Planned divorce: Opt-out options in new product co-development partnerships

Nicos Savva
London Business School, Regent's Park, London NW1 4SA, UK nsavva@london.edu

Stefan Scholtes
Judge Business School, University of Cambridge, Cambridge CB2 1AG, UK, s.scholtes@jbs.cam.ac.uk

We study contractual arrangements for the joint development of new products between a small and a large technology company, as in the case of a biotech innovator and a major pharma company. Such joint activities require significant information-sharing and joint decision making, and pose significant risks for both companies. Motivated by a real contractual agreement, we examine contracts which permit each of the two partnering firms to opt out during the development of a particular project. If the opt-out option is exercised, ownership of the project is transferred to the other company. In return, the sole owner will make pre-agreed milestone and royalty payments to the opting out party as the project proceeds.

To analyze the economic effects that opt-out clauses have on value-sharing and the efficiency of the development process, we built a simple model which is based on the prevalent risk-adjusted net present value valuation technique used in the biopharmaceutical industry. We show that giving the smaller party a unilateral opt-out option is efficient in the sense that it would see the project through to development for all scenarios in which the project was economical if developed by a single party. However, such a unilateral opt-out option constrains value-sharing and will allocate a significant share of the expected value generated by the project to the biotech company. To re-balance the value sharing without requiring a large upfront side-payment by the biotech company, we introduce a double-opt out option which allows either party to opt out of co-development after the first phase. We characterize the range of milestone-royalty payments that will render this contract efficient and show that it does not inherently favor any of the two firms and that it can be tailored to enable the exercise of options to be aligned with the different business models of the firms. It incentivizes the small company to opt out of projects with a very large market value, e.g. pharmaceutical blockbusters, especially geared to the pharma's sales power. The large firm is incentivized to opt out of small niche drugs, which are unlikely to benefit from the economies of the pharma's scale and might well be better marketed with a small specialized sales force that the biotech company should be able to develop. Our work shows that alliances should anticipate the problems caused by uncertainty, and be based on creative contract designs that are enforceable and provide the necessary flexibility for dealing with the evolving value of their projects.

Key words: New product development, pharmaceutical R&D, contracts, real options

1. Introduction

In many industries, most notably in the high-tech sector, R&D alliances and partnerships are valuable complements to the wholly owned industrial R&D labs (Hagedoorn (2002), Aggarwal and Hsu (2009)). The pharmaceutical industry is a case in point (Danzon et al. (2005)). The growth

in biomedical research and knowledge and the relatively low barriers to undertaking biomedical research have ensured that much of the innovation in the industry finds a home in relatively small biotechnology companies. These entities raise finance on the back of promising scientific and technological developments and the hope that these can be turned into products of value. As they lack the vast resources of a fully integrated pharmaceutical company they seek to partner their assets with major corporations in order to access further funding and capabilities such as full-scale clinical development, marketing and sales.

A second example is the impact of nanotechnology on materials and electronics. Much of these advances come directly from universities and associated spin-off companies, rather than the labs of major electronics firms (Libaers et al. (2006)). As in the case of the bio-pharmaceutical industry, commercialization of innovation often involves partnering with large corporations, which provide funds and capabilities in industrial manufacturing and distribution.

This paper focuses on partnerships between typically relatively small innovator firms and established, often large industry majors with specific exploitation capabilities. Following Hagedoorn et al. (2009), we distinguish between standard licensing agreements, which transfer user rights in return for a fee, and more elaborate partnership-embedded licensing agreements, which, in addition to a rights-transfer, are embedded in a broader partnership agreement that may involve collaboration on parts of the value chain, such as joint R&D, production, marketing or distribution of a new product. We focus on such partnership-embedded contracts. Hagedoorn et al. (2009) find that partnership-embedded licensing is preferred in technologically sophisticated industries, where secrecy is an important component of appropriability and when licensors are smaller than licensees.

An example in case is a co-development partnership between the UK based biotech Cambridge Antibody Technology (CAT) and AstraZeneca, signed in 2004. This long-term alliance covered specific therapeutic areas and stipulated that any promising molecule discovered by CAT over the next five years would be developed jointly by both firms, with a 50/50 share of costs and revenues. The agreement won the Business Development Deal of the Year award at the Pharmaceutical Achievement Awards conference in 2005 for its innovative use of opt-out options to manage the risk that the companies may not agree to continue with a project. These clauses give partners the right to exit a joint project at specified stages of the R&D process and revert to pre-agreed licensing terms. This paper is the result of the authors' involvement in structuring the original co-development contract. We will argue that contracts with opt-out clauses to standard licensing terms can be valuable generic templates for partnership-embedded licensing agreements.

To facilitate the exposition, we will refer to a biotech-pharma partnership throughout the paper. The results and insights, however, apply more generally to new product development alliances that share the following characteristics:

- the partnership is between a relatively small innovator who focuses on the development of intellectual property and a large firm with distinctive downstream exploitation capacity,

- both firms are interested in a long-term partnership, not just in a single project transaction,
- projects under the agreement will be conducted, at least initially, as genuine co-development efforts by teams of employees from both partners.

The focus of this paper is on the uncertainty associated with R&D. Payoffs from R&D projects are notoriously uncertain and economic valuations of such projects change unpredictably as and when new technical or commercial information becomes available. The issue is particularly pertinent when the partners are asymmetric, as in the case of a small biotech firm and a large multinational pharmaceutical company. An emerging blockbuster drug may be excellent news for the pharma company as it is fully aligned with its business model but at the same time overwhelm the biotech company and require that they focus all their funding on the further development of this drug, thus limiting their ability to progress other promising projects. Alternatively, a drug could turn out to be effective only for a fairly small segment of the initially anticipated patient population, making it a niche drug and therefore less suited to benefit from the scale of the pharma but nevertheless a good prospect for the biotech. How can one design flexible contracts that facilitate the most efficient development route for new products? This issue is addressed in this paper.

R&D projects are investments in information about the technological properties of a product candidate and its commercial prospect if successfully developed. Aligned with the revelation of information, such projects are typically structured as phased commitments, with revision points to reassess the economic prospects. This gives R&D projects an options-like characteristic, with implications for their economic valuation (Schwartz and Moon (2000)). In its simplest form, R&D has two phases, an exploratory phase to establish proof-of-principle, followed by a confirmatory phase with the aim of producing a working prototype or, in the case of a pharmaceutical drug achieving regulatory approval. The cost of exploration is typically relatively low for any one product candidate; prototyping is more expensive. Therefore, after the exploratory phase, and in the light of its results and the commercial potential at the time, a decision is made whether to "double or quit", whether to invest in further development and ultimate industrial manufacturing of the product or not.

In the case of a co-development project, the continuation decision has to be made jointly. Disagreement is natural, in particular when partners are quite different, such as a small biotech and a pharmaceutical major. Contracts will normally foresee possible disagreements and incorporate suitable escalation mechanisms. Zajac and Olsen (1993) discuss how such changes trigger a transition from a processing stage to a reconfiguration stage. However, disagreement and escalation will often require lengthy re-negotiation, which holds up swift development and can cause significant loss of value (Hendricks and Singhal (1997)). It can also lead to friction between the partners. Opt-out options are an alternative to escalation clauses in the case of continuation disagreement. We will argue that they can be very effective tie-breakers if carefully designed.

Following Hagedoorn et al. (2009), we distinguish between two basic agreements: a standard licensing agreement with milestones and royalties (M&R contract) and a co-development contract as the preferred option for partnership-embedded licensing. Standard licensing contracts spread the payments from the licensee to the licensor over the R&D phases and make this income contingent on achieving technical milestones and, via royalties, on commercial success, Mason et al. (2008). This contract enables risk sharing and allows the licensor to signal confidence in the value of the project; the later the payment, the more risk is retained by the licensor. However, later stage payments in licensing agreements have a disadvantage. They can distort the future effort that a licensee exerts in an in-licensed R&D project because any added value due to the effort will have to be shared with the licensor, who is not sharing the effort. For example the licensee can abandon projects that are economically beneficial as stand-alone projects but, after deduction of royalty payments, do not deliver sufficient revenue to recoup its expected future R&D costs, which the licensee carries alone. In the words of a senior executive from one of the top ten European pharmaceutical companies: *'The in-licensed project would need a relatively higher than expected pay-off than self-originated compounds, as the expected profits from the in-licensed compound would usually need to generate royalties for the biotech company in addition to the profit for the pharmaceutical company.'* (Lou and Rond (2006)). Standard licensing contracts are therefore inefficient in the sense that they can potentially hamper the swift development of drugs that have commercial value in a single-party development.

Fully committed co-development, without opt-out option, is conceptually identical to single-party development and therefore does not suffer from the inefficiency created by late stage payments. However, such long-term contracts come with significant resource commitments, particularly for the late stages of development. This is worrying for a smaller partner with potential funding challenges. We therefore consider the inclusion of an opt-out option: After an initial phase of co-development, the biotech company has the right to opt out of further co-development and, if so, the arrangement will at that time turn into a standard licensing contract with pre-agreed M&R terms. One might argue that this makes the contract even less efficient than standard licensing from the start. After all, standard licensing becomes inefficient because the licensing terms extract value from the pharma at a late stage - and the opt-out option extracts even more value from the pharma since its exercise is controlled by the biotech. Surprisingly, this argument is incomplete. We will show that, within a two-stage model, the contract with opt-out option is efficient because the biotech chooses not to exercise the option when it would lead to inefficiency.

If an opt-out option is included in the co-development contract, then the economic value appropriated to the two parties changes. The biotech company has an additional right, to which the pharma is subjected. If the original co-development agreement was to share costs and revenues 50/50, the inclusion of the opt-out clause increases the value for the biotech to more than 50%. In

principle such a value shift could be rectified by an upfront additional payment from the biotech to the pharma company. However, it is unlikely that a cash-hungry biotech company will have the means for large upfront payments to the pharma company. We therefore consider an alternative rebalancing mechanism: The inclusion of an opt-out option for the pharma company as well. Now each party has the right to opt out a specific time and revert to standard M&R terms. We show that if opt-out terms are sufficiently asymmetric, the contract with double opt-out is efficient and has the potential to achieve a wide range of value splits. Interestingly, asymmetric M&R arrangements that look inherently unfavorable to one partner can nevertheless be shown to split the value equally. Such double opt-out clauses with highly asymmetric terms were at the heart of the afore-mentioned alliance contract between AstraZeneca and Cambridge Antibody Technology.

Besides being efficient and fair, asymmetric M&R terms provide an additional benefit. They allow the coordination of option exercise with the firms' core competencies. They can be designed so that the biotech company opts out of blockbuster drugs, for very favorable M&R terms. The commercialization of such drugs is at the core of the big pharma business model. In return, the asymmetric M&R terms incentivize the pharma company to opt out of niche drugs that are more suited to a potentially smaller and more specialized sales force, which a biotech company might be able to develop.

