>
</tr>
<tr>
<td>Provider has some bargaining power ($\beta \in (0, 1)$)</td>
<td>Always attains first-best solution</td>
<td>Necessary conditions for first-best: outside option value high and provider’s degree of risk-aversion is low.</td>
</tr>
<tr>
<td>Provider does not have bargaining power ($\beta = 0$)</td>
<td>Necessary conditions for first-best: provider’s degree of risk-aversion is low</td>
<td>Necessary conditions for first-best: outside option value high and provider’s degree of risk-aversion is low</td>
</tr>
</tbody>
</table>

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.

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. Options-based contracts in the form of convertible equity and convertible debt are observed in practice, and milestone payments and fixed fees are also widely prevalent (Cornelli and Yosha 1997, Robinson and Stuart 2007). In addition to these contractual mechanisms, our results suggest that options based on milestone payments and fixed fees should be used more broadly. 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 expected transfer payment made to the provider by the client is $x^*$.
C3. The participation constraint of the provider is satisfied at $x^*, y^*$.
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 $\max_{P \geq 0} P^{\beta}[G(x) - P]^{-\beta} = \beta^{\beta-1} \frac{G(x)}{G(x) - P} \left( 1 - \beta \right)^{\beta} = 0 \Rightarrow P = \beta G(x)$. Therefore, from (4), the provider’s problem is:

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

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

$$\max_{y \geq 0} E[\phi|x^*, y] - y - \text{constant}. \quad (17)$$

Comparing (17) 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 conditions C2 and C3 are satisfied. Our claim is that to attain the first-best outcome we need to show the following necessary and sufficient condition:

$$\exists T_M, T_A \text{ s.t. } U^{-1}(U^*_P(x)) + \beta G(x) \leq U^{-1}(U^*_P(x^*)) + \beta G(x^*) = 0 \ \forall x \in [0, x^*). \quad (18)$$

To show sufficiency, let us assume that (18) is satisfied for some $T_M$ and $T_A$. Set $T_B$ such that $T_B - x^* = 0$. \quad (19)

Equations (18) and (19) 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, $\min\{U^{-1}(U^*_P(x)) + \beta G(x), T_B - x\} = U^{-1}(U^*_P(x)) + \beta G(x) \leq 0$ (from 18). Assume that the provider invests $x > x^*$. In this case the provider’s utility is, $\min\{U^{-1}(U^*_P(x)) + \beta G(x), T_B - x\} \leq T_B - x < 0$ (from 19). Hence the provider will invest $x = x^*$, as deviating is not beneficial.

Next we will show that (18) is also necessary for the attainment of the first-best outcome. Let us assume that $\exists \{T_M, T_A, T_B\} = \{\tau_M, \tau_A, \tau_B\}$ such that the first-best outcome is attained and $\exists \tilde{x} \in [0, x^*)$ such that $U^{-1}(U^*_P(\tilde{x})) + \beta G(\tilde{x}) > U^{-1}(U^*_P(x^*)) + \beta G(x^*)$. Since first-best is assumed to exist, from condition C2 we have that $\min\{U^{-1}(U^*_P(x^*)) + \beta G(x^*), \tau_B - x^*\} = 0$. This implies that, $U^{-1}(U^*_P(x^*)) + \beta G(x^*) \geq 0$ and $\tau_B - x^* \geq 0$. Since $U^{-1}(U^*_P(\tilde{x})) + \beta G(\tilde{x}) > U^{-1}(U^*_P(x^*)) + \beta G(x^*)$ and $\tilde{x} < x^*$, if the provider invests $\tilde{x} < x^*$, its utility is $\min\{U^{-1}(U^*_P(\tilde{x})) + \beta G(\tilde{x}), \tau_B - \tilde{x}\} > \min\{U^{-1}(U^*_P(x^*)) + \beta G(x^*), \tau_B - x^*\} = 0$; and hence the client cannot attain the first-best outcome as the condition C2 is violated. Finally, Let us assume that $\exists \{T_M, T_A, T_B\} = \{\tilde{\tau}_M, \tilde{\tau}_A, \tilde{\tau}_B\}$ such that the first-best outcome is attained and $U^{-1}(U^*_P(x)) + \beta G(x) \leq U^{-1}(U^*_P(x^*)) + \beta G(x^*) \ \forall x \in [0, x^*)$. We need to show that it must be that $U^{-1}(U^*_P(x^*)) + \beta G(x^*) = 0$. Clearly it cannot be the case that $U^{-1}(U^*_P(x^*)) + \beta G(x^*) < 0$, as then $\min\{U^{-1}(U^*_P(x^*)) + \beta G(x^*), \tau_B - x^*\} < 0$ which violates C3. If $U^{-1}(U^*_P(x^*)) + \beta G(x^*) > 0$, then $\exists \epsilon \rightarrow 0^+$ such that $U^{-1}(U^*_P(x^* - \epsilon)) + \beta G(x^* - \epsilon) > 0$, due to the continuity of the function $h(x) = U^{-1}(U^*_P(x)) + \beta G(x)$. Since first-best is assumed to exist, from condition C2 we have that $\min\{U^{-1}(U^*_P(x^*)) + \beta G(x^*), \tilde{\tau}_B - x^*\} = 0$. This implies that $\tilde{\tau}_B - x^* \geq 0$. Since $U^{-1}(U^*_P(x^* - \epsilon)) + \beta G(x^* - \epsilon) > 0$ and $\tilde{x} < x^*$, if the provider invests $x^* - \epsilon$, its utility is $\min\{U^{-1}(U^*_P(x^* - \epsilon)) + \beta G(x^* - \epsilon), \tilde{\tau}_B - x^* + \epsilon\} \geq \min\{0, \tilde{\tau}_B - x^*\} = 0$; and hence the client cannot attain the
As (25) holds if 

