INCENTIVE CONTRACTS UNDER PRODUCT MARKET COMPETITION AND R&D SPILLOVERS

By

Evangelia Chalioti

COWLES FOUNDATION PAPER NO. 1824

COWLES FOUNDATION FOR RESEARCH IN ECONOMICS
YALE UNIVERSITY
Box 208281
New Haven, Connecticut 06520-8281

2023

http://cowles.yale.edu/

Incentive contracts under product market competition and R&D spillovers*

Evangelia Chalioti

University of Illinois at Urbana-Champaign‡

Abstract

This paper studies cost-reducing R&D incentives in a principal-agent model with product market competition. It argues that moral hazard does not necessarily decrease firms' profits in this setting. In highly competitive industries, firms are driven by business stealing incentives and exert such high levels of R&D that they burn up their profits. In the presence of moral hazard, underprovision of R&D incentives due to risk-sharing can generate considerable cost-savings, implying higher profits for both rivals. This result indicates firms' incentives to adopt collusive-like behavior in the R&D market. We also examine the agents' contracts and the profits-risk relationship when cross-firm R&D spillovers occur.

Keywords: moral hazard, process innovation, Cournot competition, R&D spillovers, relative performance

JEL: D82, L13, O30

*I am indebted to Lambros Pechlivanos for the very useful discussions on this topic. I am also grateful to Dan Bernhardt, George Deltas, Johannes Hörner, Katharine Rockett, Larry Samuelson, Konstantinos Serfes and Spyros Vassilakis for their comments and suggestions. I give special thanks to Rabah Amir, Costas Arkolakis, Dirk Bergemann, Gary Biglaiser, Claude D'Aspremont, Raymond De Bondt, Mathias Dewatripont, Mehmet Ekmekci, Vitor Farinha, Gianluca Femminis, Sebastian Kranz, Silvana Krasteva, Vijay Krishna, Eric Maskin, Chrysovalantou Milliou, Ana Rodrigues, Philipp Strack, Rodrigo Velez, Nicolaos Vettas, Anastasios Xepapadeas and the participants at various conferences and meetings. Financial support from the State Scholarships Foundation in Greece is also acknowledged.

†Contact: Department of Economics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. E-mail: chalioti@illinois.edu, evachalioti@gmail.com

‡This paper is based on Chapter 3 of my thesis.

1 Introduction

In knowledge-based industries, firms' interactions and technical advance favor a decentralized organizational structure that involves separation between business units and research teams. The owners of firms appoint highly-skilled researchers or autonomous units to undertake cost-reducing R&D projects on their behalf. Thus, there is a division between ownership and control over R&D-outputs. In such R&D markets, the issue of incentive provision deserves special attention since firms also compete in the product market. The principal-agent literature based on Holmström (1979) remains narrow in its focus on the effect of moral hazard and risk on firms' profits when there are strategic interactions among firms. This paper examines whether the standard result in the literature that firms enjoy higher profits under full information applies in a setting with product market competition. We argue that moral hazard does not necessarily decrease firms' profits. Instead, in equilibrium, higher risk can make product market competitors better off.

The conventional wisdom in models with moral hazard, originating from Holmström (1979) and Holmström & Milgrom (1987), is that the optimal contract balances an increase in risk with weaker incentives for effort due to risk-sharing. Thus, the owners of the firms are better off under full information where no insurance is provided. We argue that the latter result need not hold if firms interact in the product market. We take into account the market environment and identify the conditions under which the profit-risk relationship turns out to be positive.

We consider a setting with two risk-neutral firms that first invest in cost-reducing R&D and then interact in a differentiated-final product market. To conduct R&D, the owner of each firm (the principal) appoints a risk-averse researcher (the agent) whose effort is unobservable. The bargaining power is assigned to the principals, allowing them to make take-it-or-leave-it offers to the agents and extract the entire rents of R&D activity. The incentive packages are derived in a linear principal-agent model (Holmström & Milgrom (1987)) and the payments are contingent on marginal cost reductions (Raith (2003)).[1,2] Each agent's R&D output depends on her own effort and a project-specific shock.

We derive the optimal R&D incentives and show that, in highly competitive industries, firms are driven by business stealing incentives and exert such high levels of R&D that they burn up their profits. In the presence of moral hazard, risk-sharing mitigates such R&D incentives and firms' appetite for innovation. Lower effort is exerted implying cost savings for both rivals. We argue that there exists a regime in which cost savings are substantial enough that firms' profits are higher under moral hazard. This occurs when product market competition is intensive and the cost of R&D is relatively small. This paper delves into firms' incentives to adopt collusive-like behavior in R&D and even utilize the intra-firm conflicts of interests. Separation of business and research units under moral hazard, prior to product market competition, can be used as a collusive device that mitigates

[1] Prendergast (1999) provides a review of the principal-agent literature.

[2] Cost-based schemes are consistent with real-world contracting practices. In Germany, for instance, inventors' compensation schemes based on the expected value of the R&D-outputs have been established by law (German Employees' Inventions Act passed in 1957).

firms' interactions in the subsequent stages. Firms become better off as more insurance has to be provided to researchers.

We also examine cost-reducing R&D motives and the effect of risk on equilibrium profits when R&D spillovers occur. Each firm's cost reduction now also depends on the size of the spillovers; i.e., on the amount of (unpaid) appropriation of a rival's R&D (e.g., D'Aspremont & Jacquemin (1990), Kamien, Muller & Zang (1992), Qiu (1997), Amir, Amir & Jin (2000)). Due to technological interactions between agents, each principal now offers a relative performance evaluation scheme. The explicit comparison of R&D performances is the consequence of the efficient use of information conveyed by both rivals' R&D-outputs about each agent's effort. The existing literature uses such contracts when the market shocks that hit each agent's production are correlated (Holmström & Milgrom (1987)). In this model, there is no correlation between the random factors. However, spillovers necessitate the use of such schemes. In equilibrium, a negative weight is placed on a rival firm's performance, implying that an agent is penalized if the rival does better. Such contracts introduce competition between agents and can effectively filter out spillovers from their compensation packages.