2. Literature Review

Research in new product development (NPD) has long acknowledged the collaborative, cross-functional and often complex nature of innovation (Hauser (1998), Mihm et al. (2003)). Much of this research is focused on collaboration *within* a firm, where the challenge is to coordinate conflicting internal goals (Mihm (2010), Hutchison-Krupat and Kavadias (2009)) and to manage a portfolio of projects (Anderson and Joglekar (2005), Chao and Kavadias (2008)).

Our paper adds to a recent stream of research that is concerned with collaborative NPD *between* firms. Bhaskaran and Krishnan (2009) model the innovation decisions of two firms in a collaboration and compare different collaboration arrangements with regard to the exerted effort and generated profits. Erat and Kavadias (2006) and Erat et al. (2009) focus on new product development with a technology supplier who licenses technology to competing downstream manufacturers. They show that the technology provider may find it optimal to induce partial adoption of the new technology by downstream manufacturers or make the technology difficult to integrate in order to create downstream differentiation. Crama et al. (2008) study adverse selection and moral hazard problems associated with M&R contracts in a single period model with technical risk. In contrast to our paper, these papers do not account for the staged nature of R&D investments. Most recently, Xiao and Xu (2010) study a multistage R&D alliance under a royalty contract with asymmetric information and moral hazard. They show that it is optimal to renegotiate the contract once technical uncertainty has been resolved.

Much of the recent NPD research is grounded in the longer tradition of research on the economics of licensing. Early research in this field, surveyed in Kamien (1992), argues that upfront sale, with the price determined by auction, should be the preferred technology transfer mechanism for the innovator. Later stage milestone and royalty payments are deemed inefficient because they distort downstream effort and production decisions. However, royalties become a desirable technology transfer mechanism in principal-agent models with asymmetric information (Gallini and Wright (1990), Beggs (1992), Sen (2005), Savva and Taneri (2011)) or moral hazard (Macho-Stadler et al. (1996), Choi (2001), Crama et al. (2008)). In these circumstances, the contingent nature of royalties turns them into either an information extraction mechanism, via signaling or screening, or a motivational device which better aligns the interests and efforts of both parties involved. In view of the longer-term collaborative nature of licensing-embedded partnerships moral hazard and asymmetric information are less of a concern. Within joint development teams it is more difficult to keep information private and actions are easier to observe. Our situation is therefore more aligned with the earlier work surveyed in Kamien (1992) than the principal-agent literature. We add to the literature in two respects. First, in contrast to Kamien (1992), we focus on the interplay between commercial uncertainty and the partners' decision rights during the R&D process as a source of inefficiency. To this end, we model R&D as a staged investment process (Schwartz and Moon (2000)), in contrast to most of the licensing models in the literature, which focus on one-off investments.

Secondly, in contrast to Xiao and Xu (2010), who use a multi-period model as well, we propose a contract that explicitly avoids the need for re-negotiation, ex post, to produce efficient outcomes. Re-negotiation is time-consuming and hence has a large transaction cost associated with it, in particular in industries where margins reduce drastically when patents expire. This is particularly relevant in the biopharmaceutical context. Hendricks and Singhal (1997) show that markets penalize announcements of delays for new products by an average drop of 5.25% in share price. Within our context of partnership-embedded licensing, renegotiations and the resulting hold-up problems are not only costly (Gibbons (2005)), they can also jeopardize reputation with detrimental effects for the partnership itself (Ely and Välimäki (2003)).

3. Model development

We consider two firms who engage in an R&D partnership. We will not dwell on the motives for the partnership itself. Hagedoorn (1993) reviews the relevant literature and studies collaboration motives in a large sample of alliances across industries. Motives include further advancement of research through technological synergies or complementary technology, more effective diffusion of basic scientific knowledge, reduction or sharing of costs and uncertainty, shortening of the R&D process through the partner's tacit knowledge, and market access and enhanced search opportunities. In the biopharmaceutical sector technological complementarities and sharing of costs and

risks were found to be particularly important motives for collaboration.

Within the partnership, we consider an agreement to co-develop a particular product. We will compare standard co-development with several alternatives, specifically with standard licensing and co-development with opt-out options. To gain insight into the economics of such agreements, we develop a model based on a number of simplifying assumptions.

3.1. Assumptions of the model

First, we model the important staging R&D investments in the simplest possible way, via two phases, an exploration and a confirmation phase. In the pharmaceutical context, this translates into exploratory clinical trials and confirmatory clinical trials (Girotra et al. (2007)). Exploratory trials are smaller scale clinical trials, carried out on healthy volunteers and a small panel of patients with the aim to establish safety, determine dosage and demonstrate clinical proof of concept. Confirmatory trials are large-scale clinical trials aiming to establish statistical efficacy.

Second, we assume that any uncertainty in costs and durations is much lower than uncertainty in revenues and technical performance and therefore we treat costs and durations as deterministic. This is close to reality in the pharmaceutical industry, where the minimal requirements for the eligibility and success of development phases are mandated by regulatory bodies such as the US Food and Drug Administration (FDA). To simplify the exposition, we therefore assume that costs and durations of the phases are certain. Exploratory trials are performed during the time interval $(t_0, t_1]$ and confirmatory trials during $(t_1, t_2]$. At the decision points t_0 and t_1 the project requires known cash injections C_0 and C_1 to proceed to the next phase of development. For simplicity we will assume that all costs and revenues used in the model are appropriately discounted to time t_0.

Third, we distinguish between two types of uncertainty, technical and commercial. Technical uncertainty is modeled as a binary random variable. After each phase, evidence is collected and analyzed and scientists form an opinion as to whether or not the project has, on scientific metrics, passed the hurdles set out in the phase description. If not, then the project is abandoned on technical grounds (technical failure). The chance of abandonment on technical grounds after phase 1 is estimated as p_1 and the chance of abandonment after phase 2, given technical success in phase 1, is estimated as p_2. In a partnership situation, the success probabilities are estimated jointly by both partners but they are not verifiable in court and therefore non-contractible. Technical success of a phase, however, is assumed to be verifiable and can be included in contracts, thus milestone payments can be implemented.

The market value of the project, conditional on technical success, is also uncertain and can change during the R&D process. In the case of a drug candidate, market uncertainty can be driven by factors such as epidemics, changing disease demographics, macroeconomic variables such as GDP growth in developing countries, changes in the competitive landscape, such as entries or

failures of competing drug candidates, and also as a consequence of the revealed safety and efficacy characteristics of the drug. In our model, we assume that the expected market value of the drug is estimated by a joint team of business developers and that this projection is regularly updated as the drug is developed. This market value forecast is common knowledge during the R&D phase but it is unverifiable by a third party and therefore cannot be included in the contract. However, after the drug is launched, the revenue becomes verifiable and so royalties can be implemented.

Fourth, we will assume that R&D is investment in information only, i.e. that the two firms cannot influence the technical or market uncertainties themselves. The chance of technical success is assumed to be an inherent but unknown characteristic of the product candidate, whilst any potential effort to improve the value of a technically successful product is assumed to be already incorporated in the market value projections.

Finally, we assume that both firms are risk neutral. While risk neutrality is a sensible assumption for a well diversified pharmaceutical company (Schwartz (2004), Crama et al. (2008)) the assumption is more questionable for a biotech firm. Finance orthodoxy would suggest that a biotech's shareholders are diversified and do not want their company to be unduly risk-averse (Schall (1972)). We make the risk-neutrality assumption for modeling convenience and discuss the implications of relaxing this assumption later.

3.2. Model specification

The development of the market value projection over time is uncertain and modeled as a non-negative random process $X(t)$. The value $X(t_2)$ is the market value of the fully approved drug. At any time $t < t_2$ $X(t)$ is a forecast of this market value. The forecast $X(t)$ is updated as new information arrives. We assume that the forecasting process is unbiased, i.e. $X(t) = \mathbf{E}[X(t_2)|X(t)]$. This makes the forecast $X(t)$ a martingale by construction, i.e. for $t \leq s \leq t_2$

$$\mathbf{E}[X(s)|X(t)] = \mathbf{E}[\mathbf{E}[X(t_2)|X(s)]\,|X(t)] = \mathbf{E}[X(t_2)|X(t)] = X(t).$$

The second equation holds due to the law of iterated expectations because the information at time s subsumes the information at the earlier time t.

We denote the probability density function of $X(t_1)$ at time t_0 by $f(x)$. We will not make specific assumptions about this probability distribution until section 7, where we illustrate the results for the case where $X(t)$ is a driftless Geometric Brownian Motion (GBM).

3.3. Standard co-development

In a co-development agreement the two companies will share all future costs and revenues at pre-agreed terms. We assume the biotech company holds a share s in the project and the pharma

company the residual share $1-s$, where $0 \leq s \leq 1$. All investment decisions are taken jointly. Co-development under these terms is therefore equivalent to single-party development. The value of the single-party development is allocated to the companies according to their shares $(s, 1-s)$.

To take account of the flexibility to abandon the drug before the beginning of phase 2, we calculate the single party value $V_i(X(t_i))$ of the drug at time t_i by backward induction. Conditional on technical success of phases 1 and 2, the value at time t_2 is by definition given by

$$V_2\left(X(t_2)\right) = X(t_2).$$

Using the martingale property of the market value projection we can express the value of the drug at time t_1, conditional on technical success in phase 1 as

$$\begin{aligned} V_1\left(X(t_1)\right) &= \mathbf{E}\left[p_2 V_2(X(t_2))|X(t_1)\right] - C_1 \\ &= p_2 \mathbf{E}\left[X(t_2)|X(t_1)\right] - C_1 = p_2 X(t_1) - C_1. \end{aligned}$$

The owner of the decision rights for the project will only proceed to phase 2 if the value of the drug at time t_1 is positive. Taking this individual rationality condition into account, we obtain the value of the drug at time t_0 as

$$\begin{aligned} V_0\left(X(t_0)\right) &= p_1 \mathbf{E}\left[\left(V_1(X(t_1))\right)^+ |X(t_0)\right] - C_0 \\ &= p_1 p_2 \int_{C_1/p_2}^{\infty} \left(x - C_1/p_2\right) f(x) dx - C_0. \end{aligned} \tag{1}$$

Here, and in the sequel, we use the abbreviation $z^+ = \max\{z, 0\}$. Recall that $f(x)$ denotes the density of $X(t_1)$ at time t_0. In view of (1), the biotech and pharma shares of the value under full co-development are given by

$$\begin{aligned} B_0(X(t_0)) = sV_0\left(X(t_0)\right) &= sp_1 p_2 \int_{C_1/p_2}^{\infty} \left(x - C_1/p_2\right) f(x) dx - sC_0, \\ P_0(X(t_0)) = (1-s)V_0\left(X(t_0)\right) &= (1-s)p_1 p_2 \int_{C_1/p_2}^{\infty} \left(x - C_1/p_2\right) f(x) dx - (1-s)C_0, \end{aligned}$$

respectively.