$$\exists T_M, T_A \text{s.t. } \beta(T_M g(x) + T_A - x) + (1 - \beta)U^{-1}(U^A_f(x)) \leq \beta(T_M g(x^*) + T_A - x^*) + (1 - \beta)U^{-1}(U^A_f(x^*)) = 0 \forall x \in [0, x^*].$$

(20)

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

$$\exists T_M, T_A \text{s.t. } T_M g'(x) - x \leq 0 \forall x \in [0, x^*].$$

(21)

Since $g(\cdot)$ is an increasing concave function, (21) is always satisfied by setting $T_M \geq \frac{1}{g'(x^*)}$. (11) is satisfied by setting $T_A = x^* - T_M g(x^*)$.

(ii) From Jensen’s inequality we have that $U^A_f(x) \leq U(T_M g(x) + T_A - x)$. For $T_M \geq 0$, $U(T_M + T_A - x)g(x) + U(T_A - x)(1 - g(x)) \geq U(T_A - x)$ since $U(\cdot)$ is increasing. Therefore, we have $T_A - x \leq U^{-1}(U^A_f(x)) \leq T_M g(x) + T_A - x$. Substituting this in (11) yields,

$$x^* - T_M g(x^*) \leq T_A \leq x^* - T_M g(x^*) \beta.$$

Therefore, given a finite $T_M \geq 0$, $\exists$ a finite $T_A$ that ensures that (11) is satisfied. The inequality in condition (9) can be expanded as

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

(22)

Define $A(x, T_M, T_A)$ as the left-hand-side of (22). As $U(\cdot)$ is concave and increasing, we have

$$A(x, T_M, T_A) > \beta T_M g'(x) - \beta - (1 - \beta) \frac{U'(T_A - x)}{U'[U^{-1}(U^A_f(x))] \geq 0} \forall x \in [0, x^*].$$

(23)

To complete our proof it is sufficient to show that $\beta T_M g'(x) - \beta - (1 - \beta) \frac{U'(T_A - x)}{U'[U^{-1}(U^A_f(x))] \to \infty}$ as $T_M \to \infty$. As $T_A \to -\infty$ and $U'(\cdot)$ is bounded, it is sufficient to show that $U'[U^{-1}(U^A_f(x))] > 0$ for $T_M \to \infty$. Since $U(\cdot)$ is an increasing function, $U'(\cdot) > 0$ for all $x$. Therefore, $\exists$ a finite $T_M$ such that $A(x, T_M, T_A) > 0 \forall x \in [0, x^*]$.