To study how profits change with risk in this context, we first discuss the effects of competition and spillovers on R&D incentives. In particular, the relative location of the firms in the product and technology space determines the nature of strategic interactions in the R&D market. The analysis performs a decomposition of R&D incentives and focuses on the underlying effects that arise due to product market competition: the (positive) strategic effect due to business stealing and the (negative) spillover effect due to knowledge transmission. The latter effect is detrimental to the R&D-taking firm; i.e., spillovers enhance the efficiency of the rival making this firm tougher in the product market. If the strategic effect dominates the spillover effect, efforts are strategic substitutes.

We show that in a regime where efforts are strategic substitutes, competition stimulates R&D in markets with highly elastic demand. This happens because a firm with cost advantage can more easily extend its business at the expense of its rival.[3] Thus, each firm has stronger incentives to conduct R&D as demand becomes more elastic. In this regime, spillovers also foster R&D if the cost of effort exertion is relatively small.[4] By investing in R&D, each principal wants to realize a slightly lower marginal cost from its competitor. As spillovers increase, rivals acquire more R&D exactly in order to secure a cost advantage. Thus, both competition and spillovers induce firms to invest more in R&D. However, by doing so, R&D costs increase without a commensurate increase in equilibrium profits. The presence of moral hazard on the part of the researchers leads to underprovision of R&D

[3]Aghion, Bloom, Blundell, Griffith & Howitt (2005), among others, study empirically the effect of competition on incentives. Griffith (2001) and Baggs & De Bettignies (2007) examine the relationship between competition and agency cost.

[4]Levin (1988), among others, reports extensive spillovers mainly in bioengineering and microelectronics-based industries. Computer software, chemical compounds and genetic sequences are subject to spillovers due to disclosure of knowledge through publications or patents, researchers' mobility, or even embodiment of knowledge in products (knowledge acquisition by reverse engineering). Bondt (1997) and more recently Rockett (2012) provide reviews about the effect of knowledge spillovers on R&D investments.

incentives. Therefore, a cost-saving choice for both rivals is to delegate R&D decisions ex-ante or even to appoint highly risk-averse agents in order to conduct less R&D and thereby enjoy higher profits. Firms become better off as the trade-off between effort provision and insurance is shifted towards the latter. We find that principals capitalize on such benefits only if the cost of incentivizing and insuring the researchers from the stochastic nature of their effort does not exceed a threshold. If the R&D activity is too costly, rivals' profits are higher under full information. This result sheds insight on the organizational structure firms may desire to adopt, given the cost of exerting effort and the market characteristics.

Gains from risk-sharing are also generated for firms that compete à la Bertrand in the product market. Firms enter into a price war. By being more efficient, they end up cutting prices, thereby diminishing their equilibrium profits. In this setting, investing less in R&D due to moral hazard can also increase the rivals' profits. Thus, a positive profit-risk relationship can be realized in both Bertrand and Cournot settings: it does *not* depend on the mode of competition in the product market. However, in the R&D market, agents' efforts must be strategic substitutes. If they are strategic complements, firms wish to undertake research under full information and effectively monitor the agents in order to exploit all opportunities from efficiency enhancement.

This analysis contributes to the existing literature on the theory of the firm that argues that considering a firm in isolation may be misleading. Strategic interactions play a key role in the firms' internal organization. This literature based on Fershtman & Judd (1987) and Sklivas (1987) focuses on "strategic delegation". It examines the effect of product market competition on the agents' compensation schemes and incentives.[5,6] From another perspective, Aggarwal & Samwick (1999) study how agents' incentives can influence the intensity of the strategic interactions between firms. These papers assume that agents perform in the product market and their compensation is contingent on firms' profits and sales. Effort is observable and there are no agency problems. In our model, we assume that researchers' tasks are focused on cost reduction and their rewards are directly related to the output of their task. We use the standard principal-agent model in a competitive setting where the researchers' decisions cannot affect firms' strategic interactions.

The severity of the principal-agent problem when it is faced by product market competitors has been examined by Hart (1983), Hermalin (1992), Schmidt (1997), Raith (2003), and Piccolo, D'Amato & Martina (2008), among others.[7] Raith (2003) points out the difference between the risks firms face and the risks to which agents are exposed. He considers an endogenous number of firms

[5]Other works examine the effect of competition on incentives by considering changes in the number of competitors, the market size, the transportation cost or the cost of entry (Raith (2003)). Nickell (1996) and Vickers (1995) review the existing literature about the effect of competition on incentives and Vives (2008) provides a survey about the effect of competition on innovation. Milliou & Petrakis (2011) study the technology adoption incentives of market rivals.

[6]Lai, Riezman & Wang (2009) consider cost-reducing R&D and study firms' decision to outsource the R&D project or develop it in-house. They use a principal-agent framework and find that revenue-sharing contracts increase the chance of outsourcing.

[7]Serfes (2005) assumes a continuum of principals and agents with uniform distributions and studies the relationship between risk and performance pay (incentives) in a principal-agent market. He finds conditions under which the equilibrium relationship between risk and incentives is negative, positive, or non-monotonic.

that compete in prices along a Salop circle. He argues that incentives are positively related only to firm risk because changes in competition change the value of cost reductions and the variance of firms' profits in the same direction. In our model, we examine the risk faced by agents and argue that higher degrees of risk aversion and the riskiness of the performance measures decrease the R&D incentives but can increase rivals' profits.[8] More recently, Serfes (2008) derives a positive profits-risk relationship in an endogenous matching model with heterogeneous principals and agents.

