

Milestone Payments or Royalties? Contract Design for R&D Licensing

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We study how innovators can optimally design licensing contracts when there is incomplete information on the licensee's valuation of the innovation, and limited control over the licensee's development efforts. A licensing contract typically contains an up-front payment, milestone payments at successful completion of a project phase, and royalties on sales. We use principal-agent models to formulate the licensor's contracting problem, and we find that under adverse selection, the optimal contract structure changes with the licensee's valuation of the innovation. As the licensee's valuation increases, the licensor's optimal level of involvement in the development—directly or through royalties—should decrease. Only a risk-averse licensor should include both up-front and milestone payments. Moral hazard alone is not detrimental to the licensor's value, but may create an additional value loss when combined with adverse selection. Our results inform managerial practice about the advantages and disadvantages of the different terms included in licensing contracts and recommend the optimal composition of the contract.

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1. Introduction

Licensing deals are becoming more prevalent in a variety of R&D-intensive industries. In the pharmaceutical industry, for example, many biotechnology companies develop their R&D projects up to proof of principle and then look for a large pharmaceutical industry partner. Soaring drug development costs imply that smaller biotech companies may not have the financial and organizational capabilities to fully develop new drugs. Large pharmaceutical companies, however, do have the financial means and the marketing clout to successfully bring the products to market. They are also under pressure to introduce new products to sustain their sales and, in recent years, their internal pipelines have sometimes been inadequate, prompting demand for in-licensing opportunities. This increasing demand for in-licensing has improved the biotech companies' cash position, raising their bargaining power, and has created a seller's market.

Licensing deals are governed by contracts that specify a sequence of payments from the licensee to the licensor, typically in the form of an up-front payment, milestone

payments upon completion of specific stages in the product development, and royalties on sales. During licensing negotiations, two questions may arise. First, because the magnitude of these payments taken together depends on the value of the project, the question arises how valuable the project is. Valuation of R&D projects is complex and subject to many uncertainties, both technical and commercial. As a result, disagreements can arise between the licensor and licensee. For example, in 2002, Endovasc terminated a confidentiality agreement with a pharmaceutical company reviewing scientific developments associated with Angiogenix, a nicotine-based heart treatment, amid expressions of interest from other companies and lack of progress in the discussions with the former company (*Triangle Business Journal* 2002). Endovasc finally received a grant from Philip Morris to fund their research (Market Wire 2002). This difference in expressed value can be real, or can be due to one of the negotiation partners misrepresenting their opinion in order to try and secure a more favorable licensing deal. A second question is how to structure the licensing contract itself, i.e., which of the three types of payments

should be used, and in which amounts. The licensor and licensee can have different opinions of the value of each of the three types of payments, and the structure of the contract can influence the licensee's behavior when further developing the product, by providing (dis)incentives to invest appropriately. For example, in 2002, Neopharm terminated an agreement with Pharmacia because of its alleged lack of promotion of its products under license (Neopharm 2002); in 2005, Gilead claimed that Roche underperformed at both manufacturing and promoting Tamiflu (Gilead 2005); and recently, Nektar of San Carlos, California, accused Pfizer of a poor marketing job after Pfizer decided to withdraw the in-licensed insulin inhaler Exubera, resulting in one of the pharmaceutical industry's costliest failures ever (Johnson 2007).

This research is inspired by a problem that was brought to our attention by Phytopharm, a pharmaceutical development and functional food company based in Cambridgeshire, United Kingdom, which was starting negotiations for the licensing of one of its products and required a model to value the project and to facilitate the negotiations (Crama et al. 2007). A major difficulty in reaching an agreement was a disagreement concerning the likelihood of technical success of the product, i.e., the probability that the product will successfully pass all the required clinical trials and obtain approval for launching the product on the market. This likelihood of technical success directly influences the value of the product, and therefore the magnitude of the payments specified in the contract. Additionally, differences in the probability of technical success (PTS) estimates also result in different valuations for each of the three types of payments, and may influence the licensee's behavior, over which the licensor only has limited control after granting the license. In this paper, we present a model to aid a licensor to optimally design licensing contracts when there is incomplete information on the licensee's valuation for the product, focusing on disagreements on the PTS, and limited control over the licensee's development efforts. We will use the model to derive insights on which contract structures are appropriate in different situations of information asymmetry and control over the licensee's actions.

We model the problem as follows. The licensor offers to out-license an R&D project, consisting of a sequence of research phases, each with a PTS. Both the licensor (he) and the licensee (she) make an estimate of the PTS, based on their own experience. The licensor does not know the licensee's estimate of the PTS, but has an idea of the range in which it could be. The licensor and licensee also share information regarding the required development costs and sales estimates. The licensor proposes a contract that typically contains an up-front payment at contract signature, milestone payments after successful completion of a research phase, and a royalty rate specified as a percentage of sales. The problem essentially is whether each of these contract elements should be included in the contract, and how high each payment should be, for the licensor to

obtain the maximum value out of the licensing agreement. After contract signature, the licensee will spend resources and money to further develop and market the project. It is standard practice in the pharmaceutical industry to invest in prelaunch marketing and construction of dedicated production facilities to enable fast sales growth.

Our contributions are fourfold. First, we present a licensing problem in which we explicitly allow for different priors regarding the projects' PTS. To the best of our knowledge, this problem in licensing contract design has not yet been explored in the literature. There are several reasons why a licensor and licensee could have different PTS estimates. For example, pharmaceutical companies may use their own in-house expertise to make PTS estimates based on the project data rather than rely on the licensor's estimates. As Macho-Stadler et al. (1996, p. 44) point out, "the licensee is in some cases better acquainted with [...] the application of the innovation to his productive process." The estimates may differ as the experts adjust them to the specificities of the project and the company's own expertise in the field. In situations where the licensee is a nonpharmaceutical company, it may have limited knowledge about the project, and might therefore be wary of the estimates presented by the licensor, preferring their own, typically more conservative, estimates. Because the PTS estimate has a major impact on the project's value, we also have to consider the licensee's incentive to understate her estimate to impose more favorable contract terms. Therefore, we study how the licensor can optimally design licensing contracts in the face of hidden information concerning the licensee's project valuation, which creates a problem of adverse selection. Using a contract theory framework, we develop a principal-agent model with the licensor as a principal. We also incorporate hidden action in the form of incomplete information concerning the licensee's efforts to market the product, giving rise to moral hazard.

Second, we use a richer contract structure than commonly studied in the literature, where many screening contracts are two-part tariffs, containing a fixed fee and a variable component. In accordance with observed business practice, we include a milestone payment as an additional contract element, creating a three-part tariff, and analyze its effect on the principal's ability to contract. A milestone payment is a fixed fee, but unlike the up-front payment, its valuation may differ for the licensor and the licensee as well as between licensees holding different PTS estimates. We investigate whether this allows the licensor to use the milestone payment as an instrument to screen the licensee and whether it confers an advantage over the classic two-part tariff.

Third, we obtain a number of managerial insights for designing optimal licensing contracts. We find that, although in practice a licensor often prefers an up-front payment to royalties, this can be detrimental to his value. Even a risk-averse licensor should not necessarily sell the project for an up-front payment only; if he has a higher

valuation than the licensee, he should prefer at least some amount to be paid at project completion. We show that adverse selection puts a stronger emphasis on payments at project completion in the licensor's optimal contract. Moral hazard does not have a detrimental effect on the licensor's value unless it is compounded by adverse selection. The licensor's risk attitude determines the structure of the contract: only a risk-averse licensor should offer a contract with both an up-front and a milestone payment.

Finally, this is a real problem of practical importance for licensing deals in the pharmaceutical industry. Our model can be used to explain observed contracts in practice. We propose one possible explanation for the presence of the different elements in licensing contracts, up-front payment, milestone payment, and royalty rate. Indeed, Phytopharm felt that many factors, such as their risk aversion and the licensee's valuation of the project, would influence the contract structure, but was not sure how to take them into account in their offer.