(iii) From case (ii) above we know that given a finite $T_M \geq 0$, $\exists$ a finite $T_A$ that ensures that (11) is satisfied. To show that (9) is satisfied it is sufficient to show the following:

$$\exists T_M \text{ s.t. } \beta T_M g'(x) - 1 + (1 - \beta) \left[ \frac{\beta U^A_f(x)}{U'[U^{-1}(U^A_f(x))]} + 1 \right] \geq 0 \forall x \in [0, x^*], \forall T_A.$$

(24)

To show that (24) holds, it is sufficient to show the following:

$$\frac{\beta U^A_f(x)}{U'[U^{-1}(U^A_f(x))]} + 1 \geq 0 \forall x, T_A, \forall T_M > 0.$$

(25)

Condition (25) holds if 

$$g(x)U'(T_M + T_A - x) + (1 - g(x))U'(T_A - x) \leq U'[U^{-1}(U^A_f(x))] \forall x, T_A, \forall T_M > 0.$$

(26)
Since \( U(\cdot) \) is an increasing concave function, \( U^{-1}(\cdot) \) is an increasing convex function. Since \( U''(\cdot) \leq 0 \), \( U'(\cdot) \) is a concave function. Using Jensen’s inequality we have
\[
g(x)U'(T_M + T_A - x) + (1 - g(x))U'(T_A - x) \leq U'[U^{-1}(U_p^\lambda(x))]|_{x, T_A, V T_M \geq 0}. \tag{27}
\]
Therefore, we have shown that (26) holds, which implies that (25) and (24) hold. This completes our proof.

(iv) From case (ii) above we know that given a finite \( T_M \geq 0 \), \( \exists \) a finite \( T_A \) that ensures that (11) is satisfied. Similar to the case above, to show that (9) is satisfied it is sufficient to show the following:
\[
g(x)U'(T_M + T_A - x) + (1 - g(x))U'(T_A - x) \leq U'[U^{-1}(U_p^\lambda(x))]|_{x, T_A, \forall T_M \geq 0}. \tag{28}
\]
Since \( U(\cdot) \) is an increasing concave function, \( U^{-1}(\cdot) \) is an increasing convex function. Therefore,
\[
U^{-1}(U_p^\lambda(x)) \leq g(x)U^{-1}(U(T_M + T_A - x)) + (1 - g(x))U^{-1}(U(T_M + T_A - x)) = T_M g(x) + T_A - x \forall x, T_A, \forall T_M \geq 0. \tag{29}
\]
It is easy to check that (28) holds for \( T_M = 0 \). Let \( K(T_M, T_A, x) \) be the derivative of \( g(x)U'(T_M + T_A - x) + (1 - g(x))U'(T_A - x) - U'[U^{-1}(U_p^\lambda(x))] \) with respect to \( T_M \). This implies that
\[
K(T_M, T_A, x) = g(x)U''(T_M + T_A - x) - \frac{U''[U^{-1}(U_p^\lambda(x))]}{U'[U^{-1}(U_p^\lambda(x))]} g(x)U'(T_M + T_A - x).
\]
Since \( U(\cdot) \) follows IARA, from (29) we have
\[
- \frac{U''(T_M + T_A - x)}{U'(T_M + T_A - x)} \geq - \frac{U''[U^{-1}(U_p^\lambda(x))]}{U'[U^{-1}(U_p^\lambda(x))]}.
\]
Therefore, we conclude that \( K(T_M, T_A, x) \leq 0 \). We conclude that (28) holds \( \forall x, T_A, \forall T_M \geq 0 \). This completes our proof.

(v) In this case we have \( U^{-1}(U_p^\lambda(x)) = U^{-1}(U(T_M)g(x) + T_A - x) \). The sufficient condition (9) reduces to
\[
\exists T_M \text{ s.t. } \beta_T g'(x) - 1 + (1 - \beta) \frac{U(T_M)g'(x)}{U'[U^{-1}(U(T_M)g(x))]} \geq 0 \forall x \in [0, x^*] \tag{30}
\]
Note that \( g(\cdot) \) and \( U(\cdot) \) are assumed to be concave functions. Therefore, \( \beta_T g'(x) - 1 + (1 - \beta) \frac{U(T_M)g'(x)}{U'(0)} \geq 0 \forall x \in [0, x^*], T_M \geq 0 \). It is easy to check \( \exists T_M \geq 0 \) such that (30) is satisfied; for example, by setting, \( T_M \geq \frac{1}{\beta_T g'(x^*)} \). Finally, (11) is satisfied by setting \( T_A = x^* - \beta_T g(x^*) - (1 - \beta) U^{-1}(U(T_M)g(x^*)) \).