This paper can also be tied to the literature on firms' incentives to vertically integrate. If the R&D and production units are separate, contracts are used to govern their relationship and the moral hazard problem is present. This paper shows that in highly competitive markets where profits increase with risk, vertical separation is preferable. In contrast, in a regime where competition is soft and the profits-risk relationship becomes negative, firms have incentives to vertically integrate and the moral hazard problem disappears. Several recent papers explore firm boundaries and internal organization (e.g., Aghion, Dewatripont & Rey (2004), Alonso, Dessein & Matouschek (2008), Hart & Holmström (2010)). Aghion, Griffith & Howitt (2006) provide evidence of a U-shaped relationship between product market competition and vertical integration.

An additional contribution of this paper is the following. Holmström (1979) shows that the certainty equivalent of the agent's utility can be written in the mean-variance form if constant absolute risk-averse preferences are considered, linear contracts are used, and the random terms are normally distributed. The optimal effort only affects the first two moments of the distribution of wages and the agent's problem has a closed-form solution. We establish that this is also the case if the random terms follow a *truncated* normal distribution that is symmetric around the mean. Truncation is required in order to guarantee positive post-innovation marginal costs. This assumption is essential in all models based on Holmström (1979) that consider cost-reducing incentives under moral hazard.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 solves the rivalry game, analyzes the underlying effects of risk on profits, and interprets the results. In section 4, we study the incentive contracts and profit-risk relationships in the presence of spillovers. The cost-reducing motives of Bertrand rivals and the optimal contracts when there are two forms of interdependence between the researchers' R&D outputs - i.e., due to spillovers and the correlation of the random terms - are also discussed. Section 5 concludes.

2 The model

The market features two risk-neutral and profit-seeking firms 1 and 2, indexed by i and j where $i \neq j$. Each firm is run by a principal whose task is to first invest in cost-reducing R&D and then to make output decisions. To acquire R&D, each principal hires a risk-averse researcher, whose effort is unobservable and non-contractible. Thus, the principal's problem is to offer a contract based on

[8] Chiu, Eeckhoudt & Rey (2012) study the behavior of the relative and partial risk-aversion measures. Mirrlees & Raimondo (2013) analyze strategies in a continuous-time principal-agent model.

contractible measures that is incentive compatible. The parties interact and play the three-stage game described in Figure 1.

Stage 1		Stage 2		Stage 3
Each principal, simultaneously with its rival, makes a take-it-or-leave-it offer to an agent.	$\longrightarrow$	If the agent accepts the offer, she chooses an effort level (x_i). Events beyond the agents' control occur, R&D-outputs are determined, and contracts are executed.	$\longrightarrow$	Firms observe the R&D-outputs and compete à la Cournot in the product market. Profits are realized.

Figure 1. Timing of the game

2.1 Firms' profits

The market is populated by a continuum of identical consumers with mass equal to 1. Each firm i faces the linear demand $p_i = A - q_i - bq_j$ where p_i is firm i's price, $p_i : R_+^2 \to R_+$, and q_i is its output.[9] The parameter A denotes the market size, $A > 0$, and b captures the degree of product substitutability, $b \in [0, 1]$. When $b = 0$, firms have independent demands and behave as monopolists while, at the other extreme, when $b = 1$, they act as homogeneous-product duopolists. A higher b indicates tougher competition.

Each firm begins with an initial marginal cost $\overline{c}$, but takes advantage of cost-reducing R&D opportunities. If firm i acquires the R&D output z_i, it realizes the post-innovation marginal cost $c_i = \overline{c} - z_i$ where $A > \overline{c} > 0$. The R&D output depends on the agent's effort, x_i, and a project-specific shock, ε_i, taking the form $z_i = x_i + \varepsilon_i$.[10] The random terms are drawn from a truncated normal distribution with zero mean and variance σ^2. They lie in $\Theta \equiv [-\theta, \theta]$, where $-\infty < -\theta < \theta < +\infty$, and are identically and independently distributed across agents.[11] Thus, firm i will commit to an R&D level $x_i \in X$ where $X \equiv [0, \overline{c} - \varepsilon_i]$ and $\varepsilon_i \in \Theta$. It will also enjoy the R&D profit $\pi_i = \Pi_i - w_i$ where Π_i is the Cournot profit and w_i is the agent i's compensation.

2.2 Agents' compensation and preferences

Agent i has constant absolute risk-averse (CARA) preferences with utility function

$$U_i(w_i, x_i) = -e^{-r[w_i - \psi(x_i)]}, \tag{1}$$

where r is the Arrow-Pratt measure of risk aversion, $r > 0$, and $\psi(x_i)$ is the cost-of-effort function. This function is twice continuously differentiable and convex with $\psi(0) = 0$, $\psi'(0) = 0$ and $\psi'(\infty) =$

[9] Following Singh & Vives (1984), the representative consumer's preferences are described by the standard quadratic utility function $V(q_i, q_j) = A(q_i + q_j) - \left[\frac{1}{2}\left(q_i^2 + q_j^2\right) + bq_iq_j\right]$. This function is separable and linear in the numeraire good. There are no income effects and thus we can perform partial equilibrium analysis.

[10] Instead of process (cost-reducing) innovation, one could consider product innovation; i.e., quality improvement in existing products. Product innovation can be represented by an increase in consumers' willingness to pay captured by the parameter A. Firms' profit functions remain the same implying that the optimal choices and the comparative statics in our model apply in both settings (Vives (2008)).

[11] The value of θ is specified in subsection 3.2 where assumptions on the profit functions are made.

∞. Following Holmström (1979), the agent receives a linear contract that is contingent on her R&D output and generates a payment

$$w_i = \alpha_i + \beta_i z_i, \tag{2}$$

where α_i denotes the fixed salary component and β_i is a pay-for-performance parameter, $\beta_i \geq 0$. If the agent rejects the offer, she picks the outside option, which is normalized to zero.

3 Equilibrium and R&D incentives

We recursively solve the game and derive the subgame perfect Nash equilibrium. Firms make their decisions simultaneously and independently. We also analyze the effect of moral hazard on agents' effort and competitors' equilibrium profits.