Section 2 gives an overview of the literature on innovation and licensing in economics and management science. Section 3 describes the model and notation used throughout the paper. Section 4 presents the solution to the licensor's contract design problem under different assumptions of available information concerning the licensee's project valuation and marketing effort. In §5, we conclude with the managerial insights that can be drawn from our analytical results and explore avenues for future research. All the proofs and derivations are available in the electronic companion to this paper, which is available as part of the online version that can be found at <http://or.journal.informs.org/>.

2. Literature Review

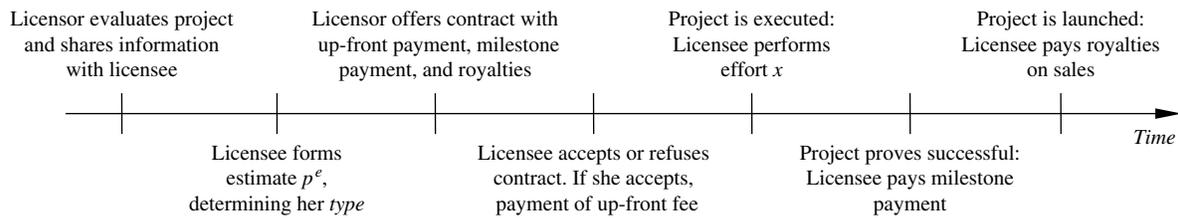
Adverse selection and moral hazard problems are studied in many different areas, such as marketing (Bergen et al. 1992, Desai and Srinivasan 1995), regulation economics (Laffont 1994), and labor markets (Prendergast 1999). A general review of information economics can be found in Stiglitz (2000). However, in this section we focus on some of the relevant papers in the literature on innovation and licensing. A first stream of research focuses on the socially optimal exploitation of innovation and the impact of licensing contracts on the incentive to innovate. Tandon (1982) analyzes the optimal patent length and compulsory licensing to prevent monopolies without destroying the incentive to innovate. Shapiro (1985) finds that licensing increases social welfare by disseminating the innovation's benefits and the inventor's incentive to innovate by generating revenues. Aghion and Tirole (1994) present a contractual model of R&D activities conducted by two different agents and analyze the allocation of property rights. They show that the allocation of ownership depends on (a) the impact of the party's effort on the project value, and (b) the ex ante bargaining power, or the intellectual property right to the research idea. The authors prove under which conditions the parties' private optimum coincides with the social optimum.

Several researchers have evaluated the conditions under which it is beneficial for an innovator to license his technology. The model in Katz and Shapiro (1985) recognizes the effect on the licensing decision of the innovation's impact and the firms' relative efficiency, using a fixed-fee contract. Rockett (1990) studies an incumbent with two potential entrants of different abilities and enumerates the conditions under which the innovator will license, against a fixed fee, to either both competitors, one competitor, or none. Her research illustrates the strategic use of know-how by the incumbent to proactively prevent entry from competitors. Her findings are revisited by Yi (1998), who finds that it is always in the licensor's interest to license to the company that has the better ability to incorporate the innovation, if a two-part contract is possible. Amit et al. (1990) show that, besides the real need for financing, risk-averse entrepreneurs are interested to sell their venture to a venture capitalist to share the risk. Risk sharing is also the driving force behind licensing contracts in Bousquet et al. (1998). Hill (1992) lists the many dimensions that influence the innovator's decision to license, such as the speed of imitation, the importance of first-mover advantages, and the transaction costs of licensing. Further factors include competitive intensity, the number of capable competitors, the rent-yielding potential of the innovation, the height of barriers to imitation, and cash flow considerations. An additional reason for licensing may be to impose the new technology in the industry (Gallini 1984, Shepard 1987).

The structure of the contract offered by the innovator has also been studied. Both Katz and Shapiro (1986) and Kamien and Tauman (1986) present the optimal licensing contracting strategy for an innovator after innovation has occurred. In Katz and Shapiro (1986), the innovator uses an auction system with a fixed number of licenses available. The authors then compare the innovator's selling price to the social optimum. Kamien and Tauman (1986) allow the innovator to pursue the following strategies: enter the market himself, license for a fixed-fee contract, or for a contract consisting of royalties. The authors find that the innovator prefers to offer a fixed-fee contract to a limited number of companies rather than a royalties contract.

Only a few of the above papers assume that some uncertain R&D activities are still to be completed, such as Aghion and Tirole (1994) or Amit et al. (1990). If one of the parties has to execute remaining R&D activities, the licensing contract structure gains additional importance as an incentive tool. Dayanand and Padman (2001) show that for projects with certain activities, the timing and the amount of the milestone payments influence the subcontractor's preferred project execution. Whang (1992) models the incentive problem for uncertain projects and presents an optimal contract that guarantees that the subcontractor's optimal project execution is equal to the principal's optimal execution.

Whereas many of these papers assume that there is no informational asymmetry, the abovementioned paper

Figure 1. Timeline of project negotiations.

by Amit et al. (1990) includes precontractual information asymmetry leading to problems of adverse selection: only the entrepreneurs with relatively lower skills sell out to venture capitalists. Gallini and Wright (1990) present a model in which the innovator signals his private knowledge of the quality of his innovation through adapted contracts in which a good innovator accepts payment partially in royalties, whereas a bad innovator demands a fixed fee. Beggs (1992) similarly concludes that the licensee can offer royalties to signal his valuation of the innovation in the presence of informational asymmetries. Thursby et al. (2005) explore a licensing model for the development and marketing of university research under different assumptions of moral hazard and adverse selection, and propose adequate contract terms to deal with each situation, including up-front payments, milestone payments and royalties, joint research cooperation, and annual payments. Other papers justifying the inclusion of royalties in the optimal contract because of moral hazard include Jensen and Thursby (2001) and Macho-Stadler et al. (1996). These papers assume an objective, shared valuation of the project.

A fundamental difference of the problem studied in this paper with the literature is that we consider situations in which the licensor and the licensee do not necessarily agree on the PTS of the R&D project, and therefore its value. A similar issue can be found in supply chain management, where the buyer may have incomplete information on the quality of the provided products or services. This problem is typically tackled using a combination of warranties, price rebates, and quality inspection (Baiman et al. 2000, 2001; Lim 2001; Iyer et al. 2005). Unfortunately, these mechanisms are difficult to implement for R&D projects. Inspection is only useful when a large number of products is delivered, rather than a single project, and warranties on pharmaceutical projects do not make a lot of sense because failure is typically the most likely outcome, and not an exception.

We choose the licensor as the principal because we have observed (Crama et al. 2007) that the licensor typically has bargaining power and initiates negotiations with several partners, offering a unique project protected by intellectual property rights, giving him monopoly power. In addition, the growing maturity of the biotech industry coupled with the increasing demand for in-licensing has increased the bargaining power of the licensor, a fact which is reflected in the value of recent deals (Hamilton 2006, Orr and Urquhart 2006).

3. Model Description

The licensor's contract design problem is modeled using a principal-agent framework with hidden information and hidden action, in which the licensor is the principal. The timing of the contract negotiations is as follows (see Figure 1). After the licensee receives the project information from the licensor, including the project scope, cost, timing, and results from previous R&D phases, she forms her PTS estimate of the project, p^e , defining her *type*. Then, the licensor offers a contract to the licensee, and if the licensee accepts the contract, the project is executed. During execution, the licensee performs a variety of demand-enhancing activities, the magnitude of which is denoted by x . The licensee makes the payments to the licensor as specified in the contract, depending on the project's development and commercial success. In this paper, we consider a project that only contains a single research phase, which is sufficient to observe the trade-off between a certain, up-front payment, and uncertain future payments in the form of a milestone payment or a royalty.

3.1. The Generic Principal-Agent Model

We will first introduce the generic principal-agent model, and then show how it can be applied and modified to our situation. Consider the following model notation:

$\theta \in \Theta \subset R$: agent's type, unknown to the principal, belonging to support Θ , a continuous interval in R .

$F(\theta), f(\theta)$: cumulative distribution and probability density function of agent's type.

$g_i(\theta): \Theta \rightarrow R, i = 1, \dots, n$: contract terms, e.g., product quality and price ($n = 2$), potentially dependent on the agent's type, continuous with a finite number of discontinuities in the first derivative.