**Proof of Proposition 3:** (i) In this case we use the constant absolute risk aversion (CARA) utility function to show that (20) always holds for \( \beta > 0 \). If \( U(\cdot) \) is given by the CARA model, then \( U(z) = \eta [1 - e^{-\zeta z}] \), where \( \eta \) is a scale parameter and \( \zeta \) is the degree of absolute risk aversion. Note that \( U^{-1}(y) = -\frac{1}{\zeta} \ln \left(1 - \frac{y}{\eta}\right) \).

Therefore, we have,
\[
U^{-1}(U(a + b)p + U(a)(1 - p)) = -\frac{1}{\zeta} \ln \left(1 - \eta [1 - e^{-\zeta(a + b)p + \eta [1 - e^{-\zeta a}(1 - p)\right] + a
\]
\[
U^{-1}(U(b)p + a). \]
This implies that the CARA function follows the property assumed in Proposition 2 case (iv), and hence for this case milestone-based options contracts always attain the first-best outcome.

(ii) In this case we assume that \( \beta = 0 \). The necessary and sufficient condition (20) reduces to

\[
\exists T_M, T_A \text{ s.t. } T_A - x - \frac{1}{\zeta} \ln \left( 1 - g(x) + g(x)e^{-CT_M} \right) \\
\leq T_A - x^* - \frac{1}{\zeta} \ln \left( 1 - g(x^*) + g(x^*)e^{-CT_M} \right) \forall x \in [0,x^*].
\]

(31)

Since \( T_A \) can be set from the equality in the second equation above, the necessary and sufficient condition for the attainment of the first-best outcome is that \( \exists T_M \) such that

\[
-x - \frac{1}{\zeta} \ln \left( 1 - g(x) + g(x)e^{-CT_M} \right) \leq -x^* - \frac{1}{\zeta} \ln \left( 1 - g(x^*) + g(x^*)e^{-CT_M} \right) \forall x \in [0,x^*].
\]

(32)

As \(-x - \frac{1}{\zeta} \ln \left( 1 - g(x) + g(x)e^{-CT_M} \right)\) is continuous, a necessary condition for (32) to be satisfied is that the slope of the left-hand-side of (32) (w.r.t. \(x\)) is non-negative at \(x = x^*\). Therefore the necessary condition for (32) to hold true is:

\[
\frac{-1}{\zeta} \frac{g'(x^*)(e^{-CT_M} - 1)}{1 - g(x^*)(1 - e^{-CT_M})} - 1 \geq 0.
\]

(33)

Simplifying (33) yields the condition that \( (1 - e^{-CT_M}) \left[ \frac{\alpha x^*}{\zeta} + g(x^*) \right] \geq 1 \). Since \( (1 - e^{-CT_M}) < 1 \), we get the following necessary condition:

\[
\zeta < \frac{g'(x^*)}{1 - g(x^*)}.
\]

(34)

**Proof of Corollary 1**: If \( g(x) \) is given by \( g(x) = 1 - e^{-\alpha x} \), then \( \frac{g'(x)}{1 - g(x)} = \alpha \forall x \). Therefore, the necessary condition (34) reduces to \( \zeta < \alpha \). Next we will show that this condition is also sufficient to attain the first-best outcome for this case. To show sufficiency, we need to show that if \( \zeta < \alpha \), then (32) can be satisfied. The slope of the left-hand-side of (32) is \( \frac{1}{\zeta} \frac{g'(x)(1 - e^{-CT_M})}{1 - g(x)(1 - e^{-CT_M})} - 1 \). Setting \( T_M \geq \frac{1}{\zeta} \ln \left( \frac{\alpha x^* + \alpha - \zeta}{\alpha - \zeta} \right) \) yields,

\[
1 \frac{g'(x)(1 - e^{-CT_M})}{\zeta (1 - g(x)(1 - e^{-CT_M}))} - 1 \geq 1 \frac{g'(x)\alpha^x (\alpha - \zeta)}{\zeta (1 - g(x))\zeta e^{-CT_M} (\alpha - \zeta)} - 1.
\]

Substituting the functional form of \( g(x) \) in the right-hand-side of (35) yields

\[
1 \frac{g'(x)(1 - e^{-CT_M})}{\zeta (1 - g(x)(1 - e^{-CT_M}))} - 1 \geq \frac{\alpha x^* - \alpha - \zeta}{\zeta e^{-CT_M} (\alpha - \zeta)} > 0 \forall x \in [0,x^*].
\]

(36)

Therefore, \( \frac{1}{\zeta} \ln \left( \frac{1 - \frac{e^{(1-x^*)}}{(\zeta \alpha x^* + \alpha - \zeta)}}{\frac{\alpha x^*}{\alpha - \zeta}} \right) - x \) is increasing in \(x \in [0,x^*]\) and hence \( \alpha > \zeta \) is necessary and sufficient. The milestone payment that attains the first-best outcome is \( T_M \geq \frac{1}{\zeta} \ln \left( \frac{\alpha x^* + \alpha - \zeta}{\alpha - \zeta} \right) \).