3.1 Cournot competition

In stage 3, firms observe the realization of the marginal costs and compete in outputs. In particular, firm i maximizes $\Pi_i = [A - q_i - bq_j - c_i]\, q_i$ and produces

$$q_i^* = \frac{1}{2+b}\left[A - \bar{c} + \frac{2z_i - bz_j}{2-b}\right]. \tag{3}$$

Its Cournot profit is $\Pi_i^* = (q_i^*)^2$. Note that firms generically end up in an asymmetric equilibrium $\left(q_i^*, q_j^*\right)$ even if the R&D decisions taken in the previous stages were identical. This reflects that firms may experience asymmetric marginal costs depending on how lucky the researchers were during the R&D process; i.e., the realizations of ε_i and ε_j may differ.

3.2 Principals' problem and R&D rivalry

To acquire R&D, each principal, simultaneously with her rival, makes a contract offer to her agent that maximizes the expected profit and is compatible with agent's incentives to perform and to participate. Thus, the principal i's contract decision depends on agent i's response to her (expected) payment as well as the rival's response to firm i's R&D. Denoting her beliefs about firm j's R&D by $\widehat{x}_j$, principal i's problem becomes

$$\max_{\alpha_i, \beta_i, x_i} E\left\{\pi_i(\alpha_i, \beta_i, x_i; \widehat{x}_j) \mid \varepsilon_i, \varepsilon_j \in \Theta\right\} = E\left\{\Pi_i - w_i \mid \varepsilon_i, \varepsilon_j \in \Theta\right\}$$

$$\text{subject to } \; x_i^* = \arg\max_{x_i} E\left\{U_i\left(w_i, x_i\right) \mid \varepsilon_i \in \Theta\right\} \qquad (IC_i)$$

$$E\left\{U_i\left(w_i, x_i\right) \mid \varepsilon_i \in \Theta\right\} \geq 0 \qquad (IR_i)$$

The incentive compatibility constraint (IC_i) guarantees that agent i chooses the (expected) utility maximizing effort. The individual rationality constraint (IR_i) shows that agent i will participate in the R&D process only if her expected utility of doing so exceeds her reservation utility of zero. In lemma 1, we state that the certainty equivalent of agent i's utility can be expressed in a mean-variance form and the truncation of the distribution of the random terms does not affect the agent's optimal decision. The agent conducts the R&D level that would also be optimal if the distribution of the shocks was normal but not truncated.

Lemma 1 (Certainty equivalent of utility & truncated normal distribution) *If agent i has CARA preferences towards risk, linear contracts are used and the random terms follow a truncated normal distribution symmetric around the mean, then agent i's expected utility is given by*

$$E\left\{U_i\left(w_i,x_i\right)\mid\varepsilon_i\in\Theta\right\}=-\Omega_i e^{-r\left[\widetilde{U}_i(x_i)\right]}\ \textit{where}\ \widetilde{U}_i\left(x_i\right)=E\left(w_i\right)-\frac{r}{2}Var\left(w_i\right)-\psi(x_i),$$

and $\Omega_i\equiv\frac{\Phi\left(\frac{\theta+\sigma^2 r\beta_i}{\sigma}\right)-\Phi\left(\frac{-\theta+\sigma^2 r\beta_i}{\sigma}\right)}{\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)}$. $\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)$ *is the probability of ε_i falling into Θ. Given that Ω_i is positive and independent of effort, agent i's maximization problem is to choose the effort x_i that maximizes the certainty equivalent of her utility $\widetilde{U}_i\left(x_i\right)$.*

Proof. See appendix. ■

Given that $\widetilde{U}_i\left(x_i\right)=\alpha_i+\beta_i x_i-\frac{r}{2}\beta_i^2\sigma^2-\psi(x_i)$, the optimal effort x_i^* satisfies the first-order condition

$$\beta_i=\psi'\left(x_i\right). \tag{4}$$

The concavity of the functions U_i and π_i in x_i, agents' CARA preferences and the (truncated) normality of the random terms allow us to use the first-order approach and replace the IC_i constraint with equation (4).[12] To derive the optimal contractual parameters, we solve simultaneously both principals' constrained maximization problems and take the Kuhn-Tucker conditions. The IR_i constraint binds at the optimum and agents earn no rents: the fixed salary component, α_i, induces agent i's participation at least cost. Thus, the optimal wage is $w_i\left(x_i\right)=\frac{r\sigma^2}{2}\left[\psi'\left(x_i\right)\right]^2+\psi\left(x_i\right)$. Each agent is rewarded for the cost of effort she incurs and the risks she bears. By (3), we also have

$$E\left\{q_i^*\mid\varepsilon_i,\varepsilon_j\in\Theta\right\}=\frac{1}{2+b}\left[A-\bar{c}+\frac{2x_i-bx_j}{2-b}\right], \tag{5}$$

[12]In a multi-agent framework, the monotone likelihood ratio property (MLRP) and the convexity of the distribution function condition (CDFC) are not sufficient for the first-order approach to be valid as in a single-agent setting. Itoh (1991) argues that, in a model with cross-agent interactions, a generalized CDFC for the joint probability distribution of the outputs is needed and the wage schemes must be nondecreasing. The coefficient of absolute risk-aversion must also not decline too quickly. In our model, given the assumptions about the agents' CARA preferences and the independently distributed random shocks as well as the (linearity of) contracts and the R&D production function, the first-order approach applies.

implying that firms' R&D decisions are strategic substitutes. To guarantee that there exists an interior solution in this contracting/R&D game, we use the following Inada-type assumptions on the profit function π_i (i.e., Amir et al. (2000)):

$(A.1)$ $A(2-b) - 2\overline{c} - b\theta > 0$

$(A.2)$ $\frac{4}{(4-b^2)(2-b)} < [1 + r\sigma^2 \psi''(x)]\, \psi''(x)$ for all $x \in X$.