$T(\theta) = \{g_1(\theta), \dots, g_n(\theta)\}$: contract function, a vector of contract term functions; principal's decision variable.

$\nu \in \Theta$: agent's revealed type, belonging to support Θ , revealed to the principal by the choice of contract by the agent; agent's decision variable.

$x \in R$: agent's action; agent's decision variable.

$u^P(T(\theta), x)$: principal's utility function.

$u^A(T(\theta), x, \theta)$: agent's utility function.

$\underline{u}^A(\theta)$: agent's reservation utility.

Let us introduce a clarifying example of the notation of the principal-agent model, in which the principal is an employer, and the agent an employee. Assume two types

of employees: efficient (θ^H) and inefficient (θ^L) employees. The employer can offer contracts specifying a fixed salary (g_1) and an outcome-based remuneration as a percentage of profit (g_2). The fixed salary and outcome-based remuneration form the contract T ($n = 2$). For example, the employer can choose to offer a contract offering a base salary only, $T^1 = \{g_1^1 = 10, g_2^1 = 0\%$, as well as an outcome-based contract, $T^2 = \{g_1^2 = 6, g_2^2 = 10\%$. Dependent on her type, the employee will choose the contract that maximizes her profit.

The principal-agent model is an optimization over functions. The principal's optimization over contract functions is subject to the agent's optimal reaction to those contract functions. The principal chooses a contract function designed to appeal differently to varying agent's types. This contract function is an input for the agent to maximize her value. The agent chooses to disclose a type, ν , which determines the contract terms she is offered, and also chooses an action, x . The principal anticipates the agent's optimal reaction to the contract function, ν^* and x^* , and incorporates it as a constraint in his maximization problem as seen below:

$$\max_{T(), \nu^*, x^*} E_\theta [u^P(T(\nu^*(T(), \theta)), x^*(T(), \theta))] \quad (1)$$

subject to $\forall \theta \in \Theta: \{\nu^*(T(), \theta), x^*(T(), \theta)\}$

$$\in \arg \max_{\nu \in \Theta, x} \{u^A(T(\nu), x, \theta)\} \quad (2)$$

$$\forall \theta \in \Theta: u^A(T(\nu^*(T(), \theta)), x^*(T(), \theta), \theta) \geq \underline{u}^A(\theta). \quad (3)$$

Equation (1) is the principal's expected utility over all agent types, taking into account the agent's optimal contract and action choice. The feasible space is determined by the agent's optimization problem and reservation utility. Each agent type optimizes her utility by choosing the optimal contract through her revealed type ν^* and her optimal action x^* (Equation (2)). If there are several alternative actions and revealed types that are equivalent for the agent, the principal can choose the one that maximizes his value. An agent only participates in the contract if her maximum utility is higher than her reservation utility (Equation (3)).

The revelation principle (Salanié 1997, p. 17) allows us to restrict the analysis to contracts that are a direct truthful mechanism such that the agent reveals her type θ , or $\nu^*(T(), \theta) = \theta$. This simplifies the principal's optimization problem because we can reduce the agent's optimization (Equation (2)) to the incentive compatibility (IC) constraints (Salanié 1997, p. 17), which ensure that an agent with type θ will obtain at least as much value from the contract $T(\theta)$ than from all other contracts $T(\nu)$, $\nu \in \Theta$, and thus will choose to reveal his type θ . The revelation principle states that any mechanism that optimizes the principal's objective given the agent's optimal behavior can be replaced with another mechanism with the following properties: (1) the only action the agents need to take is to reveal

their type, and (2) it is in the best interest of the agents to reveal their type truthfully. In other words, before invoking the revelation principle, an optimal mechanism $T()$ might have led some of the agents to misrepresent their type. After using the revelation principle, a new optimal contract function $T'()$ is found, under which the agents' optimization process leads to a truthful revelation of their type.

The generic principal-agent model can then be formulated as follows:

$$\max_{T(), x^*} E_\theta [u^P(T(\theta), x^*(T(), \theta))] \quad (4)$$

subject to $\forall \theta \in \Theta: \{\theta, x^*(T(), \theta)\}$

$$\in \arg \max_{\nu \in \Theta, x} \{u^A(T(\nu), x, \theta)\} \quad (5)$$

$$\forall \theta \in \Theta: u^A(T(\theta), x^*(T(), \theta), \theta) \geq \underline{u}^A(\theta). \quad (6)$$

Equation (4), the principal's objective function, is identical to Equation (1), except for the substitution $\nu^*(T(), \theta) = \theta$, as dictated by the revelation principle. When maximizing his utility, the principal incorporates the agent's optimal response to the contracts he proposes, modeled by the IC constraints in Equation (5). Due to the revelation principle, the agent's maximization problem can be replaced with the first-order condition for truthful revelation. Equation (6) is the individual rationality (IR) constraints, ensuring the agent's willingness to participate in the contract by ensuring that her utility is at least as high as her reservation utility.

3.2. The Licensing Contract Model

We assume that the licensor is either risk neutral or risk averse, and that the licensee is risk neutral. Biotech companies are typically risk averse because of their limited cash reserves and project pipelines containing only a few drugs in development, whereas large pharmaceutical companies are well diversified (Plambeck and Zenios 2003, Thursby et al. 2005). The licensor proposes a project to the licensee that can be executed at a cost c and has an unknown PTS p . The licensee reviews the project and evaluates $p^e \in [\underline{p}^e, \bar{p}^e] \subset [0, 1]$, her subjective PTS estimate of the project, which determines her type. The licensor does not know this value but knows the probability density function $f(p^e)$ and cumulative distribution function $F(p^e)$ on $[\underline{p}^e, \bar{p}^e]$, from which p^e is drawn. The licensor's estimate of the PTS is $p^o \in [0, 1]$. The licensee can also invest in demand-enhancing activities x , such as marketing and promotional effort, which determine the final payoff $s(x)$, provided the project is successful. The payoff function is concave with $s_x(x) > 0$ and $s_{xx}(x) < 0$, reflecting diminishing marginal returns. All the cash flows are expressed in present value and discounted to the project's start date.

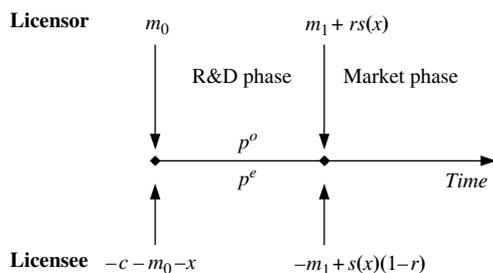
The licensee's PTS estimate and thus her project valuation is her private information and is unknown to the licensor. This creates *hidden information* or *adverse selection*

(AS). Thus, the licensor will have to design incentive-compatible contracts, which will make it unfavorable for an optimistic, or high-type, licensee to pretend to be a pessimistic, or low-type, licensee. Furthermore, because the licensee’s effort x is unknown at the contracting stage, the model includes *hidden action*, or *moral hazard* (MH).

The licensor proposes a contract $T = (m_0, m_1, r)$, defined in terms of a contract signature fee m_0 , a milestone payment m_1 at successful project completion, and a royalty percentage of the sales r . He can also offer a menu of contracts specifying different combinations of those terms, allowing the licensee to choose the contract she prefers, depending on her type. This happens as follows. The licensor can offer several different contracts, containing different combinations of contract elements, among which the licensee can choose. For example, the licensor could offer to sell the project for an up-front payment of 10 million without any future payments, or offer a contract including future payments, consisting of an up-front payment of 5 million, a milestone payment of 2 million, and 5% royalties on sales. The licensee can decide between those two contracts. Although the contract terms are not explicitly defined in terms of the licensee’s probability estimate, the valuation of the different contracts, and thus the licensee’s choice, will depend on the licensee’s probability estimate. Thus, the innovator can design contracts that are targeted at different licensee types.