**Proof of Proposition 4**: (i) From (12), the provider’s problem is:

\[
\max_{x \geq 0} \min_{y \geq 0} \left\{ U^{-1} \left( U^{-1}_p(x) \right) + \beta G(x), T_2 - x \right\}.
\]

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

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

(37)

Comparing (37) 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 conditions C2 and C3 are satisfied. Our claim is
that to attain the first-best outcome we need to show that for a given \( \hat{M} \), the following condition is necessary and sufficient:

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

(38)

To show sufficiency, let us assume that (38) is satisfied for some \( T_1 \). Set \( T_2 \) such that

\[
T_2 - x^* = 0.
\]

(39)

Equations (38) and (39) 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, \( \min \{ U^{-1}(U_p^1(x)) + \beta G(x), T_2 - x \} = U^{-1}(U_p^1(x)) + \beta G(x) \leq 0 \) (from 38). Assume that the provider invests \( x > x^* \). In this case the provider’s utility is, \( \min \{ U^{-1}(U_p^1(x)) + \beta G(x), T_2 - x \} \leq T_2 - x < 0 \) (from 39). Hence the provider will invest \( x = x^* \), as deviating is not beneficial.

Next we will show that (38) 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 \( U^{-1}(U_p^1(\tilde{x})) + \beta G(\tilde{x}) > U^{-1}(U_p^1(x^*)) + \beta G(x^*) \). Since first-best is assumed to exist, from condition C2 we have that \( \min \{ U^{-1}(U_p^1(x)) + \beta G(x^*), \tau_2 - x^* \} = 0 \). This implies that, \( U^{-1}(U_p^1(x^*)) + \beta G(x^*) \geq 0 \) and \( \tau_2 - x^* \geq 0 \). Since \( U^{-1}(U_p^1(\tilde{x})) + \beta G(\tilde{x}) > U^{-1}(U_p^1(x^*)) + \beta G(x^*) \) and \( \tilde{x} < x^* \), if the provider invests \( \tilde{x} < x^* \), its utility is \( \min \{ U^{-1}(U_p^1(\tilde{x})) + \beta G(\tilde{x}), \tau_2 - \tilde{x} \} > \min \{ U^{-1}(U_p^1(x^*)) + \beta G(x^*), \tau_2 - x^* \} = 0 \); and hence the client cannot attain the first-best outcome as the condition C2 is violated. 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 \( U^{-1}(U_p^1(x^*)) + \beta G(x^*) \leq U^{-1}(U_p^1(x^*)) + \beta G(x^*) \forall x \in [0, x^*]. \) We need to show that it must be that \( U^{-1}(U_p^1(x^*)) + \beta G(x^*) = 0 \). Clearly it cannot be the case that \( U^{-1}(U_p^1(x^*)) + \beta G(x^*) < 0 \), as then \( \min \{ U^{-1}(U_p^1(x^*)) + \beta G(x^*), T_2 - x^* \} < 0 \) which violates C3. If \( U^{-1}(U_p^1(x^*)) + \beta G(x^*) > 0 \), then \( \exists \epsilon \to 0^+ \) such that \( U^{-1}(U_p^1(x^* - \epsilon)) + \beta G(x^* - \epsilon) > 0 \), due to the continuity of the function \( h(x) = U^{-1}(U_p^1(x)) + \beta G(x) \). Since first-best is assumed to exist, from condition C2 we have that \( \min \{ U^{-1}(U_p^1(x^*)) + \beta G(x^*), \tilde{\tau}_2 - x^* \} = 0 \). This implies that \( \tilde{\tau}_2 - x^* \geq 0 \). Since \( U^{-1}(U_p^1(x^* - \epsilon)) + \beta G(x^* - \epsilon) > 0 \) and \( \tilde{x} < x^* \), if the provider invests \( x^* - \epsilon \), its utility is \( \min \{ U^{-1}(U_p^1(x^* - \epsilon)) + \beta G(x^* - \epsilon), \tilde{\tau}_2 - x^* + \epsilon \} > \min \{ 0, \tau_2 - x^* \} = 0 \); and hence the client cannot attain the first-best outcome as the condition C2 is violated. Therefore, (38) gives the necessary and sufficient condition for the attainment of the first-best outcome. Substituting \( G(x) \) in (38) yields the necessary and sufficient condition stated in the proposition