Assumption $(A.1)$ requires market demand to be high enough relative to the initial marginal cost, so that each firm has incentives to undertake some R&D regardless of its rival's R&D choice. Assumption $(A.2)$ requires a strong form of convexity of the cost-of-effort function, so that the equilibrium of this game is unique. In particular, given that R&D decisions are strategic substitutes and thus the slope of R&D reaction functions is negative, $(A.2)$ guarantees that this slope is also higher than -1.[13,14]

Lemma 2 (Existence of unique interior equilibrium) *Under assumptions* $(A.1) - (A.2)$*, there exists a unique subgame perfect Nash equilibrium in R&D in the interior of the jointly effective strategy space* X^2.

Proof. See appendix. ■

The optimal R&D level is

$$x^* = \frac{1}{4}\left(4 - b^2\right)(2 + b)\left[1 + r\sigma^2 \psi''(x^*)\right] \psi'(x^*) - (A - \overline{c}) . \tag{6}$$

Risk plays a key role in the optimal decisions. Under full information, the principal extracts the complete rents via the base payment and the agent i's wage is equal to the marginal disutility of labor, $\psi'(x_i)$. However, under moral hazard, risk-aversion on the part of agents and uncertainty about performance induce the agents to seek insurance against low realizations of the R&D outputs. Weaker incentives can provide such insurance. Thus, effort falls short of its efficient level. In other words, the optimal effort decreases with risk, measured by $r\sigma^2$; i.e., $\frac{\partial x^*}{\partial(r\sigma^2)} < 0$ for all $x \in X$.[15]

3.3 Profits-risk relationship

The effect of risk on profits is not clear cut. In particular, firm i's equilibrium profits take the form $\pi^* = \Pi^* - \frac{r\sigma^2}{2}\left[\psi'(x^*)\right]^2 - \psi(x^*)$ where the R&D level is given by (6) and $\Pi^* = \frac{1}{(2+b)^2}(A - \overline{c} + x^*)^2$

[13] Let the cost-of-effort function be $\frac{k}{2}x_i^2$ where higher k indicates lower efficiency. Assumption $(A.1)$ always holds and $(A.2)$ requires $\frac{4}{(4-b^2)(2-b)} < k\left(1 + kr\sigma^2\right)$. Assumption $(A.2)$ also suffices to guarantee that the sufficient condition of the principal i's problem holds.

[14] Provided that the assumptions hold for the extreme value θ, they also hold for the mean of the random terms, which is zero.

[15] Appendix $(A.3)$ provides a proof.

by equation (5). Taking the derivative

$$\frac{\partial \pi^*}{\partial (r\sigma^2)} = \frac{2}{(2+b)^2}(A - \bar{c} + x^*)\frac{\partial x^*}{\partial (r\sigma^2)} - \left[\frac{1}{2}\psi'(x^*) + r\sigma^2 \frac{\partial \psi'(x^*)}{\partial (r\sigma^2)}\right]\psi'(x^*) - \frac{\partial \psi(x^*)}{\partial (r\sigma^2)}, \tag{7}$$

we examine the underlying effects. First, the Cournot profits decrease with $r\sigma^2$: given that Π^* increases with efficiency-enhancing R&D and higher values of $r\sigma^2$ distort effort downwards, lower Cournot profits are realized as a result. Second, there are the direct and indirect effects on human capital insurance. In particular, higher degrees of risk-aversion and uncertainty about performance induce the agent to seek additional insurance, implying lower residual profits for the principals. However, underprovision of R&D incentives due to risk-sharing also decreases the variable part of agent's compensation and thus the variance of the payment; i.e., $r\sigma^2 \frac{\partial \psi'(x^*)}{\partial (r\sigma^2)}\psi'(x^*) < 0$. Agent i is induced to exert lower effort and incurs lower risks. This (indirect) effect works in favor of the principal since she is required to provide less insurance. Third, there is the effect on the disutility of effort; i.e., $\frac{\partial \psi(x^*)}{\partial (r\sigma^2)} < 0$. The latter two effects capture the cost a firm saves by acquiring less R&D in response to higher risk.

We argue that there exists a regime in which cost-savings by providing lower-power R&D incentives due to moral hazard are substantial enough that the profit-risk relationship turns out to be positive. This occurs when the gain in profit due to cost-savings exceeds the loss of profit due to lower market power a firm can possess by investing less in R&D. In this regime, the optimal profits increase as more insurance is provided. This result counters the prediction of the principal-agent theory where principals wish to have full information so as to perfectly monitor agents and achieve the optimal allocation of effort from their own perspective. We show that such motives can be reversed when firms compete aggressively in the product market.

Proposition 1 (Positive profits-risk relationship) *Under assumptions* $(A.1) - (A.2)$*, Cournot competitors' profits can increase with risk when the cost of incentive provision is small enough and goods are close substitutes so that competition is stiff; i.e.,* $\frac{\partial \pi^*}{\partial (r\sigma^2)} > 0$*, if and only if,*

$$\frac{4}{(4-b^2)(2+b)(1-b)} > \left[1 + r\sigma^2 \psi''(x^*)\right]\psi''(x^*).$$

Proof. See appendix. ■

Proposition 1 states that if effort exertion is not too costly (low $r\sigma^2$) and product market rivals compete (sufficiently) aggressively against each other (high b), they acquire such high levels of R&D that they burn up their profits.[16] Under moral hazard, risk-sharing diminishes such appetite for innovation. Underprovision of incentives exactly due to the trade-off between effort exertion and

[16] The product $(4-b^2)(2+b)(1-b)$ decreases with b.

insurance may generate considerable cost-savings, and thus higher profits for both rivals.[17] However, if $r\sigma^2$ exceeds the threshold specified in proposition 1, the cost of conducting R&D is so high that it decreases profits. This result indicates the desirability of the R&D rivals to adopt collusive-like behavior in R&D so as to behave less aggressively in the product market. Thus, before firms meet in the market place, the separation between the business and research units, which implies the division between the ownership and control of R&D outputs under moral hazard, can be used as a commitment device for both rivals that softens their subsequent responses. Rivals will enjoy higher profits as a result.