The contract terms determine how the payoff of the project is divided between the partners. The key characteristic of the contract design problem is the trade-off between a certain, up-front payment and uncertain future payments in the form of a milestone payment and royalties. The cash flows are shown in Figure 2. The repartition of the project value depends on the relative bargaining power of both parties. To capture this, we introduce $\underline{u}^e(p^e) = \underline{u}^e$, the reservation utility of the licensee. This is the minimum payoff she requires to participate in the deal and can be considered as her opportunity cost. We do not consider the reservation utility to be dependent on the licensee type because her type is specific to the project, and not to outside opportunities (Salanié 1997). Furthermore, relaxing this assumption does not affect the qualitative results from our model, while greatly complicating the analytical exposition. Laffont and Martimort (2002) illustrate the complications that arise with type-dependent reservation utilities,

Figure 2. Contract structure.



and Jullien (2000) offers a characterization of the resulting optimal contract. A constant reservation utility is also in line with financial valuation theory, which recommends that management should undertake a project if its net present value exceeds zero.

If the licensee declares $q \in [p^e, \bar{p}^e]$ under a contract function $T(\cdot)$, she receives a value $V^e(q, p^e)$:

$$-c - m_0(q) - x^*(r(q), p^e) + p^e[(1 - r(q))s(x^*(r(q), p^e)) - m_1(q)],$$

with $x^*(r(q), p^e) = \arg \max_x \{-c - m_0(q) - x + p^e[(1 - r(q))s(x) - m_1(q)]\}$. We write $x^*(r(q), p^e)$ rather than $x^*(T(q), p^e)$ because the optimal effort level is only influenced by the royalty rate and not by the other contract elements.

With probability $(1 - p^o)$ the licensor receives the contract signature fee m_0 only; with probability p^o he receives a total of $m_0 + m_1 + rs(x)$. Thus, the licensor’s total expected utility, depending on the licensee type, is

$$p^o u^o(m_0(p^e) + m_1(p^e) + r(p^e)s(x^*(r(p^e), p^e))) + (1 - p^o)u^o(m_0(p^e)), \tag{7}$$

where we assume that $u^o(z)$ is the licensor’s Von Neumann-Morgenstern utility function, with $u^o_z \geq 0$, $u^o_{zz} \leq 0$, and where the contract terms $m_0(p^e)$, $m_1(p^e)$, and $r(p^e)$ are designed for a licensee with PTS estimate p^e . Future sales depend on the licensee’s demand-enhancing activity $x^*(r(p^e), p^e)$. We write the sales as $s(x^*(r(p^e), p^e))$.

The licensor maximizes his expected utility over the cumulative distribution function $F(p^e)$ of the licensee types. The licensor can propose a menu of contracts depending on the licensee’s PTS estimate. Similar to the final version of the principal-agent model, the licensor’s optimization problem is

$$\max_{m_0(\cdot), m_1(\cdot), r(\cdot), x^*} \int_{p^e}^{\bar{p}^e} [p^o u^o(m_0(p^e) + m_1(p^e) + r(p^e)s(x^*(r(p^e), p^e))) + (1 - p^o)u^o(m_0(p^e))] dF(p^e) \tag{8}$$

subject to

$$\forall p^e \in [\underline{p}^e, \bar{p}^e]: \{p^e, x^*(r(p^e), p^e)\} \in \arg \max_{q \in [\underline{p}^e, \bar{p}^e], x} \{-c - m_0(q) - x + p^e[-m_1(q) + (1 - r(q))s(x)]\}, \tag{9}$$

$$\forall p^e \in [\underline{p}^e, \bar{p}^e]: -c - m_0(p^e) - x^*(r(p^e), p^e) + p^e[-m_1(p^e) + (1 - r(p^e))s(x^*(r(p^e), p^e))] \geq \underline{u}^e, \tag{10}$$

$$\forall p^e \in [\underline{p}^e, \bar{p}^e]: m_0(p^e) \geq 0; m_1(p^e) \geq 0; r(p^e) \geq 0. \tag{11}$$

Table 1. Application of the generic principal-agent model to our licensing contract design model.

Classical model	Explanation	Licensing model
$\theta \in \Theta \subset R$	Agent's type: a characteristic of the agent that determines her utility from the contract	$p^e \in [\underline{p}^e, \bar{p}^e], 0 \leq \underline{p}^e \leq \bar{p}^e \leq 1$
$F(\theta), f(\theta)$	Cumulative distribution and probability density function of agent's type	$F(p^e), f(p^e)$
$T(\theta) = \{g_1(\theta), \dots, g_n(\theta)\}$	Contract function, vector of n contract term functions, potentially dependent on the agent's type	$\{m_0(p^e), m_1(p^e), r(p^e)\}$: $m_0(p^e)$: up-front payment $m_1(p^e)$: milestone payment $r(p^e)$: royalty rate
$\nu \in \Theta$	Agent's revealed type	$q \in [\underline{p}^e, \bar{p}^e]$
$x \in R$	Agent's action	$x \in R^+$: licensee's effort level, it is optimal when $(1-r)p^e s_x = 1$
$u^P(T(\theta), x)$	Principal's utility from the contract with a licensee choosing the contract terms designed for type θ and taking action x	$p^o u^o(m_0(p^e) + m_1(p^e) + r(p^e)s(x)) + (1-p^o)u^o(m_0(p^e))$
$u^A(T(\theta), x, \theta)$	Type θ agent utility from the contract designed for type θ when taking action x	$-c - x - m_0(p^e) + p^e[(1-r(p^e))s(x) - m_1(p^e)]$
$\underline{u}^A(\theta)$	Type θ agent's reservation utility: the value of her outside opportunity	\underline{u}^e
$E_\theta[u^P(T(\theta), x^*(T(\cdot), \theta))]$	Principal's expected utility taken over the possible licensee types, with revelation principle	$\int_{\underline{p}^e}^{\bar{p}^e} [p^o u^o(m_0(p^e) + m_1(p^e) + r(p^e)s(x^*(r(p^e), p^e))) + (1-p^o)u^o(m_0(p^e))] dF(p^e)$
$\forall \theta \in \Theta: \{\theta, x^*(T(\cdot), \theta)\} \in \arg \max_{\nu \in \Theta, x} \{u^A(T(\nu), x, \theta)\}$	Agent's incentive compatibility constraint: ensures that the agent chooses the contract that was designed for her within the menu of contracts	$\forall p^e \in [\underline{p}^e, \bar{p}^e]:$ $\{p^e, x^*(r(p^e), p^e)\} \in \arg \max_{q \in [\underline{p}^e, \bar{p}^e], x} \{-c - m_0(q) - x + p^e[(1-r(q))s(x) - m_1(q)]\}$
$\forall \theta \in \Theta: u^A(T(\theta), x^*(T(\cdot), \theta), \theta) \geq \underline{u}^A(\theta)$	Agent's individual rationality constraint: ensures the agent's willingness to participate in the contract, with revelation principle	$\forall p^e \in [\underline{p}^e, \bar{p}^e]:$ $-c - m_0(p^e) - x^*(r(p^e), p^e) + p^e[-m_1(p^e) + (1-r(p^e))s(x^*(r(p^e), p^e))] \geq \underline{u}^e$

Equation (9) is the IC constraints. Under the revelation principle, we know that the contracts should be such that a licensee of type p^e will obtain at least as much value from the contract $T(p^e)$ as from all other contracts $T(q), q \in [\underline{p}^e, \bar{p}^e]$. The IC constraints ensure that optimal contract is a truthful mechanism, i.e., the licensee's revealed PTS $q^*(T(\cdot), p^e) = p^e$. The objective function, Equation (8), can directly use the licensee's type because Equation (9) ensures that it is equal to her revealed type. The contracts should also respect the licensee's IR constraints, Equation (10). These ensure the licensee's participation by requiring that the licensee's expected value from the contract exceed her reservation utility \underline{u}^e . Finally, we have the nonnegativity constraints on the contract elements typical for licensing contracts (Equation (11)).

In Table 1, we show how the generic principal-agent model is modified for R&D licensing contract design and list the notation employed throughout the paper.