\[
\exists T_1 \text{ s.t. } \beta (V(x)g(x) - T_1 - x) + (1 - \beta)U^{-1}(U_p^1(x)) \leq \beta (V(x^*)g(x^*) - T_1 - x^*) + (1 - \beta)U^{-1}(U_p^1(x^*)) = 0 \forall x \in [0, x^*].
\]

(40)

(ii) When \( \beta = 1 \), (40) reduces to

\[
\exists T_1 \text{ s.t. } V(x)g(x) - T_1 - x \leq V(x^*)g(x^*) - T_1 - x^* = 0 \forall x \in [0, x^*].
\]

(41)

The above condition is true by definition of \( x^* \) and by setting \( T_1 = V(x^*)g(x^*) - x^* \).

**Proof of Corollary 2:** (i) If \( \hat{M} = 0 \) then \( U^{-1}(U_p^1(x)) = -T_1 - x \). The necessary and sufficient condition to attain the first-best solution becomes:

\[
\exists T_1 \text{ s.t. } \beta V(x)g(x) - T_1 - x \leq \beta V(x^*)g(x^*) - T_1 - x^* = 0 \forall x \in [0, x^*].
\]

(42)
Since $\beta V(x)g(x) - T_1 - x$ is a continuous function, for (42) to hold it must be that
\[
\beta \frac{\partial V(x)g(x)}{\partial x} |_{x=x^*} \geq 1. \tag{43}
\]
From the definition of $x^*$, we know that
\[
\frac{\partial V(x)g(x)}{\partial x} |_{x=x^*} = 1. \tag{44}
\]
Since $\beta < 1$, (44) implies that (43) cannot be true and hence the first-best outcome is not attained.

(ii) Since $\beta V(x)g(x) - T_1 - x + (1 - \beta)U^{-1}(U^T_1(x))$ is a continuous function, for the necessary and sufficient condition in Proposition 4 to hold it must be that
\[
\beta \left(\frac{\partial V(x)g(x)}{\partial x} - 1\right) |_{x=x^*} + (1 - \beta) \frac{\partial U^{-1}(U^T_1(x))}{\partial x} |_{x=x^*} \geq 0. \tag{45}
\]
From the definition of $x^*$, we know that
\[
\left(\frac{\partial V(x)g(x)}{\partial x} - 1\right) |_{x=x^*} = 0. \tag{46}
\]
Since $\beta < 1$, for (45) to hold we necessarily need
\[
\frac{\partial U^{-1}(U^T_1(x))}{\partial x} |_{x=x^*} \geq \frac{\partial V(x)g(x)}{\partial x} - 1 |_{x=x^*} = 0.
\]

**Proof of Proposition 5:** Assume that for a given $\tilde{M}$, $\exists T_1$ s.t. $U^{-1}(U^T_1(x)) \leq U^{-1}(U^T_\tilde{M}(x^*)) = 0 \forall x \in [0, x^*)$. This implies that the buyout options contract attains the first-best outcome. The necessary and sufficient condition to attain the first-best outcome for milestone-based options contract is $\exists T_M, T_A$ s.t. $U^{-1}(U^T_M(x)) \leq U^{-1}(U^T_A(x^*)) = 0 \forall x \in [0, x^*)$. Therefore it is straightforward to check that by setting $T_M = \tilde{M}$ and $T_A = -T_1$, the necessary and sufficient condition for milestone-based options contracts are satisfied.

We omit the proof of showing that when milestone-based options contracts attain the first-best it is not necessary that buyout options contracts will also attain the first-best outcome. This result follows directly from Proposition 6.