[Figure 2 is about here]

This analysis gives new insights into firms' organizational structure. In industries where competition is low and R&D is costly, firms should adopt an organization structure that eliminates the information asymmetries about agents' actions. By doing so, firms will be able to manage the innovation process more efficiently and decrease incentive distortions. In contrast, much of the use of incentive pay could be in volatile industries, such as in high-technology industries and the financial sector. For instance, in microelectronics-based industries where competition is intensive, firms have strong incentives to mutually commit themselves to lower R&D levels. By delegating R&D decisions to a second party - i.e., a research team, an autonomous unit, etc. - or even by appointing more risk-averse researchers, rivals' strategic interactions are weakened and principals can become better-off.

4 R&D Incentives under spillovers

This section examines firms' decisions in the presence of R&D spillovers. Spillovers from a firm's R&D (costlessly) decrease the rival's initial marginal cost, creating a disincentive for the R&D taking firm. However, we argue that if imperfect spillovers occur and firms' R&D decisions are strategic substitutes, spillovers can induce the product market competitors to intensify their R&D efforts in order to secure a cost advantage, decreasing their profits even further. Thus, we show that as spillovers increase, there are additional benefits of using a self-control device that mutually decreases rivals' R&D efforts and allows for higher profits. To anticipate the effect of spillovers and competition on rivals' R&D, we decompose the R&D incentives and perform a comparative statics analysis.

[17] For a quadratic cost-of-effort function of the form $\frac{k}{2}x_i^2$, $\frac{\partial \pi^*}{\partial r\sigma^2} > 0$ if and only if $r\sigma^2 < \frac{1}{k}\left[\frac{4}{(4-b^2)(2+b)(1-b)k} - 1\right]$. Note that for homogeneous-product duopolists, $b = 1$, the profits-risk relationship is positive for all parameter values; i.e., $\pi^* = \frac{(A-\bar{c})^2\left[9k\left(1+kr\sigma^2\right)-8\right]k\left(1+kr\sigma^2\right)}{\left[9k(1+kr\sigma^2)-4\right]^2}$ and $\frac{\partial \pi^*}{\partial r\sigma^2} = \frac{32(A-\bar{c})^2k^2}{\left[9k(1+kr\sigma^2)-4\right]^3} > 0$.

4.1 Equilibrium

The R&D process is now subject to cross-firm R&D spillovers. As in D'Aspremont & Jacquemin (1990), agent i's R&D-output depends on the size of (unpaid) appropriation of its rival's research, hx_j. The R&D production function takes the form

$$z_i = x_i + hx_j + \varepsilon_i, \tag{8}$$

where $x_i \in \left[0, \bar{c} - \overline{h}x_j - \varepsilon_i\right]$. The parameter h measures the spillover rate, $h \in [0,1]$; i.e., the fraction of agent j's R&D that improves agent i's performance. If it is less than one, it indicates the imperfect nature of spillovers.

Agent i's compensation is now restricted to be linear in both agents' R&D-outputs due to spillovers (Holmström (1979), Holmström & Milgrom (1987), Holmström & Tirole (1989)). Relative performance evaluations provide a richer information base on which to write contracts and allow each principal to better assess its agent's effort by looking at its rival's performance. The contract takes the form $(\alpha_i, \beta_i, \gamma_i)$ and agent i receives

$$w_i = \alpha_i + \beta_i z_i + \gamma_i z_j, \tag{9}$$

where γ_i denotes the pay-for-rival performance parameter.[18,19] Thus, each agent's reward is conditional on how well she performs compared to the other.

The certainty equivalent of agent i's utility is

$$\widetilde{U}_i = \alpha_i + (\beta_i + h\gamma_i)\, x_i + (h\beta_i + \gamma_i)\, x_j - \frac{r}{2}\left[(\beta_i + h\gamma_i)^2 + (h\beta_i + \gamma_i)^2\right]\sigma^2 - \psi(x_i), \tag{10}$$

and the optimal effort satisfies the condition

$$\beta_i + h\gamma_i = \psi'(x_i). \tag{11}$$

The left hand side represents the "total" sensitivity of agent i's compensation to her own effort. In equilibrium, $\frac{\partial Var(w_i)/\partial\beta_i}{\partial\psi'(x_i^*)/\partial\beta_i} = \frac{\partial Var(w_i)/\partial\gamma_i}{\partial\psi'(x_i^*)/\partial\gamma_i}$ implying that each principal has two equivalent incentive tools available to use in order to affect the agent's behavior. By (3) and (8), we also have

$$E\left\{q_i^* \mid \varepsilon_i, \varepsilon_j \in \Theta\right\} = \frac{1}{2+b}\left[A - \bar{c} + \frac{(2-bh)\, x_i - (b-2h)\, x_j}{2-b}\right]. \tag{12}$$

[18] Instead, the payment could be $w_i = \alpha_i + \beta_i (z_i - hz_j)$. In equilibrium, this contract is equivalent to that in (9).

[19] Lacetera & Zirulia (2012) consider agents that exert effort for applied research and basic research (two tasks). Efforts are unverifiable, while only effort for basic research is assumed to be diffused. The marginal costs are non-contractible and an agent's contract is contingent on verifiable signals of her own efforts. We consider the agent to have one task and the marginal cost to be contractible. Due to spillovers, we establish the necessity of relative performance evaluation schemes based on both firms' marginal cost reductions.