4. Optimal Contract Structure

4.1. No Adverse Selection

First, we solve the problem under information symmetry, the first-best situation, to serve as a benchmark to the case with informational asymmetry. In the first-best situation, the licensor knows the estimate p^e of the licensee and her level of investment in the demand-enhancing activities x . Thus, the model can be solved for each possible realization of p^e separately, making the IC constraint redundant, because each licensee will be presented with one contract only, as determined by her type. The licensor selects a contract appropriate for the licensee's type, ensuring that the IR constraint holds with equality, i.e., the licensee receives her reservation utility. The optimal contract structure is described in Propositions 1 and 2 below. The proofs can be found in the online supplement to this paper.

PROPOSITION 1. *When the licensee's effort level is contractible, there always exists an optimal contract that does not contain royalties.*

We introduce the following notation: $z_f = m_0$ is the licensor's payoff in case of failure and $z_s = m_0 + m_1 + rs(x)$ is the payoff in case of success. The optimal solution is defined in Proposition 2. Using Proposition 1, we consider contracts with an up-front fee and milestone payment only. Equivalent contracts with royalties can be easily determined.

PROPOSITION 2. *If the licensor knows the licensee's type p^e and can control her effort level x , then the optimal effort level $x^*(p^e)$ is determined by equating the marginal expected sales to the marginal cost of effort, i.e., $p^e s_x = 1$, and the licensor's optimal contract contains the following elements:*

- *Case 1. $p^e \geq p^o$: The optimal contract is $(m_{0,\max}(p^e), 0, 0)$, where $m_{0,\max}(p^e) = -c - x^*(p^e) + p^e s(x^*) - \underline{u}^e$ is the maximum up-front payment that the licensee is willing to pay.*
- *Case 2. $p^e < p^o$: If*

$$p^e(1 - p^o)u_{z_f} \Big|_{z_f=0} \leq p^o(1 - p^e)u_{z_s} \Big|_{z_s=m_{1,\max}},$$

where $m_{1,\max}(p^e) = (-c - x^*(p^e) + p^e s(x^*) - \underline{u}^e)/p^e$ is the maximum milestone payment that the licensee is willing to pay, then the optimal contract is $(0, m_{1,\max}(p^e), 0)$.

Otherwise, the optimal contract is $(m_0^*(p^e), m_1^*(p^e), 0)$ such that $p^e(1 - p^o)u_{z_f} = p^o(1 - p^e)u_{z_s}$ and the individual rationality constraint holds.

The derivations can be found in the online appendix. The intuition behind these results is as follows. If the licensor's PTS estimate is lower than the licensee's (Case 1), the licensor should choose for an up-front payment. In this way, the licensor avoids all the risk, which is entirely borne by the licensee. However, if the licensor's estimate is higher than the licensee's (Case 2), the licensor may opt for a mix of a payment at contract signature and a milestone payment. The composition of the optimal contract is determined such that the weighted expected marginal utilities of both payments are equal. The optimal contract contains a milestone payment, although this exposes the licensor to risk, because the licensor values a payment at project completion more than the licensee believes it is worth. This result contrasts with observations made by other researchers using similar models (e.g., Mas-Colell et al. 1995, pp. 187–188), who found that under information symmetry, the risk-neutral party should bear all the risk if the other party is risk averse. Our result is different because of the divergence in the licensor's and licensee's PTS estimates.

To maximize his own utility, the licensor enforces an effort level x that maximizes the value of the project given the type of the licensee, i.e., when the cost of an additional unit of effort is equal to the expected marginal sales

increase. Indeed, the licensor's utility does not depend on sales, but only on the two lump-sum payments. Therefore, the higher the licensee's value, the more the licensor can claim. Consequently, even if the licensor cannot control the effort level x , the licensee will choose that effort level herself, and the licensor can propose the same contract defined by Proposition 2 and obtain the same value. In other words, moral hazard does not reduce the licensor's value in the absence of adverse selection. This finding is in line with Mas-Colell et al. (1995, pp. 482–483) and Desai and Srinivasan (1995).

This illustrates the superiority of a three-part tariff over a two-part tariff. In a two-part tariff, the licensor obtains a future cash flow by including a royalty in the contract, which reduces the licensee's incentive to invest in the demand-enhancing activity and thus decreases the project value and the licensor's utility. The three-part tariff has the advantage that the future milestone payment is a lump sum, which does not distort the licensee's incentive to invest.

Also note that because the project value increases in p^e and the licensee only receives her reservation utility irrespective of her type, it is clear that the licensor's utility is strictly increasing in the licensee's type.

A risk-neutral licensor, maximizing his expected net present value, should propose a contract with either an up-front payment or a milestone payment, but not both, unless $p^e = p^o$, when an infinite number of mixed optimal contracts exist. In the online appendix, we show that

- *Case 1. $p^e > p^o$: $m_0^*(p^e) = -c - x^*(p^e) + p^e s(x^*(p^e)) - \underline{u}^e$, $m_1^*(p^e) = 0$, $r^*(p^e) = 0$.*
- *Case 2. $p^e < p^o$: $m_0^*(p^e) = 0$, $m_1^*(p^e) = (-c - x^*(p^e) + p^e s(x^*(p^e)) - \underline{u}^e)/p^e$, $r^*(p^e) = 0$.*
- *Case 3. $p^e = p^o$: $m_0^*(p^e) \in [0, -c - x^*(p^e) + p^e s(x^*(p^e)) - \underline{u}^e]$,*

$$m_1^*(p^e) = \frac{-c - x^*(p^e) - m_0^*(p^e) + p^e s(x^*(p^e)) - \underline{u}^e}{p^e},$$

$$r^*(p^e) = 0.$$

Note that the licensor offers the same contract irrespective of his risk attitude when $p^e > p^o$, but not when $p^e < p^o$. Rewriting the risk-neutral licensor's objective function using the IR constraint (Equation (9)) to substitute for m_0 allows us to clarify the intuition behind the solution obtained above:

$$\max_{m_1(x)} [-c - x(p^e) + p^e s(x(p^e)) - \underline{u}^e] + (p^o - p^e)m_1(p^e). \quad (12)$$

The first term in (12) represents the expected NPV in excess of the licensee's reservation utility, which is the maximum value the licensee is willing to give to the licensor. The second term results from the difference in the PTS estimates. If the licensor is more pessimistic than the licensee (Case 1), the second term is negative, and the

licensor will not request any milestones, but completely sell the project to the licensee at contract signature. However, if the licensee is more pessimistic about the project than the licensor, it is to the latter's benefit to request a milestone payment (Case 2). In that case, the licensee considers future milestones less likely and underestimates their value, thereby allowing a relatively higher payment. Expression (12) also shows that the licensor's optimal choice of the licensee's effort level is set by maximizing the licensee's perception of the project value, represented by the first term.

4.2. Adverse Selection and Moral Hazard

In reality, the licensor will typically not know the licensee's PTS estimate. Hence, the licensor faces adverse selection and only knows the prior probability distribution of licensee types $f(p^e)$. The licensor can either offer a single contract or a menu of contracts.

Moral hazard implies that the licensee sets her effort level x^* so as to maximize her own utility because it cannot be imposed as part of the contract terms. The licensee will always set it such that the marginal expected sales accruing to the licensee equals the marginal cost of the effort, or $(1 - r(p^e))p^e s_x = 1$, which maximizes her expected value.