In our model world, the single-party value is the maximal total value of any development route. It will therefore serve as benchmark against which we compare the value of the project in a collaborative contract. Specifically, we will call a development contract *inefficient* if the sum of the expected project values allocated to the individual partners by the contract is less than the expected value of the single-party project. Since co-development is analogous to single-party development, with pre-agreed sharing of costs and revenues, this agreement is efficient. We will next show that standard licensing is inefficient in our context.

3.4. Standard licensing

Before we consider co-development agreements with opt-out options, we establish, as a second benchmark value, the economic value of the project and its appropriation to the two parties under a standard milestone-royalty licensing agreement (M&R contract). The pharma company licenses the drug candidate from the biotech company at time t_0. It therefore incurs all future development costs. The biotech company obtains an upfront payment M_0, two milestones M_1 and M_2 payable upon technical success in phases 1 and 2 respectively, and a share k of the value of the drug at time t_2 as a royalty payment.

As before, we work backwards to find the value of the M&R contract for each party. Notice that the pharma company, as the new owner of the drug, will take all future continuation decisions, while the biotech company is a passive observer whose payoff from the contract is influenced by the decisions of the pharma company.

At time t_2, assuming technical success, the pharma value V_2^P and the biotech value V_2^B are

$$\begin{aligned} V_2^P(X(t_2)) &= (1-k)\,X\,(t_2) - M_2 \\ V_2^B(X(t_2)) &= kX(t_2) + M_2. \end{aligned}$$

Backtracking to time t_1, we obtain

$$\begin{aligned} V_1^P(X(t_1)) &= p_2 \mathbf{E}\left[V_2^P(X(t_2))|X(t_1)\right] - C_1 - M_1 \\ &= p_2((1-k)\,X\,(t_1) - M_2) - C_1 - M_1, \\ V_1^B(X(t_1)) &= p_2 \mathbf{E}\left[V_2^B(X(t_2))|X(t_1)\right] + M_1 \\ &= p_2(kX(t_1) + M_2) + M_1. \end{aligned}$$

At time t_0 we need to take the pharma's future continuation decision at time t_1 into account. Upon technical success in the first stage the pharma incurs the milestone payment M_1 but will only continue to the second stage if future expected revenues exceed costs, i.e., if $p_2\left((1-k)X(t_1) - M_2\right) \geq C_1$. If the drug is abandoned, the biotech will neither receive the second stage milestone payment nor any royalty payments. Hence, by the law of iterated expectations,

$$V_0^P(X(t_0)) = p_1 p_2 \int_{\frac{C_1+p_2M_2}{p_2(1-k)}}^{\infty} \left((1-k)x - M_2 - C_1/p_2\right) f(x)dx - p_1M_1 - C_0 - M_0, \tag{2}$$

$$V_0^B(X(t_0)) = p_1 p_2 \int_{\frac{C_1+p_2M_2}{p_2(1-k)}}^{\infty} \left(kx + M_2\right) f(x)dx + p_1M_1 + M_0. \tag{3}$$

The total value of the project is therefore

$$V_0^P(X(t_0) + V_0^B(X(t_0)) = p_1 p_2 \int_{\frac{C_1+p_2M_2}{p_2(1-k)}}^{\infty} \left(x - C_1/p_2\right) f(x)dx - C_0.$$

A comparison with (1) reveals the source of inefficiency of M&R contracts in our model: Profitable projects might be abandoned by the pharma company because the agreed royalty payments reduces the pharma's value. The remaining revenues, after royalty payments, are not sufficient to cover the full costs of phase 2. This inefficiency at the beginning of phase 2 occurs if

$$X(t_1) \in \left[\frac{C_1}{p_2}, \frac{C_1/p_2 + M_2}{1-k}\right]. \tag{4}$$

PROPOSITION 1. *The M&R contract is inefficient in the sense that* $V_0^P + V_0^B < V_0$ *for every strictly positive royalty rate* k *or milestone* M_2 *as long as* $\int_{\frac{C_1}{p_2}}^{\frac{C_1/p_2+M_2}{1-k}} f(x)d(x) > 0$.

All proofs are presented in the appendix.

One may argue that renegotiation is a way to restore efficiency in this context. However, as we have argued above, renegotiation is costly and can have detrimental reputational effects within the partnership. In addition, renegotiation may not restore efficiency because of information asymmetry at the time of renegotiation, when the pharma company has been developing the drug alone and will therefore have privileged information about its value. In the following sections we propose option-based contracts that do not require renegotiation to achieve efficiency.

4. Co-development with opt-out options

We have so far established that, on efficiency grounds, co-development with a fixed sharing arrangement $(s, 1-s)$ is preferable to standard licensing in our context. However, co-development poses one critical issue for the small company: Will the firm have enough funds to proceed to the typically more expensive second phase of development? If not, this could lead to the need for a complex re-negotiation. Even if the firm has sufficient funds, it may wish to invest them in other projects with higher potential return. To allow the biotech company to manage this risk, we consider an opt-out option that gives the company the right to opt out of co-development at the end of the first phase. If the option is exercised, ownership of the drug is transferred to the pharma company, who will then have to cover all of the remaining development costs and take the continuation decision unilaterally. If the project is successful in phase 2, the biotech firm will receive a milestone M_2 and a royalty percentage k at time t_2. To avoid trivial situations where the options is always or never exercised, we assume that $0 \leq k \leq s \leq 1$.

Notice that this option contract is quite different from co-development during phase 1, followed by *pre-agreed* exit to milestones and royalites. In fact, the latter contract is equivalent to a standard M&R licensing contract with negative upfront payment $M_0 = -sC_0$ and first milestone $M_1 = 0$. Notice that the inefficiency region of a M&R contract (equation (4)) does not depend on the first two milestone payments M_0 and M_1 but only on the milestone M_2, paid at project completion, and the royalty k, so the forced exit contract inherits the inefficiency of the M&R contract.

The co-development with opt-out contract can be naturally analyzed via backwards induction as a closed-loop game between the two parties. To this end, we need some additional notation. The

payoffs of the two parties at time t_2 are conditional on their decisions after phase 1. We therefore denote the final payoffs to the pharma and biotech by P_2^{ij}, B_2^{ij}, respectively, where $i,j \in \{C,O\}$ correspond to the "opt-out" (O) and "continuation" (C) decisions by the pharma (i) and biotech (j), respectively. Assuming the contract was signed at time t_0, the payoffs at time t_2, conditional on the decisions at time t_1 are given by

$$P_2^{CO} = (1-k)\,X(t_2) - M_2\ ,\ \ B_2^{CO} = M_2 + kX(t_2)$$
$$B_2^{CC} = sX(t_2),\ P_2^{CC} = (1-s)X(t_2)\ ,\ \ P_2^{OC} = B_2^{OC} = P_2^{OO} = B_2^{OO} = 0.$$

Moving to time t_1, we denote by (P_1^{kl}, B_1^{kl}) the value to each of the two parties at time t_1, conditional on signing the contract or not, i.e. $k,l \in \{Y,N\}$, where Y (N) indicates (not) signing the contract. If one of the parties decides not to agree to co-development at time t_0, the value of the contract is zero

$$P_1^{YN} = B_1^{YN} = P_1^{NY} = B_1^{NY} = P_1^{NN} = B_1^{NN} = 0.$$

If $k = l = Y$ then the two parties play a simultaneous move game with the following objective functions

$$B_1^{YY}(i) = \max_{j\in\{C,O\}} \mathbf{E}\left[p_2 B_2^{ij} - C_B^{ij} | X(t_1)\right]$$
$$P_1^{YY}(j) = \max_{i\in\{C,O\}} \mathbf{E}\left[p_2 P_2^{ij} - C_P^{ij} | X(t_1)\right]$$

where C_{ij} refers to the cost of co-developing/opting out, i.e.,

$$C_B^{CC} = sC_1,\ C_P^{CC} = (1-s)C_1,\ C_P^{OC} = C_1,\ C_B^{CO} = C_B^{OO} = C_P^{OO} = C_P^{OC} = 0.$$

At time t_0 the firms play a simultaneous move game with decisions $a,b \in \{Y,N\}$ and objectives

$$B_0(a) = \max_{b\in\{Y,N\}} \mathbf{E}\left[(p_1 B_1^{ab} - C_B^{ab}) | X(t_0)\right]$$
$$P_0(b) = \max_{a\in\{Y,N\}} \mathbf{E}\left[(p_1 P_1^{ab} - C_P^{ab}) | X(t_0)\right],$$

where

$$C_B^{YY} = sC_0,\ C_P^{YY} = (1-s)C_0$$
$$C_B^{ab} = C_P^{ab} = 0 \text{ otherwise.}$$

At time t_0 the game is a two-stage nested matrix game. The extensive form of the game, provided that the two firms have decided to sign the contract at time t_0, is depicted in Figure 1.

PROPOSITION 2. *At time t_1 there exists a unique pure strategy equilibrium. The equilibrium depends on the realization of $X(t_1)$, but is independent of the distribution of $X(t_2)$ at time t_1:*

$$OO \text{ if:} \qquad X(t_1) \le C_1/p_2$$

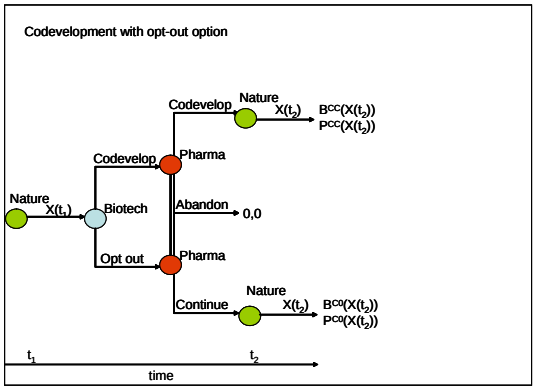


Figure 1 Co-development with biotech opt-out option

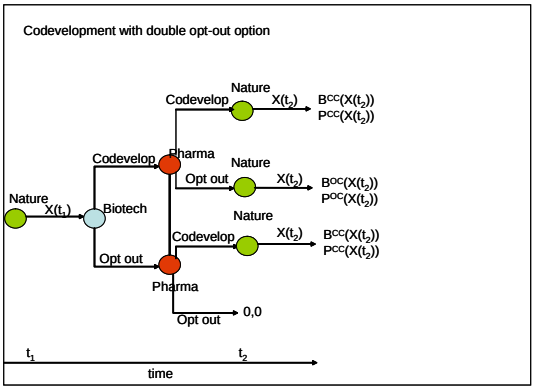


Figure 2 Co-development with biotech and pharma out-out options

$$\begin{aligned} &CO \text{ if: } \tfrac{C_1+M_2p_2}{(1-k)p_2} \leq X(t_1) \leq \tfrac{sC_1+p_2M_2}{(s-k)p_2} \\ &CC \text{ if: } \qquad\qquad \text{otherwise} \end{aligned}$$

The equilibrium is unique if $X(t_1)$ falls into the interior of one of the regions. At time t_0 the firms sign the contract, provided the expected value of co-development for each firm $\mathbf{E}[B_1^{YY}], \mathbf{E}[P_1^{YY}]$ is non-negative.