The nature of R&D strategic interactions now depends on the sign of $b-2h$. If spillovers are small enough so that $h<\frac{b}{2}$, efforts are strategic substitutes, but if spillovers are relatively intensive so that $h>\frac{b}{2}$, efforts are strategic complements. In the knife-edge case where $h=\frac{b}{2}$, each firm has a dominant strategy on R&D. To guarantee that a solution exists in this game, as in subsection 3.2, we make the following assumptions:

$(A.3)$ $A(2-b)-2(1-h)\overline{c}-(b-2h)\theta>0$

$(A.4)$ $\frac{2(2-bh)[2-bh+|2h-b|]}{(4-b^2)^2}<[1+r\sigma^2\psi''(x)]\,\psi''(x)$

Assumption $(A.3)$ guarantees the interiority of the equilibrium since it ensures that each firm finds it best to do some R&D. Assumption $(A.4)$ guarantees the uniqueness of this equilibrium. When R&D decisions are strategic substitutes, it ensures that the slope of R&D reaction functions is larger than -1. When R&D decisions are strategic complements, the cost-of-effort function needs to be strongly convex in order to moderate the R&D incentives and ensure that the slope of R&D reaction functions is smaller than 1.[20]

Proposition 2 (Spillovers & relative performance) *Under assumptions* $(A.3)-(A.4)$*, there exists a subgame perfect Nash equilibrium in performance-based parameters in which*

$$\left(1-h^2\right)\beta^*=\psi'(x^*)\ \ \textit{and}\ \gamma^*=-h\beta^*,$$

where the optimal R&D-effort level x^* *is*

$$x^*=\frac{1}{1+h}\left[\frac{(4-b^2)(2+b)\left[1+r\sigma^2\psi''(x^*)\right]\psi'(x^*)}{2(2-bh)}-(A-\overline{c})\right].$$

Proof. See appendix. ■

The positive sign of β^* indicates that an agent's higher own performance is compensated with a higher wage. In contrast, the principal sets γ^* to be negative, giving the agent a short position in her rival's performance. The principal anticipates the positive contribution of spillovers on her agent's output and penalizes her when the rival does better. Such evaluation schemes can be used effectively as means of filtering out spillovers from agent's compensation. Thus, agent i's payment is no longer sensitive to agent j's R&D. The "compensation ratio" $\left|\frac{\gamma^*}{\beta^*}\right|$ is also higher in compensation packages that are offered in industries with intensive spillovers.[21] The higher is h, the more valuable is the information contained in the rival's performance and thus the use of relative performance evaluations becomes more essential.

[20] Assumption $(A.3)$ is needed only if $h<\frac{b}{2}$. If $h>\frac{b}{2}$, the unit cost of doing R&D needs to be large enough that the post-innovation marginal cost is positive.

[21] Any compensation scheme that is a linear transformation of this cost-based contract will induce the same level of effort in equilibrium. However, the incentive parameters will differ. For instance, if compensation is contingent on outputs, agent i receives $w_i=\alpha_i+\beta_i q_i+\gamma_i q_j$ and the optimal compensation ratio is $\left|-\frac{2h-b}{2-bh}\right|$. The intensity of product market competition now matters for the optimal piece rates.

4.2 Moral hazard & spillovers

The existence of spillovers changes the nature of R&D strategic interactions as well as the effect of moral hazard on firms' equilibrium profits. To analyze firms' decisions, we first consider the underlying effects of R&D on firm's profits. The decomposition of R&D incentives implies $\frac{\partial \pi_i}{\partial x_i} = \frac{\partial \Pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \Pi_i}{\partial c_i}\frac{\partial c_i}{\partial x_i} - \left[1 + r\sigma^2\psi''(x_i)\right]\psi''(x_i)$. The direct effect of effort on profits comes through marginal cost reduction; i.e., the more a firm produces at a lower cost, the more it profits, $\frac{\partial \Pi_i}{\partial c_i}\frac{\partial c_i}{\partial x_i} = q_i$. This is the *scale effect*, which is positive. If $b > 0$, indirect effects on firms' revenues are also at work; i.e., $\frac{\partial \Pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} = \frac{\partial \Pi_i}{\partial q_j}\frac{1}{\Lambda}\left(\frac{\partial p_j}{\partial q_i} - 2h\frac{\partial p_i}{\partial q_i}\right) = \frac{b(b-2h)}{4-b^2}q_i$, where $\Lambda \equiv 4\frac{\partial p_i}{\partial q_i}\frac{\partial p_j}{\partial q_j} - \frac{\partial p_j}{\partial q_i}\frac{\partial p_i}{\partial q_j}$ is implied from the stability condition. First, there is the (positive) *strategic effect*: effort enhances the efficiency of production, allowing the R&D-taking firm to produce more and increase its market share vis-à-vis its rival. Second, there is the (negative) *spillover effect*: agent i's effort also reduces firm j's initial marginal cost due to spillovers, allowing the rival to be tougher in the product market. This effect is detrimental to the R&D-taking firm. The derivative $\frac{\partial \pi_i}{\partial x_i}$ shows the trade-off among all these effects against the increase in the cost of doing R&D.

Rivals' R&D responses depend on the relative intensity of the strategic and spillover effect. Efforts are strategic substitutes when the strategic effect dominates the spillover effect. If the opposite holds, they are strategic complements. Corollary 1 states that a positive profits-risk relationship can only exist if efforts are strategic substitutes. If efforts are strategic complements, risk always decreases profits.[22]

Corollary 1 (Profits-risk relationship under spillovers) *Under assumptions* $(A.3)-(A.4)$*, Cournot competitors' profits can increase with risk when efforts are strategic substitutes,* $h < \frac{b}{2}$*, and the cost of incentive provision is small enough; i.e.,* $\frac{\partial \pi^*}{\partial (r\sigma^2)} > 0$*, if and only if,*

$$\frac{2\left(2-bh\right)^2\left(1+h\right)}{\left(4-b^2\right)\left(2+b\right)\left[2\left(1-b\right)+h\left(4-b\right)\right]} > \left[1 + r\sigma^2\psi''(x^*)\right]\psi''(x^*) .$$

We argue that, if efforts are strategic substitutes and the cost of doing R&D is relatively small, the R&D activity is intensified when a firm is driven by business-stealing incentives due to the product market competition and by attempts to ensure that the cost-advantage will not be dissipated due to spillovers. In such a case, principals are eager to acquire more R&D and exert such a high level of R&D effort that it harms them. Under moral hazard, providing insurance against the risk diminishes such incentives, and cost-savings by conducting less R&D exactly due to risk-sharing may allow firms to realize higher profits in equilibrium.