4.2.1. Single Contract. For the sake of simplicity, the licensor may opt to offer a single contract, independent of the licensee type. In that case, the royalty rate allows the licensor to participate in the upside of contracting with a high-type licensee by making his revenue proportional to the project sales. However, a high royalty rate discourages the licensee from investing in the project. Therefore, the optimal royalty rate is determined by the equilibrium of those two forces. The optimal contract can be characterized by four cutoff values for p^o (see the online appendix):

- $p_1 = \frac{\underline{p}^e s(x^*(0, \underline{p}^e))}{E[s(x^*(0, p^e))]}$;
- $p_2 = \frac{\underline{p}^e u_{z_f}^o |_{z_f=m_0^*}}{\underline{p}^e u_{z_f}^o |_{z_f=m_0^*} + (1 - \underline{p}^e) \int_{\underline{p}^e}^{\bar{p}^e} u_{z_s}^o |_{z_s=m_0^*+r_2^*(x^*)} dF(p^e)}$,

with r_2^* , $m_0^* = -c - x^*(r_2^*, \underline{p}^e) + \underline{p}^e(1 - r_2^*)s(x^*(r_2^*, \underline{p}^e)) - \underline{u}^e$ and $m_1^* = 0$ solutions to

$$\int_{\underline{p}^e}^{\bar{p}^e} u_{z_s}^o [r_2^* s_x x_r^* + s(x^*(r_2^*, p^e)) - s(x^*(r_2^*, \underline{p}^e))] dF(p^e) = 0$$

and

$$\underline{p}^e(1 - p^o)u_{z_f}^o = p^o(1 - \underline{p}^e) \int_{\underline{p}^e}^{\bar{p}^e} u_{z_s}^o dF(p^e);$$

- $p_3 = \frac{\underline{p}^e u_{z_f}^o |_{z_f=0}}{\underline{p}^e u_{z_f}^o |_{z_f=0} + (1 - \underline{p}^e) \int_{\underline{p}^e}^{\bar{p}^e} u_{z_s}^o |_{z_s=m_1^*+r_3^*(x^*)} dF(p^e)}$,

with r_3^* , $m_1^* = (-c - x^*(r_3^*, \underline{p}^e) + \underline{p}^e(1 - r_3^*)s(x^*(r_3^*, \underline{p}^e)) - \underline{u}^e) / \underline{p}^e$ and $m_0^* = 0$ solutions to

$$\int_{\underline{p}^e}^{\bar{p}^e} u_{z_s}^o [r_3^* s_x x_r^* + s(x^*(r_3^*, p^e)) - s(x^*(r_3^*, \underline{p}^e))] dF(p^e) = 0$$

and

$$\underline{p}^e(1 - p^o)u_{z_f}^o = p^o(1 - \underline{p}^e) \int_{\underline{p}^e}^{\bar{p}^e} u_{z_s}^o dF(p^e);$$

- $p_4 = \left(\underline{p}^e s(x^*(r_{\max}, \underline{p}^e)) u_{z_f}^o |_{z_f=0} \right) \cdot \left(\underline{p}^e s(x^*(r_{\max}, \underline{p}^e)) u_{z_f}^o |_{z_f=0} + \int_{\underline{p}^e}^{\bar{p}^e} u_{z_s}^o (r_{\max} s_x x_r^* + s(x^*(r_{\max}, p^e))) - \underline{p}^e s(x^*(r_{\max}, \underline{p}^e)) dF(p^e) \right)^{-1}$,

with r_{\max} such that $m_0^* = m_1^* = 0$ and the licensee's IR holds; with $p_1 < p_2 < p_3$, $p_1 \leq \underline{p}^e$, and $p_2 \geq \underline{p}^e$. Two cases can occur:

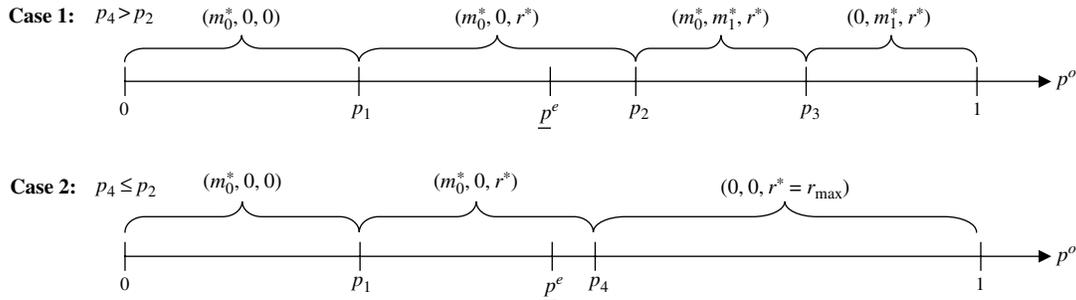
- *Case 1.* $p_4 > p_2$:
 $p^o \leq p_1$: $m_0^* > 0$, $m_1^* = 0$, $r^* = 0$, with m_0^* such that the IR constraint holds.
 $p_1 < p^o \leq p_2$: $m_0^* > 0$, $m_1^* = 0$, $r^* > 0$; the optimal royalty rate increases in p^o .
 $p_2 < p^o < p_3$: $m_0^* > 0$, $m_1^* > 0$, $r^* > 0$; the optimal payment at contract signature decreases in p^o , in favor of the milestone payment.
 $p^o \geq p_3$: $m_0^* = 0$, $m_1^* > 0$, $r^* > 0$; the contract terms do not change with p^o .
- *Case 2.* $p_4 \leq p_2$: This may occur if the licensee's reservation utility is high.
 $p^o \leq p_1$: $m_0^* > 0$, $m_1^* = 0$, $r^* = 0$, with m_0^* such that the IR constraint holds.
 $p_1 < p^o < p_4$: $m_0^* > 0$, $m_1^* = 0$, $r^* > 0$; the optimal royalty rate increases in p^o .
 $p^o \geq p_4$: $m_0^* = 0$, $m_1^* = 0$, $r^* > 0$; with $r^* = r_{\max}$, or such that the IR constraint holds.

A visual interpretation of the characteristics of the optimal contract depending on p^o is given in Figure 3.

The values of the cutoff probabilities on p^o reflect the licensor's attempt to balance his utility from the different sources of cash flow available in the contract terms, while respecting the IR constraint for the lowest-type licensee. For example, the licensor will prefer a contract with an up-front fee exclusively if his expected increase in value from an increase in the royalty rate, $p^o E[s(x^*(0, \underline{p}^e))]$, is lower than the decrease in the payment at contract signature required to respect the licensee's IR constraint, $\underline{p}^e s(x^*(0, \underline{p}^e))$, thus if $p^o \leq \underline{p}^e (s(x^*(0, \underline{p}^e)) / E[s(x^*(0, p^e))]) = p_1$. The definition of p_2 and p_3 is more involved, but essentially stems from the same logic. Finally, p_4 is determined such that the optimal royalty rate equals the maximum allowable royalty rate.

Intuitively, one would expect that if the licensor knows with certainty that the licensee's estimate will always be higher than his own, if $p^o \leq \underline{p}^e$, he will request a payment at contract signature only. However, this is not necessarily the case: only if $p^o \leq p_1 < \underline{p}^e$ will the licensor request a payment at contract signature only. Indeed, if $p^o > p_1$,

Figure 3. Risk-averse licensor’s optimal single contract for different values of p^o .



the licensor should offer a contract with a positive royalty rate, thereby incurring some risk. The licensor does so because he cannot rule out that the licensee has a high estimate p^e , and will therefore invest heavily in demand-enhancing activities, thus raising sales. The only way to benefit from this upside is to include a royalty rate in the contract. Hence, we see that the licensor requests a positive royalty rate to reduce the negative effect of adverse selection through participation in the sales. Note that the optimal royalty rate is increasing in p^o : the more the licensor believes in the project, the more he is interested in participating in the upside potential.

If the licensee’s reservation utility is not too high, i.e., if $p_4 > p_2$ (Case 1) and if the licensor’s estimate $p^o > p_2 > p^e$, he will introduce a milestone payment. In that case, the difference between the licensor’s estimate p^o and the lowest-type licensee’s PTS estimate makes it profitable for the licensor to ask for a milestone payment despite the increased risk exposure. Finally, the licensor may be so optimistic about the project that he prefers not to take any payment at contract signature at all, namely, if $p^o \geq p_3$. In Case 2, the up-front payment’s nonnegativity constraint becomes binding as the optimal royalty rate increases in p^o , and a licensor with an estimate $p^o \geq p_4$ will ask for the maximum royalty rate and no up-front or milestone payment.

Similar results are obtained for a risk-neutral licensor, with the exception that a risk-neutral licensor should not mix an up-front fee and a milestone payment except for

$p^o = p^e$, when he may be indifferent between the two (see the online appendix). The results are shown in Figure 4.

The licensor’s value is nondecreasing in the licensee’s type. However, it is easy to see that it will not increase as fast as in the case without adverse selection because all but the lowest-type licensee will receive more than their reservation utility.