The proof of the proposition proceeds by elimination of strictly dominated strategies in the interior of the regions in Proposition 2, and elimination of weakly dominated strategies on the boundaries. If iterated elimination of strictly dominated strategies produces a unique strategy, then this strategy is the unique Nash equilibrium of the game. If the iterated elimination of weakly dominated strategies produces a unique solution then this solution is a Nash equilibrium, but there may be other Nash equilibria. Also, the solution derived at by iterated elimination of weakly dominated strategies can depend on the starting point, in the sense that the solution might change if we start eliminating dominated strategies of player i instead of j. For more details we refer to Mas-Colell et al. (1995).

The value of the contract for each company at time t_0 is given by:

$$\begin{aligned} B_0 &= p_1 \mathbf{E}\left[B_1^{YY}\right] - sC_0 \qquad (5) \\ &= p_1 \left[\int_{C_1/p_2}^{\frac{C_1+M_2p_2}{(1-k)p_2}} s(p_2x - C_1) f(x)\, dx + \int_{\frac{C_1+M_2p_2}{(1-k)p_2}}^{\frac{sC_1+M_2}{(s-k)p_2}} p_2(kx + M_2) f(x)\, dx \right. \\ &\quad \left. + \int_{\frac{sC_1+M_2p_2}{(s-k)p_2}}^{\infty} s(p_2x - C_1) f(x)\, dx \right] - sC_0 \\ P_0 &= p_1 \mathbf{E}\left[P_1^{YY}\right] - (1-s)C_0 \qquad (6) \\ &= p_1 \left[\int_{C_1/p_2}^{\frac{C_1+M_2p_2}{(1-k)p_2}} (1-s)(p_2x - C_1) f(x)\, dx + \int_{\frac{C_1+M_2p_2}{(1-k)p_2}}^{\frac{sC_1+M_2p_2}{(s-k)p_2}} p_2((1-k)x - M_2) - C_1 f(x))\, dx \right. \end{aligned}$$

$$+ \int_{\frac{sC_1+M_2p_2}{(s-k)p_2}}^{\infty} (1-s)(p_2x - C_1) f(x)\, dx \Bigg] - (1-s)C_0$$

where $f(x)$ is the distribution of $X(t_1)$ at time t_0.

PROPOSITION 3. *If the contract is signed, i.e. if $P_0 \geq 0$ and $B_0 \geq 0$, the contract is efficient.*

Recall that efficiency means that whenever it is profitable for a single firm to continue the drug development, the drug will also continue to be developed within the contract. As we argued before, we can regard co-development in the first phase and pre-agreed exit by the biotech company to M&R terms at time t_1 as a pure M&R contract. The co-development with opt-out option contract can therefore be interpreted equivalently as an M&R contract with opt-in option. The biotech has the option to opt into further co-development at time t_1. As shown in Proposition 1 M&R contracts are inefficient because the pharma company has to bear the full cost of development of the drug but has to share the revenues with the biotech. At first glance, one might expect that giving the biotech an opt-in option would widen the efficiency gap, since the option gives even more value to the biotech. It is surprising that the opposite occurs, i.e., the efficiency gap closes completely. The reason is that, as shown in Proposition 3, the contract also gives the biotech the flexibility to opt into co-development of marginal projects that would be abandoned under the standard M&R agreement. By doing so, these projects are rescued, which makes the contract efficient.

PROPOSITION 4. *Let $\alpha = \frac{B_0}{V_0}$ be the share of the expected total project value at time t_0 that the options contract allocates to the biotech company. Then $\alpha \geq s$ and there exists $z \in [s,1]$ such that for any $\beta \in [s,z]$, there exists opt-out option terms (k, M_2) such $\alpha = \beta$.*

Not surprisingly, Proposition 4 shows that the addition of the option skews the value sharing in the biotech's favor; the option is exercised only when opting out has a higher value than co-development. This is not to say that the option will *necessarily* give more value to the biotech. A comparison of (5) and (6) shows that if $f(x) = 0$ for all x in $\left[\frac{C_1+M_2p_2}{(1-k)p_2}, \frac{sC_1+M_2p_2}{(s-k)p_2}\right]$ then the biotech's share of the value is s. In the numerical example in section 7, where $s = \frac{1}{2}$, the contract can be designed to give the biotech any share in $(\frac{1}{2}, 1)$. The fact that the biotech takes more value would not be a problem in principle. Since the contract is efficient, the two firms can rectify any undesirable sharing of the total value through an upfront side payment. However, such payments are not desirable for small companies with funding difficulties. They would not wish and may not be able to divert funds from their primary research activities. An alternative to upfront side-payments from the biotech to the pharma company is the addition of an opt-out option for the pharma company. This is in fact what happened in the case of the AZ-CAT contract mentioned in the introduction. When the biotech company suggested the inclusion of opt-out options, the pharma company did not negotiate compensation payments but wanted opt-out options as well. We will analyse such a contract within our model world in the next section.

5. Co-development with double opt-out options

As before, we assume that the two parties begin development jointly by sharing any costs and revenues at pre-agreed shares $(s, 1-s)$. In contrast to the previous section where only the biotech had the right to opt-out of joint development, we will now allow both companies the choice to opt out for M&R terms at time t_1, following a successful phase 1. If the biotech firm opts out to M&R terms, it will receive royalties k and a milestone payment M_2; if the pharma company opts out, it will receive royalties m and a milestone payment L_2. To avoid trivial situations where one or both companies would always or never exercise their options we assume $0 \leq k \leq s \leq 1-m \leq 1$. The contract analyzed in the previous section is of course a special case of this contract with $m=0$ and $L_2=0$.

Again we will solve the game by backwards induction. Assuming that both parties have agreed to co-development at t_0, the value of the contract for each partner at time t_2 given their actions at time t_1 is

$$\begin{aligned} P_2^{CO} = (1-k)\,X(t_2) - M_2 \ , \ \ B_2^{CO} = M_2 + kX(t_2) \\ P_2^{OC} = L_2 + mX(t_2) \ , \ \ B_2^{OC} = (1-m)\,X(t_2) - L_2 \\ B_2^{CC} = sX(t_2),\ P_2^{CC} = (1-s)X(t_2) \ , \ \ P_2^{OO} = B_2^{OO} = 0. \end{aligned}$$

Assuming the contract was signed at time t_0, the parties will play a simultaneous move game at time t_1 with the following payoff functions

$$\begin{aligned} B_1^{YY}(i) &= \max_{j\in\{C,O\}} \mathbf{E}\left[p_2 B_2^{ij} - C_B^{ij} | X(t_1)\right] \\ P_1^{YY}(j) &= \max_{i\in\{C,O\}} \mathbf{E}\left[p_2 P_2^{ij} - C_P^{ij} | X(t_1)\right], \end{aligned}$$

where C_P^{ij}, C_B^{ij} refers to the cost of co-developing or opting out:

$$C_B^{CC} = sC_1,\ C_P^{CC} = (1-s)C_1,\ C_B^{OC} = C_P^{CO} = C_1,\ C_B^{CO} = C_B^{OO} = C_P^{OC} = C_P^{OO} = 0.$$

If one party does not agree to the contract terms at time t_0, the contract value at t_1 is zero.

$$P_1^{YN} = B_1^{YN} = P_1^{NY} = B_1^{NY} = P_1^{NN} = B_1^{NN} = 0.$$

Finally, at time t_0 the firms play a simultaneous move game with objectives

$$\begin{aligned} B_0(a) &= \max_{b\in\{Y,N\}} \mathbf{E}\left[(p_1 B_1^{ab} - C_B^{ab}) | X(t_0)\right] \\ P_0(b) &= \max_{a\in\{Y,N\}} \mathbf{E}\left[(p_1 P_1^{ab} - C_P^{ab}) | X(t_0)\right], \end{aligned}$$

where $a, b \in \{Y, N\}$ and

$$C_B^{YY} = sC_1,\ C_P^{YY} = (1-s)C_1$$

$$C_B^{ab} = C_P^{ab} = 0 \text{ otherwise.}$$

As before, this is a two-stage nested matrix game. The existence and efficiency results of Propositions 2 and 3 translate to the double opt-out option.

PROPOSITION 5. *At time t_1 there exists a pure strategy equilibrium if $\frac{C_1/p_2+M_2}{1-k} \geq \frac{(1-s)C_1/p_2+L_2}{1-s-m}$. This equilibrium depends on the realization $X(t_1)$, but is independent of the probability distribution $X(t_2)$ at time t_1:*

$$OO: \text{ if } \quad X(t_1) \leq C_1/p_2 \tag{7}$$

$$CC: \text{ if } \quad C_1/p_2 \leq X(t_1) \leq \tfrac{C_1/p_2+L_2}{1-m} \tag{8}$$

$$OC: \text{ if } \quad \tfrac{C_1/p_2+L_2}{1-m} \leq X(t_1) \leq \tfrac{(1-s)C_1/p_2+L_2}{1-s-m} \tag{9}$$

$$CC: \text{ if } \quad \tfrac{(1-s)C_1/p_2+L_2}{1-s-m} \leq X(t_1) \leq \tfrac{C_1/p_2+M_2}{1-k} \tag{10}$$

$$CO: \text{ if } \quad \tfrac{C_1/p_2+M_2}{1-k} \leq X(t_1) \leq \tfrac{sC_1/p_2+M_2}{s-k} \tag{11}$$

$$CC: \text{ if } \quad X(t_1) \geq \tfrac{sC_1/p_2+M_2}{s-k} \tag{12}$$

The equilibrium is unique if $X(t_1)$ falls into the interior of one of the regions. At time t_0 the firms participate in the contract if their expected value $\mathbf{E}[B_1^{YY}], \mathbf{E}[P_1^{YY}]$ are non-negative.

Note that a symmetrical proposition holds with the roles of the biotech and pharma companies reversed if $\frac{sC_1/p_2+M_2}{s-k} \leq \frac{C_1/p_2+L_2}{1-m}$. Proposition 5 gives a condition for the existence of an equilibrium. Notice that for $s = 0.5$ this condition requires that $\frac{C_1/p_2+M_2}{1-k} \geq \frac{C_1/p_2+2L_2}{1-2m}$ (or $\frac{C_1/p_2+2M_2}{1-2k} \leq \frac{C_1/p_2+L_2}{1-m}$). This would hold if, for example, $M_2 \geq 2L_2$ and $k \geq 2m$. In other words, the opt-out terms for the two parties have to differ substantially. This is required to avoid "stalemate" situations where both parties would like to opt out at the same value $X(t_1)$. In fact, such considerably different opt-out terms were an important part of the AZ-CAT contract mentioned in the introduction. Interestingly, such different opt-out terms can have a strategic advantage. They allow the alignment of opt-out decisions with the companies' business models. In fact, proposition 5 provides the ranges of value forecasts at time $X(t_1)$ that lead to development by the pharma (CO) and development by the biotech (OC), respectively. The boundaries of these regions are functions of the M&R terms upon opt-out. They can be chosen in such a way that the CO region, where the pharma company develops alone coincides with high-value drugs, aligned with the pharma's blockbuster model, while the OC region, where the biotech company develops alone coincides with niche drugs. This can be done so that the option exercise regions do not overlap, i.e., that the efficiency condition is satisfied. The numerical illustration in Section 6 will demonstrate this effect.