**Proof of Proposition 6:** In this case we assume that $\beta < 1$. If $U(\cdot)$ is given by the CARA model, then the necessary and sufficient condition (40) reduces to
\[
\exists T_1 \text{ s.t. } \beta V(x)g(x) - T_1 - x - (1 - \beta) \frac{1}{\zeta} \ln \left(1 - g(x) + g(x)e^{-\zeta T_1}\right)
\leq \beta V(x^*)g(x^*) - T_1 - x^* - (1 - \beta) \frac{1}{\zeta} \ln \left(1 - g(x^*) + g(x^*)e^{-\zeta T_1}\right) = 0 \forall x \in [0, x^*). \tag{47}
\]
Therefore, it is necessary that $T_1 = \beta V(x^*)g(x^*) - x^* - (1 - \beta) \frac{1}{\zeta} \ln \left(1 - g(x^*) + g(x^*)e^{-\zeta T_1}\right)$. The necessary and sufficient condition (47) reduces to
\[
\beta V(x)g(x) - x - (1 - \beta) \left(\frac{1}{\zeta} \ln \left(1 - g(x) + g(x)e^{-\zeta T_1}\right) + x\right)
\leq \beta V(x^*)g(x^*) - x^* - (1 - \beta) \left(\frac{1}{\zeta} \ln \left(1 - g(x^*) + g(x^*)e^{-\zeta T_1}\right) + x^*\right) \forall x \in [0, x^*). \tag{48}
\]
Using the definition of $x^*(48)$ reduces to
\[
\frac{1}{\zeta} \ln \left(1 - g(x) + g(x)e^{-\zeta T_1}\right) + x \geq \frac{1}{\zeta} \ln \left(1 - g(x^*) + g(x^*)e^{-\zeta T_1}\right) + x^* \forall x \in [0, x^*). \tag{49}
\]
Define $\delta(x)$ as the derivative of $\frac{1}{\zeta} \ln \left(1 - g(x) + g(x)e^{-\zeta M}\right) + x$ with respect to $x$. Therefore, we have the following:

$$\delta(x) = 1 - \frac{1}{\zeta} \frac{g'(x)(1 - e^{-\zeta M})}{1 - g(x)g(x)e^{-\zeta M}}.$$  \hfill (50)

As $x + \frac{1}{\zeta} \ln \left(1 - g(x) + g(x)e^{-\zeta M}\right)$ is continuous, a necessary condition for (49) to be satisfied is that $\delta(x^*)$ is non-positive. Therefore the necessary condition for (49) to hold true is:

$$1 - \frac{1}{\zeta} \frac{g'(x^*)(1 - e^{-\zeta M})}{1 - g(x^*)(1 - e^{-\zeta M})} \leq 0.$$  \hfill (51)

Simplifying (51) yields the condition that $(1 - e^{-\zeta M})\left(\frac{g'(x^*)}{\zeta} + g(x^*)\right) \geq 1$. Since $(1 - e^{-\zeta M}) < 1$, we get the following necessary conditions:

$$\zeta < \frac{g'(x^*)}{1 - g(x^*)},$$  \hfill (52)

$$\tilde{M} \geq \frac{1}{\zeta} \ln \left(\frac{g'(x^*) + \zeta g(x^*)}{g'(x^*) + \zeta g(x^*) - \zeta}\right).$$  \hfill (53)

From Proposition 3 case (i), we know that when $\beta > 0$ and $U(\cdot)$ has the CARA functional form, milestone-based options contract always attain the first-best outcome. From Proposition 3 case (ii) we know that milestone-based options contracts attain the first-best outcome only if $\zeta < \frac{g'(x^*)}{1 - g(x^*)}$.

**Functions and parameters values for numerical example**

We assume the following functional forms for all the numerical examples presented in the paper: $g(x) = 1 - e^{-\theta x}, f(\phi, x, y) = \lambda(x, y)e^{-\lambda(x, y)\phi}, 1/\lambda(x, y) = \beta x^\gamma y^\delta, U(z) = \eta(1 - e^{\zeta z})$.

The parameter values assumed are, $\gamma = 10^{-4}, \theta = 0.7, \beta = 150, \alpha = 5.0 \times 10^{-7}, \zeta = 2 \times 10^{-8}, \eta = 10^7$.

With these functions and parameters we have, $x^* = 3.2367 \times 10^5, y^* = 5.4846 \times 10^6, g(x^*) = 0.14942, E[\phi] = \beta (x^*)^\gamma(y^*)^\delta = 7.835 \times 10^6$.

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