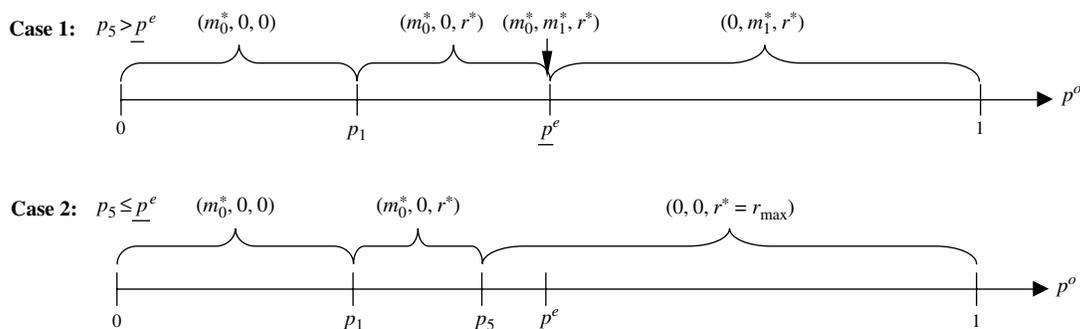
4.2.2. Menu of Contracts. The licensor can also offer a menu of contracts $(m_0(p^e), m_1(p^e), r(p^e))$ tailored for different licensee types. In that case, the licensor has to ensure that the contracts are incentive compatible. We rewrite the IC constraints (Equation (9)) using the first-order condition on the licensee’s optimal contract choice:

$$m_{0p^e} = -p^e [r_{p^e} s(x^*(r(p^e), p^e)) + m_{1p^e}]. \tag{13}$$

Equation (13) gives the relationship between the contract term functions m_0 , m_1 , and r , such that the licensee’s optimal choice will be to truthfully declare her type. The optimal contract scheme can be implemented only if the licensee’s second-order conditions also hold.

For a risk-averse licensor, we can only reach an analytical solution under certain conditions that guarantee an interior solution to the problem. Indeed, nonnegativity constraints on the contract terms are nonholonomic, complicating the analytical analysis (Hadley and Kemp 1971). However, we can compute the first-order conditions that are valid for an interior solution to the licensor’s problem

Figure 4. Risk-neutral licensor’s optimal single contract for different values of p^o .



(see the online appendix), equating the weighted marginal utility of the licensor's payoff at project failure and project success:

$$p^o u_z^o \left(\frac{1}{p^e(1-r)} - 1 \right) = (1-p^o) u_{z_f}^o. \quad (14)$$

When the licensor is risk neutral, we can solve the value maximization problem analytically using optimal control theory combined with our knowledge that, in the optimal contract, up-front payments and milestone payments should never be simultaneously included. Let us define p_0 such that $p_0 - (1 - F(p_0))/f(p_0) = p^o$. Then, the optimal menu of contracts can be described as follows (see the online appendix):

- $p^o \leq p_0$: $m_0^* = 0, m_1^* \geq 0, r^* > 0$; the optimal royalties rate is nonincreasing, and the milestone payment is nondecreasing in p^e .

- $p^o \geq p_0$: $(p^o + (1 - F(p^e))/f(p^e) - p^e) s(x^*(0, p^e)) + p^e((1 - F(p^e))/f(p^e)) s_x x_p^*|_{r=0} > 0$: $m_0^* \geq 0, m_1^* = 0, r^* > 0$; the optimal royalty rate is nonincreasing, and the up-front fee is nondecreasing in p^e .

- $(p^o + (1 - F(p^e))/f(p^e) - p^e) s(x^*(0, p^e)) + p^e((1 - F(p^e))/f(p^e)) s_x x_p^*|_{r=0} \leq 0$: $m_0^* > 0, m_1^* = r^* = 0$; the up-front payment remains constant.

We can now make the following observations concerning the structure of the optimal contract. First, we see that the optimal menu of contracts includes a royalty rate, which decreases the project value by reducing the licensee's incentive to invest, resulting in a lower-than-optimal investment in demand-enhancing activities. The royalty rate is decreasing in the licensee's type, to encourage the licensee to reveal her true value for the project: if the licensee believes in the project, she would prefer to invest heavily in demand-enhancing activities, and would be willing to pay a higher up-front or milestone payment to reduce the royalty rate, contrary to a low-type licensee who is willing to bear the burden of a high royalty rate. Note that the royalty rate serves a different purpose than in the single-contract case: when the licensor offers a single contract, the royalty rate is used to receive a cash flow proportional to the licensee's type, whereas in a menu of contracts the royalty rate is primarily designed to induce discrimination through its interaction with the licensee's optimal level of demand-enhancing activities. A menu of contracts is designed to penalize low-type licensees to encourage high-type licensees to reveal their valuation, whereas the single contract, with its constant royalty rate, is proportionately more harmful to a high-type licensee than a low-type licensee.

Second, we observe that as a consequence of adverse selection, the licensor's expected value decreases. On the one hand, the licensor now bears an informational rent for all licensee types, except for the lowest. Informational rent is defined as the value the licensee obtains on top of her reservation utility. The licensor's and the licensee's valuation of the informational rent may differ and the licensor's valuation of the informational rent need not be strictly

increasing in the licensee's type. Except for the lowest-type licensee, the licensor is now unable to reap the whole surplus above the reservation utility from the licensee, but rather has to reward the licensee for revealing her valuation of the project by offering contract terms leaving her strictly more than the reservation utility. Moreover, the licensor accepts to lose value on low-type licensees to reduce the informational rent on high-type licensees. Thus, even though the licensor can still extract the whole surplus from the lowest-type licensee, the project value, and the corresponding surplus, have become smaller because of the lower effort level, resulting from the nonzero royalty rate.

Third, we note that the optimal menu of contracts may contain a range over which the licensor is less optimistic than the licensee, but nonetheless asks for a milestone payment at project completion, despite the fact that the up-front payment of equivalent value to the licensee is higher than the licensor's value of the milestone payment. The licensor's valuation of a unit of milestone payment is its expected value, p^o , plus the expected value of switching to an up-front payment for licensee types higher than p^o , who value the milestone higher and will offer a higher equivalent up-front payment. The extra value balances the gain of switching for licensee types higher than p_0 , occurring with likelihood $1 - F(p_0)$, with the missed opportunity on the licensee type p_0 , occurring with likelihood $f(p_0)$, taking into account how much the licensee is willing to pay in up-front fee for each unit of milestone payment, i.e., p^e . The licensor therefore not only chooses whether to ask for a milestone payment or an up-front payment based on the comparison of his valuation to the licensee's, but also takes into account the expected value he forgoes by asking for the payment at contract signature at that particular licensee type rather than at a higher type.

Fourth, bunching, when the same contract is offered for different licensee types, can occur both for low-type and for high-type licensees. For low-type licensees, this occurs when the optimal royalty rate found in the range $p^e < p_0$ is higher than the maximum allowable royalty rate, i.e., a rate such that the nonnegativity constraints on the lump-sum payments become binding. For high-type licensees, bunching occurs if the nonnegativity constraint becomes binding for the royalty rate.

Fifth, we would like to point out the licensor's limitation in manipulating the royalty rate to discriminate between the licensee types. In the literature, adverse selection is usually tackled by the introduction of royalties (Gallini et al. 1990, Beggs 1992). However, Proposition 1 suggests contracting directly on the licensee's effort if possible: this yields better results than using royalties because the licensor can directly impose the desired investment level in demand-enhancing activities, which is independent of the licensee's payment to the licensor. To discriminate between licensee types, the licensor imposes investment levels lower than the licensee deems optimal because a high-type licensee will

Table 2. Optimal contract structures.