The value of the contract for each company at time t_0 can be straight-forwardly calculated as

$$B_0 = p_1 \mathbf{E}\left[B_1^{CC}\right] - sC_0 \tag{13}$$

$$
\begin{aligned}
&= p_1 \left[\int_{C_1/p_2}^{\frac{C_1/p_2+L_2}{1-m}} s(p_2x - C_1) f(x)\, dx + \int_{\frac{C_1/p_2+L_2}{1-m}}^{\frac{(1-s)C_1/p_2+L_2}{1-s-m}} p_2((1-m)x - C_1 f(x)\, dx \right. \\
&+ \int_{\frac{(1-s)C_1/p_2+L_2}{1-s-m}}^{\frac{C_1/p_2+M_2}{1-k}} s(p_2x - C_1) f(x)\, dx + \int_{\frac{C_1/p_2+M_2}{1-k}}^{\frac{sC_1/p_2+M_2}{s-k}} p_2 kx f(x)\, dx \\
&\left. + \int_{\frac{sC_1/p_2+M_2}{s-k}}^{\infty} \frac{p_2x - C_1}{2} f(x)\, dx \right] - sC_0 \\
P_0 &= p_1 \mathbf{E}\left[P_1^{CC}\right] - (1-s)C_0 \qquad (14) \\
&= p_1 \left[\int_{C_1/p_2}^{\frac{C_1/p_2+L_2}{1-m}} (1-s)(p_2x - C_1) f(x)\, dx + \int_{\frac{C_1/p_2+L_2}{1-m}}^{\frac{(1-s)C_1/p_2+L_2}{1-s-m}} p_2 mx f(x)\, dx \right. \\
&+ \int_{\frac{C_1/p_2+L_2}{1-s-m}}^{\frac{C_1/p_2+M_2}{1-k}} (1-s)(p_2x - C_1) f(x)\, dx + \int_{\frac{C_1/p_2+M_2}{1-k}}^{\frac{(1-s)C_1/p_2+M_2}{1-s-k}} p_2(1-k)x - C_1 f(x)\, dx \\
&\left. + \int_{\frac{(1-s)C_1/p_2+M_2}{1-s-k}}^{\infty} (1-s)(p_2x - C_1) f(x)\, dx \right] - (1-s)C_0.
\end{aligned}
$$

PROPOSITION 6. *If the contract is signed, i.e., if $P_0 \geq 0$ and $B_0 \geq 0$, the contract is efficient.*

The skewed value-sharing of Proposition 4 can now be re-balanced.

PROPOSITION 7. *There exists $0 \leq z' \leq s \leq z \leq 1$ such that for any $\alpha \in [z', z]$, there exists opt-out option terms (k, M_2, m, L_2) such that the share of the value allocated to the biotech is $\frac{B_0}{V_0} = \alpha$.*

For a number of realistic model parameters that we have experimented with, the contract permits any value sharing $\alpha \in [0, 1]$ (see Section 6 for an example). This can be understood by considering the single opt-out case, where $m = 0$ and $L_2 = 0$. As k and M_2 increase the contract allocates more value to the biotech at the expense of the pharma, until it will possibly reach a point where it allocates all of the value to the biotech. Beyond this point the pharma will not want to participate in the project. Note that all of these contracts are efficient. Conversely, we could start with $k = 0$ and $M_2 = 0$. As m and L_2 increase, the contract allocates more value to the pharma at the expense of the biotech, until all value is allocated to the pharma.

6. Market value as geometric Brownian motion

Our model set-up is very close to practical valuation models used in the bio-pharmaceutical industry under the name of *risk-adjusted net present value*, see e.g. Jeffrey et al. (2001), which accounts for technical uncertainty via phase transition probabilities p_i. Our model adds commercial uncertainty via the forecasting process $X(t)$ and the game theory element for the two-party valuation. The purpose of the following section is to illustrate that our approach is not only useful in providing theoretical justifications but can actually be used for practical contract design. The general results presented so far does not require any specific assumptions regarding the stochastic process of the

market value forecast $X(t)$ other than the martingale property. In order to operationalize the approach in practice, we will have to make some assumption on these forecasts. In our case, we assume that the prediction of market value $X(t)$ follows a driftless geometric Brownian motion (GBM)

$$dX(t) = X(t)\sigma dz$$

with instantaneous volatility σ and Gaussian increment dz (see Schwartz (2004) for a similar model of market value evolution). This allows us to calculate closed-form solutions which not only demonstrate the practicality of the approach but also allow us to investigate the effect of volatility on the value sharing and the inefficiency induced by simple licensing contracts.

The GBM assumption implies that future value forecasts at time $t \leq t_2$ follow the log-normal distribution. The zero drift assumption translates into an unbiased forecasting procedure that determines $X(t)$. Where we illustrate results with graphs, we will use the parameters in Figure 3 for the drug project.

Parameter	Value	Units
p_1	50%	
p_2	50%	
C_0	60M	\$
C_1	600M	\$
t_0	0	
t_1	2	years
t_2	5	years
$X(t_0)$	1550M	\$
σ^2	10%	per annum

Figure 3 Drug project parameters

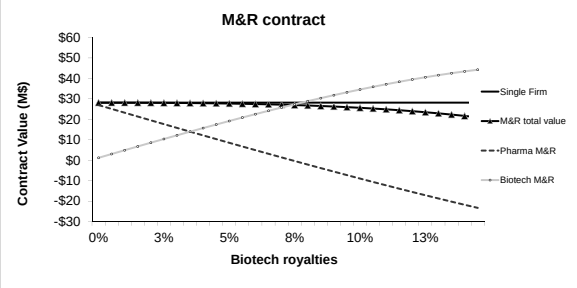


Figure 4 Value vs. royalty with biotech milestones set to $M_0 = M_1 = 0,\ M_2 = \$5M$.

6.1. The value of the drug

In the case where the drug is owned by a single company, the valuation at time t_0, given by equation (1), is analogous to a European call option on the underlying $p_2X(t)$ with a strike price C_1. Its value is given by the Black-Scholes formula (see appendix for details):

$$V_0\left(X(t_0)\right) = p_1p_2\Phi(d_1)X(t_0) - p_1C_1\Phi(d_2) - C_0.$$

where $\Phi(.)$ is the standard Normal cumulative distribution function and

$$d_1 = \frac{\ln\frac{p_2X(t_0)}{C_1} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sqrt{t_1 - t_0}\sigma}, \quad d_2 = d_1 - \sqrt{t_1 - t_0}\sigma.$$

Note that $1-\Phi(d_2)$ is the probability of abandonment for commercial reasons, while technical failure is captured by the transition probabilities p_1, p_2. As $\frac{p_2 X(t_0)}{C_1}$ increases, the project is less and less likely to be abandoned. In the formula, d_1 and d_2 tend to infinity and the value $V_0(X(t_0))$ tends to the expected net present value $p_1 p_2 X(t_0) - p_1 C_1 - C_2$, also referred to as risk-adjusted NPV in the pharmaceutical industry, (Jeffrey et al. (2001)). This value accounts for technical risk but does essentially discard commercial uncertainty and the option value of abandoning the drug if the market valuation drops. Since $d_1 > d_2$ and therefore $\Phi(d_1) > \Phi(d_2)$, and $p_2 X(t_0) > C_1$ the abandonment option adds value to the project. Since the distance between d_1 and d_2 increases as the volatility σ increases, the value of the project increases with increased commercial uncertainty. The value of the project decreases as the probability of technical success $p_1 p_2$ decreases.

6.2. The standard licensing contract

As before, valuing the project for the owner of the license, the pharma company, is conceptually equivalent to pricing a European call option. However, the valuation has to take account of the royalties percentage k and the milestone payment M_2 to the biotech company, i.e., the underlying for the option is $p_2(1-k)X(t)$ and the strike price is $p_2 M_2 + C_1$. The Black-Scholes formula provides the closed form solution to equation (2)

$$V_0^P(X(t_0)) = p_1 p_2 (1-k) X(t_0) \Phi(d_3) - p_1 (p_2 M_2 + C_1) \Phi(d_4) - p_1 M_1 - C_0 - M_0$$

and equation (3)

$$V_0^B(X(t_0)) = p_1 \left[p_2 k X(t_0) \Phi(d_3) + p_2 M_2 \Phi(d_4) + M_1 \right] + M_0,$$

where

$$d_3 = \frac{\ln \frac{(1-k) p_2 X(t_0)}{C_1 + M_2 p_2} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sqrt{t_1 - t_0}\sigma}, \; d_4 = d_3 - \sqrt{t_1 - t_0}\sigma.$$

The probability of abandonment, $1-\Phi(d_4)$, is larger than the probability of abandonment of the single company development, $1-\Phi(d_2)$, because $d_3 < d_1$ and hence $d_4 < d_2$. Furthermore, assuming $X(t_0) > 0$,

$$\begin{aligned} V_0^P + V_0^B &= p_1 p_2 X(t_0) \Phi(d_3) - p_1 C_1 \Phi(d_4) - C_0 \\ &< p_1 p_2 X(t_0) \Phi(d_1) - p_1 C_1 \Phi(d_2) - C_0 = V_0, \end{aligned}$$

i.e. the standard licensing contract is inefficient. The efficiency gap is illustrated in Figure 4. The gap is small for the typical royalty range of 2%-6% used in early stage deals in the pharmaceutical industry (Love (2005)). However, the gap becomes substantial if royalties increase, as in the case of deals further downstream in the development process.

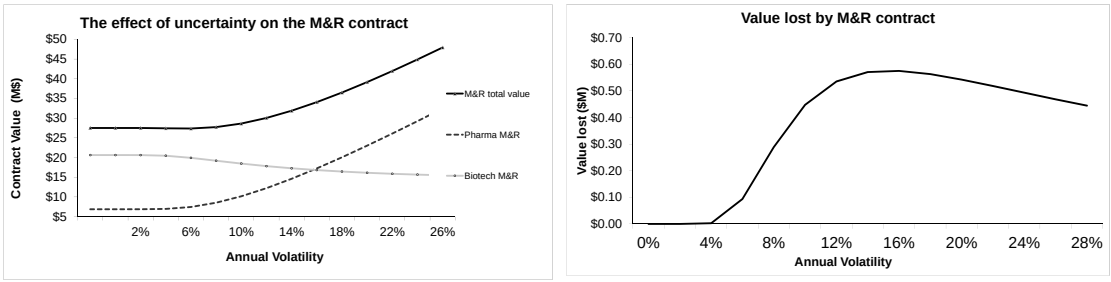


Figure 5 The effect of uncertainty. Biotech milestones set to $M_0 = M_1 = 0,\ M_2 = \$5M$ and royalty at $k = 4\%$.

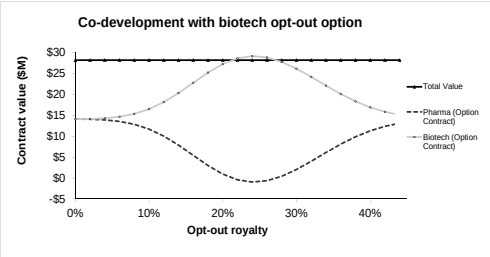
The geometric Brownian motion assumption allows us to investigate the effect of uncertainty on the value of each party.

$$\begin{aligned}
\frac{dV_0}{d\sigma} &= p_1 p_1 X(t_0)\phi(d_1)\sqrt{t_1 - t_0} \geq 0 \\
\frac{dV_0^P}{d\sigma} &= p_1 p_1 (1-k) X(t_0)\phi(d_3)\sqrt{t_1 - t_0} \geq 0 \\
\frac{dV_0^B}{d\sigma} &= -p_1 p_1 k X(t_0)\phi(d_3)\sqrt{t_1 - t_0} \\
&\quad - \frac{p_1 p_1 k X(t_0)}{C_1 + p_2 M_2}\phi(d_3)\left(\sqrt{t_1 - t_0}(2p_2(1-k)M_2) + \frac{d_3}{\sigma}(C_1 k + M_2 p_2)\right) \leq 0 \\
\frac{d(V_0^P + V_0^B)}{d\sigma} &= \frac{p_1 p_1 k X(t_0)}{C_1 + p_2 M_2}\phi(d_3)\left(\sqrt{t_1 - t_0}(c_1 + p_2 M_2 - 2p_2(1-k)M_2) - \frac{d_3}{\sigma}(C_1 k + M_2 p_2)\right).
\end{aligned}$$

The value of the drug for a single company increases with growing commercial uncertainty σ, as does the value to the pharma company in an M&R contract, albeit at a lower rate. The value to the biotech company in an M&R contract, however, decreases with increasing uncertainty. These results are illustrated in the first graph of Figure 5. The total value of the drug in an M&R contract, i.e. the sum of the values of both parties, is a non-monotonic function of commercial uncertainty. This can be seen in the second graph of Figure 5, which shows the difference between the value of the drug for a single firm and the value of the M&R contract.

6.3. Co-development with opt-out option

Under the GBM assumption, the value of the biotech and the pharma given in equations (5) and (6), respectively, can be calculated explicitly. The exact formulas are given in the Appendix. To compute the value effects for our illustrative drug project we assume that both parties share costs and revenues equally, i.e. $s = 0.5$. The values for the two parties as a function of royalty rate and milestone payment, respectively are shown in Figure 6 and Figure 7.



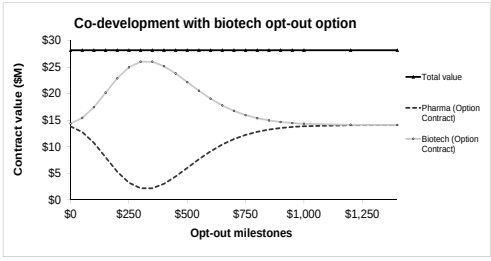


Figure 6 Biotech opt-out milestone $M_2 = \$5M$. **Figure 7** Biotech opt-out royalty $k = 4\%$.

These graphs show that the opt-out option gives between 50% and 100% of the value to the biotech, depending on the choice of milestones and royalties. Figure 9 shows how the value share depends on commercial uncertainty. While the total value of the contract is a monotonic function of volatility, the value of the contract for each of the two companies is non-monotonic. From a theoretical standpoint it is interesting to note that the value shares of the two companies converge asymptotically. This happens because for very high uncertainty the expected value of the option becomes small as the probability that the option is exercised becomes small, while the payoff conditional on options exercise is independent of commercial uncertainty.

6.4. Co-development with double opt-out options

The parties respective values of co-development with double opt-out option can be solved in closed form under the GBM assumption and are given in the Appendix. To illustrate the effects on our illustrative example we maintain the equal sharing assumption $s = 0.5$ and specify the opt-out option terms as $M = 100$, $L = 10$, $k = 33.5\%$ and $m = 5\%$ are shown in Figure 8. In contrast to the single opt-out contract, which allocated between 50% and 100% of the value to the biotech (see Figure 6), the contract with the double opt-out option can give any value between 0% and 100% to either company.

Given that we assumed equal share co-development as default ($s = 0.5$), the question arises whether there exist efficient non-trivial contracts with opt-out options that allocate the value equally. Some solutions were estimated numerically and are shown in Figure 11. Finally, the effect of commercial uncertainty on the values of the contract for both parties is examined in Figure 10. For low levels of commercial uncertainty the pharma company gets the lion's share of the value, even though it has much lower royalties than the biotech. For higher levels of commercial uncertainty the situation is reversed. Asymptotically, as commercial uncertainty increases, the values converge.

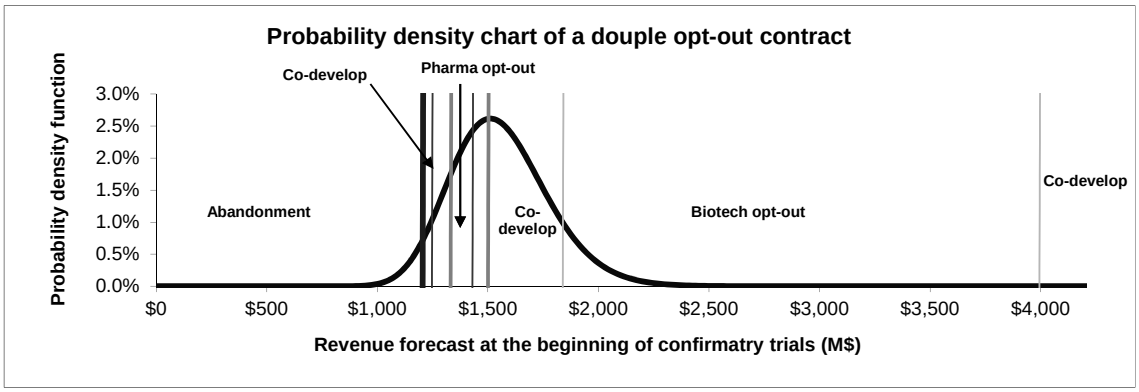


Figure 8 Probability density chart ($M = 100, L = 10, k = 33.5\%$, $m = 5\%$, $s = 50\%$).

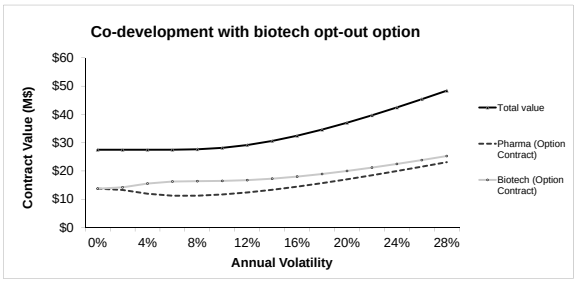


Figure 9 Biotech opt-out milestone $M = \$5M$ and royalty $k = 10\%$. Pharma does not have an opt-out option.

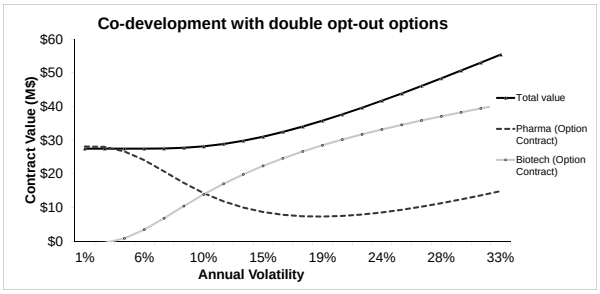


Figure 10 Biotech opt-out milestone $M = \$5M$ and royalty $k = 35\%$. Pharma opt-out milestone $L = 0$ and royalty $m = 15\%$.

7. Relaxation of model assumptions

In this section we discuss consequences of relaxations of two simplifying assumptions: the use of more than two R&D phases and the effect of risk-aversion on the biotech's side.

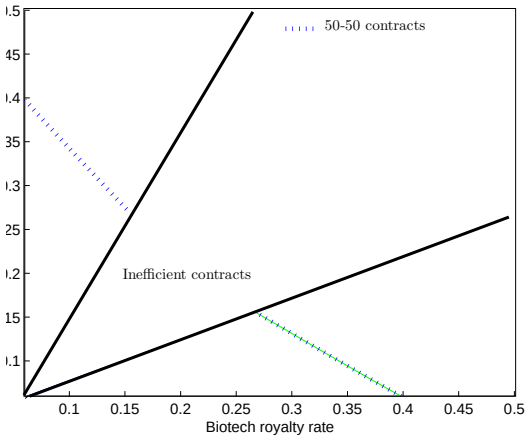


Figure 11 Equal share contracts, $M = \$100M$ and $L = \$10M$

7.1. Drug development as a multi-stage process

In our analysis we have assumed that there are only two stages, exploration and confirmation, with the option exercised at the end of the first stage. If there are more stages between opt out and launch then the opt-out option is no longer fully efficient but is still more efficient than an M&R contract. If there are more stages between signing the contract and opt out, a new source for inefficiency occurs. It would be possible that at a stage after the contract is signed but before the option point, i.e. at stages when decisions are still taken jointly and development costs are shared, one of the two partners has a negative value for the project and the other a positive value. Therefore they would not agree on continuation. This can be seen by working backwards: at the opt-out point, the option is possibly exercised, which reduces the value for the company that then has to develop the project alone. However, the reduced value may still be positive, so the drug is developed further. Nevertheless, this reduced value for the company that does not exercise the option pushes down its valuation at an earlier stage and this value may then not be enough to cover its share of the co-development costs at this earlier stage.

7.2. Risk-averse biotechs

If we assume the biotech is risk-averse and maintain the assumption that the pharma company is risk-neutral and there is no asymmetric information and unobservable effort, then it is in the interest of both parties to transfer risky payoffs from the risk-averse party to the risk-neutral party. Hence the only efficient contract is a straight acquisition of the entire project by the pharma company for a direct payment to the biotech.

Pure co-development contracts are inefficient in the following sense: When the project is marginally profitable on expectation, a risk-averse biotech may want to abandon the project while the risk-neutral pharma would want to continue. This disagreement problem is not resolved by an opt-out option. If the biotech opts out the pharma's payoff is reduced and it is possible that this

reduced payoff is not high enough to justify the continuation costs. However, this inefficiency occurs only for marginally profitable projects and the parties may be willing to tolerate this, provided the biotech's risk aversion is moderate.

Remarkably, the potential disagreement about continuation of marginally profitable drugs is the only inefficiency that risk-aversion of the smaller party causes in the opt-out options contract, provided the contract terms satisfy the necessary and sufficient conditions for efficiency of Proposition 5 and the risk averse company has the higher opt-out terms.