	Risk-averse licensor	Risk-neutral licensor
First-best	$p^o > p^e: p^e(1 - p^o) u_{z_f}^o$ $= p^o(1 - p^e) u_{z_s}^o; (m_0^*, m_1^*, 0)$ $p^o \leq p^e: (m_0^*, 0, 0)$	$p^o > p^e: (0, m_1^*, 0)$ $p^o = p^e: (m_0^*, m_1^*, 0)$ $p^o < p^e: (m_0^*, 0, 0)$
Adverse selection: Single contract	<i>Case 1: $p_4 > p_2$</i> $p^o \leq p_1: (m_0^*, 0, 0)$ $p_1 < p^o \leq p_2: (m_0^*, 0, r^*)$ $p_2 < p^o < p_3: (m_0^*, m_1^*, r^*)$ $p^o \geq p_3: (0, m_1^*, r^*)$ <i>Case 2: $p_4 \leq p_2$</i> $p^o \leq p_1: (m_0^*, 0, 0)$ $p_1 < p^o < p_4: (m_0^*, 0, r^*)$ $p^o \geq p_4: (0, 0, r^* = r_{\max})$	<i>Case 1: $p_5 > \underline{p}^e$</i> $p^o \leq p_1: (m_0^*, 0, 0)$ $p_1 < p^o \leq \underline{p}^e: (m_0^*, 0, r^*)$ $\underline{p}^e < p^o < p_3: (m_0^*, m_1^*, r^*)$ $p^o \geq p_3: (0, m_1^*, r^*)$ <i>Case 2: $p_5 \leq \underline{p}^e$</i> $p^o \leq p_1: (m_0^*, 0, 0)$ $p_1 < p^o < p_5: (m_0^*, 0, r^*)$ $p^o \geq p_5: (0, 0, r^* = r_{\max})$
Adverse selection: Menu of contracts	Interior solution: $p^o u_{z_s}^o \left(\frac{1}{p^e(1-r)} - 1 \right) = (1-p^o) u_{z_f}^o$ $m_{0_{p^e}} = -p^e(r_{p^e} s + m_{1_{p^e}})$ Contracts: (m_0^*, m_1^*, r^*)	$p^e < p_0: (0, m_0^*, r^*)$ $p^e = p_0: (m_0^*, m_1^*, r^*)$ $p^e \left(1 - \frac{1-F(p^e)}{f(p^e)} s_{p^e} \Big _{r=0} \frac{1}{s(x)} \right) < p^o + \frac{1-F(p^e)}{f(p^e)} < p^e: (m_0^*, 0, r^*)$ $p^o + \frac{1-F(p^e)}{f(p^e)} \leq p^e \left(1 - \frac{1-F(p^e)}{f(p^e)} s_{p^e} \Big _{r=0} \frac{1}{s(x)} \right): (m_0^*, 0, 0)$

then be willing to pay more in up-front or milestone payments to gain the right to invest appropriately in the project. This contrasts with Desai and Srinivasan (1995), who show that manipulating the effort level is not efficient when the single-crossing property does not hold. Unfortunately, such a contract would be difficult to enforce because investments in demand-enhancing activities may be difficult to monitor. Therefore, the licensor may have to resort to using a variable royalty rate. The royalty rate has two effects: first, it influences the licensee’s incentive to invest; and second, it results in a payment stream after successful project completion. However, we have seen that the licensor would prefer an up-front payment if the licensee’s type exceeds p_0 . Therefore, for very high licensee types, the licensor may be better off to forgo royalties and its discriminating power and ask for an up-front payment only. Therefore, we note that in the presence of adverse selection, moral hazard may compound the licensor’s value loss by preventing him from discriminating between the different types of licensees. In that case, bunching occurs, and all the licensee types higher than a threshold level will be offered the same contract.

On its own, a milestone payment does not significantly add to the licensor’s ability to discriminate between licensee types. However, it is still a valuable contract element to add to the two-part tariff because it removes the need to use the royalty rate as a revenue-generating tool, allowing it to be used exclusively for the purpose of discrimination. In a two-part tariff, the royalty is the only

instrument capable of generating future cash flows. However, imposing a high royalty rate can reduce the project value excessively, limiting the amount the licensor will receive in the future and may force him to propose an up-front payment, even though the licensor has a higher valuation for future payments than the licensee. Adding the milestone payment alleviates this problem to a certain extent because it becomes possible to delay revenue without impacting project execution.

4.3. Summary

Table 2 summarizes the optimal contract structure under different conditions of adverse selection and moral hazard.

5. Discussion and Conclusions

Licensing contracts studied in the literature have evolved from contracts specifying a single element, either a fee or a royalty rate (Katz and Shapiro 1985, 1986; Kamien and Tauman 1986; Beggs 1992), through two-part tariff contracts (Shapiro 1985, Macho-Stadler et al. 1996, Jensen and Thursby 2001), to contracts with more elements (Thursby et al. 2005). We show that a three-part tariff contract structure with a milestone payment is superior to the commonly studied two-part tariff. Because a milestone payment might be valued differently by different licensee types, it can act as a discriminating element, without distorting the licensee’s incentives to invest in the project. A milestone

payment by itself, however, is ineffective at discriminating, especially for a risk-neutral licensor. Thus, our analysis confirms the need for a royalty rate to fight adverse selection. Nonetheless, milestone payments can be useful because they allow generating future cash flows without the incentive distortion resulting from a royalty rate.

Our analysis studies the effect of adverse selection and moral hazard separately. Under adverse selection, discriminating contracts act by manipulating the licensee's effort level, preferably by contracting directly on it. When this is not possible, i.e., in a hidden action model, a varying royalty rate can be used to induce a variable effort level, allowing discrimination between licensee types. Adverse selection biases the optimal contract toward the use of a milestone payment: only under adverse selection does the licensor's optimal contract include a milestone payment for licensee types with a higher PTS estimate than his own. Adverse selection reduces the licensor's value through (a) the suboptimal effort level of the licensee, and (b) the informational rent the licensor pays to the licensee (Salanié 1997, Laffont and Martimort 2002). Furthermore, adverse selection forces the risk-averse licensor to bear more risk by including an uncertain milestone payment more often than in the first-best case. Consistent with Desai and Srinivasan (1995), our results confirm that moral hazard without adverse selection does not reduce the principal's value. However, moral hazard added to adverse selection may decrease the licensor's value if it leads to bunching and makes complete discrimination impossible.

Each element in the contract structure serves a different purpose. Lump-sum payments have the advantage of not distorting the licensee's incentive to invest, but only offer a limited scope to discriminate. The royalty rate enables the licensor to discriminate more extensively, but distorts the licensee's incentive to invest, decreasing the total project value. In the case of a single contract, the royalty rate allows participating in the potential upside of signing with a high-type licensee. In practice, we have observed that a licensor often prefers up-front payments to avoid risk. However, this may not be in the licensor's benefit. The licensee's type, p^e , impacts her valuation of the project and of the contract terms. If the licensee is of a low type, the licensor can exploit the difference in valuation by asking for a milestone payment, balancing the higher risk against the higher expected cash flow value. Under informational asymmetry, the optimal set of contracts favors payments at project completion, both in the form of a milestone payment or a royalty rate. A risk-averse licensor may offer contracts with both an up-front and a milestone payment. We recommend that the licensor carefully craft the licensing contract with the respective contribution of all the contract terms in mind. To summarize, we agree that it is the combination of distortions that necessitates complex contracts (Thursby et al. 2005). However, our contract design suggestions are based on a stylized model of

the real issue, and care must be taken before extrapolating our conclusions to situations where our assumptions do not apply.

There are several avenues for further research. One option would be to expand the model to projects with several research phases. We expect that in that case the licensor will still differentiate amongst licensee types, using the trade-off between milestone payments and royalties to optimize his return depending on the licensee's belief. It will be challenging to solve because of the multidimensional nature of the licensee's type (Salanié 1997, Armstrong and Rochet 1999, Rochet and Stole 2003). A second option would be to analyze the licensor's optimal contracts when the licensor has his own reservation utility. Because the licensor can approach several licensees, he can determine a minimum PTS that the licensee should hold for him to consider offering a contract. Another extension would allow the licensor to write more-complex contracts, including, for example, nonlinear royalty schemes, the opportunity for the licensor to provide continuing input in the R&D activities (Iyer et al. 2005). Finally, we could look at the mirror image of this research, and analyze the licensee's contract design problem, for those cases where it is more reasonable to assume that the licensee has the higher bargaining power.

6. Electronic Companion

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

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