To see this note first that when the opt-out option is exercised, the risk of the opting-out party is reduced and the risk of the then full owner of the project is increased. The effect of risk-aversion is best illustrated by checking its impact on the exercise regions depicted in Figure 8. As risk-aversion increases, the biotech is more likely to exercise the opt-out option. The right boundary of the biotech's opt-out region moves further to the right. The left boundary, which is the lowest revenue forecast for which the biotech's opt-out leaves enough value for the risk neutral pharma to continue with development, is independent of the biotech's risk aversion. Similarly, the right boundary of the pharma's option exercise region, at which point the pharma's opt-out payoff is higher than the co-development payoff, is not affected by the biotech's risk-aversion, while the left boundary of this region moves to the right; the revenue forecast at which the pharma chooses not to exercise its opt-out option is higher under risk-aversion because although a risk-neutral biotech would have continued with development, the risk-averse biotech would abandon the project.

In summary, with the exception of the inefficiency for marginally profitable drugs, the efficiency of the double opt-out contract is robust with respect to biotech risk-aversion. Notice that if the biotech is very risk averse, the pharma's opt-out region becomes empty and therefore the pharma's opt-out option is worthless; the pharma never opts out as the very risk-averse biotech would never take on the project alone.

8. Conclusions

The starting premise in this paper is an existing or developing partnership between a small and a large technology company, as in the case of a biotech innovator and a major pharma company. Within the partnership, both parties intend to repeatedly develop new products jointly, with joint R&D and possibly joint activities further down the value chain as the default mode of engagement. Such joint activities require significant information-sharing and joint decision making. Most importantly, long and costly R&D projects pose significant risks for both companies in terms of their ability and desire to honor the joint commitment of future resources. Strategic priorities change, funds may be difficult to raise, alternative allocations of funds may be more profitable. In such cases, it would seem beneficial to allow both parties to opt-out of any individual project without the need to re-negotiate on a case-by-case basis, to avoid procrastination of the project

or even a threat to the wider partnership through potential litigation. Opt-out clauses are natural mechanisms to implement such planned divorces in a contract.

In this paper, we analyzed economic effects that opt-out clauses have on value-sharing and the efficiency of the development process. To this end, we built a simple model which is close to the prevalent risk-adjusted net present value valuation technique in the biopharmaceutical industry, but adds commercial risk and abandonment decisions. We show, within a two-stage model, that a contract that gives the smaller party a unilateral opt-out option is efficient in the sense that it would see the project through for all scenarios in which the project was economical if developed by a single party. However, such a unilateral opt-out option constrains value-sharing and will add a significant share of the expected value generated by the project to the biotech company. To re-balance the value sharing without requiring a large upfront side-payment by the biotech company, we introduce a double-opt out option which allows either party to opt out of co-development after the first phase. We characterize the range of milestone-royalty payments that will render this contract efficient and show that it does not inherently favor any of the two firms and that it can be tailored to enable the exercise of options to be aligned with the different business models of the firms. It incentivizes the small company to opt out of projects with a very large market value, e.g. pharmaceutical blockbusters, especially geared to the pharma's sales power. The large firm is incentivized to opt out of small niche drugs, which are unlikely to benefit from the economies of the pharma's scale and might well be better marketed with a small specialized sales force that the biotech company should be able to develop.

Our work shows that uncertainty does not need to be regarded as an inhibitor of alliance formation. However, effective partnership arrangements need to recognize that flexibility is a core value driver for R&D projects in high-risk environments. Alliances should anticipate the problems caused by uncertainty, and be based on creative contract designs that are enforceable and provide the necessary flexibility for dealing with the evolving value of their projects.

The pharmaceutical industry is not the only sector where innovation is increasingly a collaborative effort. University-based research, e.g. in nanotechnology, is another example of innovation commercialized in partnership, in fact often with more than two stake-holders (Dechenaux et al. (2009)). However, this industry displays different characteristics to pharmaceuticals, which will have a bearing on the portability of our findings. For example, the symmetric information assumption, which is motivated by the scientific spirit underlying the partners in biotechnology/pharma R&D alliances is not necessarily valid in other industries. Further research is necessary in order to identify sensible contracts and property right agreements to foster collaborative innovation (see for example, Aghion and Tirole (1994)) and to develop the most effective models for commercialization (Cassiman and Ueda (2006)).

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9. Appendix

9.1. Proofs of Propositions

Proof of Proposition 1: Let $\Delta V = V_0 - (V_0^P + V_0^B)$. The equations (1), (2) and (3) imply

$$\Delta V = p_1 p_2 \int_{\frac{C_1}{p_2}}^{\frac{C_1+p_2M_2}{p_2(1-k)}} \left(x - \frac{C_1}{p_2}\right) f(x)dx.$$

The integral is nonnegative because $f(x)$ is a density function and $x - \frac{C_1}{p_2}$ is nonnegative over the integration interval and. Furthermore, when $\int_{\frac{C_1}{p_2}}^{\frac{C_1+p_2M_2}{p_2(1-k)}} f(x)dx > 0$ the integral is strictly positive as claimed. $\square$

Proof of Proposition 2: There are two situations in which the outcome CC is the dominant strategy. The first situation is where co-development is more profitable for the biotech than opting out and co-development is profitable for the pharma company, i.e.,

$$p_2\mathbf{E}[B_2^{CO}] = p_2(kX(t_1) + M_2) < p_2\mathbf{E}[B_2^{CC}] - sC_1 = s(p_2X(t_1) - C_1),$$
$$p_2\mathbf{E}[P_2^{CC}] - (1-s)C_1 = (1-s)(p_2X(t_1) - C_1) > 0.$$

The first inequality is equivalent to $X(t_1) > \frac{p_2M_2+sC_1}{p_2(s-k)}$ and implies the second inequality because the term on the left-hand side of the first inequality is positive. CC is also the dominant strategy if the biotech company would find it more profitable to opt-out but realizes that the value for the pharma, if it were to opt out, would become negative and that the pharma company would therefore abandon the project, turning the biotech value itself negative. For CC to be acceptable in this situation, both firms must have a positive co-development value. Formally this situation occurs when

$$\begin{aligned} p_2\mathbf{E}[B_2^{CO}] = p_2(M_2 + kX(t_1)) &> p_2\mathbf{E}[B_2^{CC}] - sC_1 = s(p_2X(t_1) - C_1), \\ p_2\mathbf{E}[P_2^{CO}] - C_1 = p_2((1-k)X(t_1) - M_2) - C_1 &< 0, \\ p_2\mathbf{E}[B_2^{CC}] - sC_1 = s(p_2X(t_1) - C_1) &\geq 0, \\ p_2\mathbf{E}[P_2^{CC}] - (1-s)C_2 = (1-s)(p_2X(t_1) - C_1) &\geq 0. \end{aligned}$$

The first two inequalities are equivalent to

$$X(t_1) < \frac{p_2M_2 + sC_1}{p_2(s-k)} \text{ and } X(t_1) < \frac{p_2M_2 + C_1}{p_2(1-k)}.$$

Notice that the second inequality implies the first since the derivative of $g(s) = \frac{p_2M_2+sC_1}{p_2(s-k)}$ is $g'(s) = -\frac{kC_1+M_2}{p_2(s-k)^2}$ is negative. Hence the four inequalities are equivalent $C_1/p_2 < X(t_1) < \frac{p_2M_2+C_1}{p_2(1-k)}$.

The outcome CO occurs when the biotech's preferred action is to opt out of co-development, i.e., opt out is more valuable than co-development, and the pharma would still have a profitable project:

$$p_2\mathbf{E}[B_2^{CO}] = p_2(kX(t_1) + M2) > p_2\mathbf{E}[B_2^{CC}] - sC_1 = s(p_2X(t_1) - C_1),$$
$$p_2\mathbf{E}[P_2^{CO}] - C_1 = p_2((1-k)X(t_1) - M_2) = C_1 > 0.$$

This translates to $\frac{p_2M_2+C_1}{p_2(1-k)} < X(t_1) < \frac{p_2M_2+sC_1}{p_2(s-k)}$..

Finally, the outcome OO occurs if co-development is unprofitable for the biotech company and the single development is unprofitable for the pharma company, i.e., if

$$p_2\mathbf{E}[B_2^{CC}] - sC_1 = s(p_2X(t_1) - C_1) < 0$$
$$p_2\mathbf{E}[P_2^{CC}] - (1-s)C_1 = (1-s)(p_2X(t_1) - C_1) < 0$$

which are equivalent to $X(t_1) < C_1/p_2$.

On the boundaries of the respective intervals the firms are indifferent between the different actions

This concludes the proof at the beginning of the second stage. The game for the beginning of the first stage is trivial: if the value for both firms is positive at time t_0 they agree and the contract is signed, otherwise the contract is not signed. □

Proof of Proposition 3: We have to show that $B_0 + P_0 = V_0$. This is a direct consequence of (5) and (6)

$$\begin{aligned}
B_0 + P_0 = p_1 \Bigg[& \int_{C_1/p_2}^{\frac{C_1+p_2M_2}{(1-k)p_2}} s(p_2x - C_1) f(x))\, dx + \int_{\frac{C_1+p_2M_2}{(1-k)p_2}}^{\frac{sC_1+p_2M_2}{(s-k)p_2}} (kx + M_2) f(x)\, dx \\
& + \int_{\frac{sC_1+p_2M_2}{(s-k)p_2}}^{\infty} s(p_2x - C_1) f(x)\, dx \Bigg] - sC_0 + p_1 \Bigg[\int_{C_1/p_2}^{\frac{C_1+p_2M_2}{(1-k)p_2}} (1-s)(p_2x - C_1) f(x)\, dx \\
& + \int_{\frac{C_1+p_2M_2}{(1-k)p_2}}^{\frac{sC_1+p_2M_2}{(s-k)p_2}} p_2((1-k)x - M_2 - C_1) f(x)\, dx + \int_{\frac{sC_1+p_2M_2}{(s-k)p_2}}^{\infty} (1-s)(p_2x - C_1) f(x)\, dx \Bigg] - (1-s)C_0 \\
= {} & p_1p_2 \int_{C_1/p_2}^{\infty} (x - C_1/p_2)\, f(x) dx - C_0 = V_0. \quad \square
\end{aligned}$$

Proof of Proposition 4: We will first show that for any (k, M_2) the value $\alpha = \frac{B_0}{V_0} \in [s, 1]$. First, since the contract is efficient, $V_0 = B_0 + P_0$ and $B_0, P_0 \geq 0$, the biotech's share of the value α is bounded from above by 1. To show that $\alpha \geq s$ it suffices to show that $\Delta = B_0 - sV_0 \geq 0$ because $\alpha = \frac{B_0}{V_0} = \frac{\Delta}{V_0} + s$. To show this, we can constrain our attention to the interval

$$\frac{C_1 + M_2p_2}{(1-k)p_2} \leq X(t_1) \leq \frac{sC_1 + p_2M_2}{(s-k)p_2}$$

because when $X(t_1)$ is outside this interval the biotech firm obtains a share s and the pharma a share $(1-s)$ of the realized total value (see (5 and (6). These are the scenarios where the biotech opts out and the pharma continues (see Proposition 2).

$$\begin{aligned}
\Delta(s, k, M_2) &= B_0(s, k, M_2) - sV_0 \\
&= p_1 \int_{\frac{C_1+p_2M_2}{(1-k)p_2}}^{\frac{sC_1+p_2M_2}{(s-k)p_2}} (p_2(kx + M_2) - s(p_2x - C_1))\, f(x)\, dx \\
&= p_1p_2(s-k) \int_{a(1)}^{a(s)} (a(s) - x) f(x) dx,
\end{aligned} \tag{15}$$

where $a(s, k, M_2) = \frac{sC_1+p_2M_2}{(s-k)p_2}$ in the last line. Since $a'(s) = -\frac{C_1+p_2M_2}{p_2(s-k)^2} < 0$ it follows that $\Delta \geq 0$. Notice that if $k = M_2 = 0$ then $\Delta = 0$, hence $\alpha = s$. Notice also that $\Delta(s, k, M_2)$ is a continuous function of k and M, and hence achieves all values between zero and its maximum as k and M vary. This proves the proposition. □

Proof of Proposition 5: The proof is analogous to the proof of Proposition 2. As the value of the drug $X(t_1)$ moves from high to low, the following equilibria occur:

$$\begin{aligned}
&\text{C,C:} && s\mathbf{E}(V(t_2)) \geq \mathbf{E}[B_2^{CO}] \geq 0,\ (1-s)\mathbf{E}(V(t_2)) \geq \mathbf{E}[P_2^{OC}] \geq 0\\
&\text{C,O:} && \mathbf{E}[B_2^{CO}] \geq s\mathbf{E}[V(t_2)] \geq 0,\ \mathbf{E}[P^{CO}] \geq 0\\
&\text{C,C:} && \mathbf{E}[B_2^{CO}] \geq s\mathbf{E}[V(t_2)] \geq 0,\ \mathbf{E}[P_2^{CO}] \leq 0\\
&\text{O,C:} && \mathbf{E}[P_2^{OC}] \geq (1-s)\mathbf{E}[V(t_2)] \geq 0,\ \mathbf{E}[B^{OC}] \geq 0\\
&\text{C,C:} && \mathbf{E}[P_2^{OC}] \geq (1-s)\mathbf{E}[V(t_2)] \geq 0,\ \mathbf{E}[B_2^{OC}] \leq 0\\
&\text{O,O:} && \mathbf{E}[V(t_2)] \leq 0
\end{aligned}$$

Expressing these inequalities in terms of $X(t_1)$ gives conditions (7-12). A sufficient condition for non-overlapping regions is $\frac{C_1/p_2+M_2}{1-k} \geq \frac{(1-s)C_1/p_2+L_2}{1-s-m}$ (or symmetrically $\frac{sC_1/p_2+M_2}{s-k} \leq \frac{C_1/p_2+L_2}{1-m}$ with the roles of the biotech and pharma changed). □

Proof of Proposition 6: It is easy to show that $B_0 + P_0 = V_0$ as in Proposition 3. □

Proof of Proposition 7: Since the contract is efficient ($V_0 = B_0 + P_0$) and $P_0 \geq 0$ and $B_0 \geq 0$ it follows that the biotech's value share is bounded between 0 and 1. We proceed as in the proof of Proposition 4 and define $\hat{\Delta} = B_0 - sV_0$.

$$\begin{aligned}
\hat{\Delta} &= B_0 - sV_0\\
&= p_1 \int_{\frac{C_1/p_2+L_2}{1-m}}^{\frac{(1-s)C_1/p_2+L_2}{1-s-m}} \left((p_2((1-m)x - L_2) - C_1) - s(p_2x - C_1)\right) f(x)\, dx\\
&+ p_1 \int_{\frac{C_1/p_2+M_2}{1-k}}^{\frac{sC_1/p_2+M_2}{s-k}} \left(p_2(kx + M_2) - s(p_2x - C_1)\right) f(x)\, dx\\
&= \Delta(s,k,M_2) - \Delta(1-s,m,L_2)
\end{aligned}$$

where we have used $a(s,x,y) = \frac{sC_1/p_2+M_2}{s-k}$ and $\Delta(s,x,y)$ is as defined in equation 15. Since the range of $\frac{\Delta}{V_0}$ is $[0,u]$ as shown in Proposition 4, the range of $\alpha = \frac{B_0}{V_0}$ is $[z',z]$, which completes the proof. □

9.2. Valuation formulas for the geometric Brownian motion model

We begin with some useful integral formulas. For a log-normally distributed random variable x with zero drift and volatility σ, the expectation $\mathbf{E}[\min(a,x)] = \int_{-\infty}^{\alpha} xf(x)dx$ can be evaluated by changing variables to $y = \log(\frac{x}{X_0})$ which is normally distributed, as shown in Hull (2003), pp. 262-264:

$$\begin{aligned}
\int_{-\infty}^{\alpha} xf(x)dx &= \int_{-\infty}^{\log\frac{\alpha}{X_0}} \frac{1}{\sqrt{2\pi\sigma^2 t}} X_0 \exp(y) \exp -\frac{(\frac{1}{2}\sigma^2 t + y)^2}{2\sigma^2 t} dy\\
&= X_0 \left[1 - \Phi\left(\frac{\log\frac{X_0}{\alpha} + \frac{1}{2}\sigma^2 t}{\sigma\sqrt{t}}\right)\right],
\end{aligned}$$

where $\Phi(x)$ is the standard Normal cumulative density function. The last line makes use of the symmetry of the Normal distribution: $\Phi(x) = 1 - \Phi(-x)$. We can similarly derive useful expressions for two further integrals:

$$\int_{\alpha}^{\infty} xf(x)dx = X_0\Phi\left(\frac{\log\frac{X_0}{\alpha} + \frac{1}{2}\sigma^2 t}{\sigma\sqrt{t}}\right), \int_{-\infty}^{\alpha} f(x)dx = \Phi\left(\frac{\log\frac{\alpha}{X_0} + \frac{1}{2}\sigma^2 t}{\sigma\sqrt{t}}\right).$$

9.2.1. The value of the co-development contract with a single opt-out option

$$\begin{aligned}
B_0 &= p_1p_2sX(t_0)\left[\Phi(d_1) - \Phi(d_6) + \Phi(d_7) + k/s\left(\Phi(d_6) - \Phi(d_7)\right)\right] \\
&\quad - p_1sC_1\left[\Phi(d_2) - \Phi(d_8) + \Phi(d_9)\right] + p_1p_2M_2\left[\Phi(d_8) - \Phi(d_9)\right] - sC_0 \\
P_0 &= p_1p_2(1-s)X(t_0)\left[\Phi(d_1) - \Phi(d_6) + \Phi(d_7) + (1-k)/(1-s)\left(\Phi(d_6) - \Phi(d_7)\right)\right] \\
&\quad - p_1(1-s)C_1\left[\Phi(d_2) - \Phi(d_8) + \Phi(d_9) + 1/(1-s)\left(\Phi(d_8) - \Phi(d_9)\right)\right] \\
&\quad - p_1p_2M_2\left[\Phi(d_8) - \Phi(d_9)\right] - (1-s)C_0,
\end{aligned}$$

where

$$d_1 = \frac{\ln\frac{p_2X(t_0)}{C_1} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sigma\sqrt{t_1 - t_0}}, d_6 = \frac{\ln\frac{(1-k)p_2X(t_0)}{C_1 + M_2p_2} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sigma\sqrt{t_1 - t_0}}, d_7 = \frac{\ln\frac{(s-k)p_2X(t_0)}{sC_1 + M_2p_2} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sigma\sqrt{t_1 - t_0}},$$
$$d_2 = d_1 - \sqrt{t_1 - t_0}\sigma, d_8 = d_6 - \sqrt{t_1 - t_0}\sigma, d_9 = d_7 - \sqrt{t_1 - t_0}\sigma.$$

9.2.2. The value of the co-development contract with double opt-out options Using the integral expression of the previous section on the value of the two firms yields:

$$\begin{aligned}
B_0 &= p_1p_2sX(t_0)\left[\Phi(g_1) - \Phi(g_2) + \Phi(g_3) - \Phi(g_4) + (1-m)/s\left(\Phi(g_2) - \Phi(g_3)\right)\right. \\
&\quad \left. + \; k/s(\Phi(g_4) - \Phi(g_5)) + \Phi(g_5)\right] + p_1p_1M_2\left[\Phi(g_9) - \Phi(g_10)\right] - sC_0 \\
&\quad - p_1sC_1\left[\Phi(g_6) - \Phi(g_7) + \left(\Phi(g_7) - \Phi(g_8)\right)/s + \Phi(g_8) - \Phi(g_9) + \Phi(g_{10})\right] \\
P_0 &= p_1p_2(1-s)X(t_0)\left[\Phi(g_1) - \Phi(g_2) + \Phi(g_3) - \Phi(g_4) + m/(1-s)\left(\Phi(g_2) - \Phi(g_3)\right)\right. \\
&\quad \left. + \; (1-k)/s(\Phi(g_4) - \Phi(g_5)) + \Phi(g_5)\right] + p_1p_1L_2\left[\Phi(g_7) - \Phi(g_8)\right] - (1-s)C_0 \\
&\quad - (1-s)C_1\left[\Phi(g_6) - \Phi(g_7) + \Phi(g_9) - \Phi(g_7) + \left(\Phi(g_9) - \Phi(g_{10})\right)/(1-s) + \Phi(g_{10})\right],
\end{aligned}$$

where $g_1 = d_1$, $g_6 = d_2$,

$$\begin{aligned}
g_2 &= \frac{\ln\frac{(1-m)p_2X(t_0)}{C_1 + p_2L_2} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sigma\sqrt{t_1 - t_0}}, \; g_7 = g_2 - \sqrt{t_1 - t_0}\sigma \\
g_3 &= \frac{\ln\frac{(1-s-m)p_2X(t_0)}{(1-s)C_1 + p_2L_2} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sigma\sqrt{t_1 - t_0}}, \; g_8 = g_3 - \sqrt{t_1 - t_0}\sigma \\
g_4 &= \frac{\ln\frac{(1-k)p_2X(t_0)}{C_1 + p_2M_2} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sigma\sqrt{t_1 - t_0}}, \; g_9 = g_4 - \sqrt{t_1 - t_0}\sigma \\
g_5 &= \frac{\ln\frac{(1-s-k)p_2X(t_0)}{sC_1 + p_2M_2} + \frac{\sigma^2}{2}(t_1 - t_0)}{\sigma\sqrt{t_1 - t_0}}, \; g_{10} = g_5 - \sqrt{t_1 - t_0}\sigma.
\end{aligned}$$