To shed insight, we examine how the optimal R&D incentives change with product market competition and spillovers. We first conduct a Slutsky-like analysis to anticipate the effect of product substitutability on R&D; i.e., $\frac{d(\partial \pi_i/\partial x_i)}{db} = 0 \Leftrightarrow \frac{\partial(\partial \pi_i/\partial x_i)}{\partial b} + \frac{\partial^2 \pi_i}{\partial x_i^2}\frac{\partial x^*}{\partial b} = 0$. Assumption $(A.4)$ suffices to

[22] The proof of corollary 1 is similar to that of proposition 1 and provided in the supplementary material.

guarantee the concavity of the profit function in x_i, implying $\frac{\partial^2 \pi_i}{\partial x_i^2} < 0$. Therefore, as goods become closer substitutes, rivals' optimal R&D will increase in the regime where the marginal profitability of R&D is also increasing. However, the sign of $\frac{\partial(\partial \pi_i/\partial x_i)}{\partial b}$ is ambiguous. In particular, the optimal R&D effort increases with b if competition is stiff; i.e., $\frac{\partial x^*}{\partial b} > 0$, if and only if, $b > \frac{3+h-\left(9-2h-7h^2\right)^{\frac{1}{2}}}{2h}$. This can happen only if efforts are strategic substitutes.

In line with the literature, if efforts are strategic substitutes, the relationship between competition and cost-reducing R&D is U-shaped. The intuition is as follows. On the one hand, the strategic effect increases with b: as demand becomes more elastic, a firm with a cost advantage can more easily steal business from its rival. Thus, intensified competition increases the marginal benefit of cost reduction. On the other hand, the scale effect decreases: for higher b, the willingness to pay for firms' goods decreases, implying lower prices. In turn, a drop in output is required to compensate for the fall in profit. The (negative) spillover effect is also intensified. For higher b, a reduction in rival's marginal cost due to spillovers harms the R&D-taking firm by more, since a lower-cost rival can more easily gain in market share. Therefore, competition strengthens R&D incentives when it makes the strategic effect more important than the other two effects, so that firms are driven by business stealing incentives.

Spillovers can also induce firms to invest more in R&D. This can happen when goods are close substitutes, spillovers are small enough, and incentive provision is not too costly; i.e., $\frac{\partial x^*}{\partial h} > 0$ only if $h < \frac{2-b}{2b}$ and $\frac{2(2-bh)^2(A-\bar{c})}{[2-b(1+2h)](4-b^2)(2+b)} < \left[1 + r\sigma^2\psi''(x^*)\right]\psi'(x^*)$.[23] In particular, spillovers intensify all three effects, and thus R&D increases when the positive strategic and scale effects become more important relative to the negative spillover effect. In particular, if efforts are strategic substitutes, $h < \frac{b}{2}$, a lower cost firm cost is tougher in the product market. Thus, given the imperfect nature of spillovers, as h increases, firms provide higher-power R&D incentives in order to secure a cost advantage. This requires the cost of effort exertion to be relatively small. Otherwise, if this cost exceeds a threshold, principals seem to be unwilling to bear such high R&D costs and exert lower effort in respond to higher h.

It all boils down to the following: if efforts are strategic substitutes and the cost of incentivizing the researchers is small enough, Cournot rivals undertake more R&D when business-stealing incentives are strong due to the product market competition and rivals are eager to secure their cost advantage in the presence of imperfect spillovers. In turn, rivals invest so heavily in R&D that they dissipate their profits. Under moral hazard, such R&D incentives are weakened due to risk-sharing, resulting in considerable enough cost-savings to increase the equilibrium profits for the rivals.

In the regime where efforts are strategic complements, $h > \frac{b}{2}$, profits always decrease with risk. For instance, in the monopoly case, $b = 0$, where only the scale effect is at work, complementarities in R&D allow firms to exploit the spillovers only for efficiency enhancing (not strategic) reasons. There are mutual benefits from doing R&D. Thus, monopolists are always better-off under full information

[23] If $\psi(x_i) = \frac{k}{2}x_i^2$, $\frac{\partial x^*}{\partial h} = \frac{2(A-\bar{c})\left[2(2-bh)^2-\left(4-b^2\right)(2+b)bk\left(1+kr\sigma^2\right)\right]}{\left[(4-b^2)(2+b)k(1+kr\sigma^2)-2(2-bh)(1+h)\right]^2}$.

where they can perfectly monitor their agents. Less distorted decisions will enhance profits. For low cost of R&D, this result holds even for $b > 0$. However, if the R&D cost is high, risk decreases profits, but the intuition is different. Each firm now has strong incentives to free-ride on its rival's research. Free-riding decreases effort, and thus further reduction in R&D due to risk-sharing will result in even lower profits.

4.3 Discussion and extensions

By analyzing the equilibrium R&D incentives, one can also argue that as equilibrium effort increases with competition or spillovers, so does the agency cost. Under moral hazard, for higher $r\sigma^2$, the principals are less willing to exert effort as the contracts are 'rewritten' to accommodate intensified competition and spillovers. Effort responds less to an increase in b or h, and thus there is far more distortion in incentives. The use of a self-commitment device that mutually weakens the incentives for effort exertion becomes increasingly more effective. The benefits from delegating R&D under asymmetric information as a profit-enhancing decision are augmented.

This model can be extended in many ways and different directions. We can show that higher profits can be realized under moral hazard even if firms compete à la Bertrand. Firms' interactions in Bertrand and Cournot settings differ mainly in the following. For Bertrand competitors, the strategic effect is negative. In particular, cost-reducing R&D allows the R&D-taking firm to set a lower price. Competing for market share, the rival responds by also cutting its own price, implying lower profits for the innovator. Thus, product market competition gives rise only to detrimental effects on the innovator's profit. However, the cost-reducing incentives are also strong for Bertrand rivals exactly because firms behave so aggressively in the product market. Due to the anticipated price war and the imperfect nature of spillovers, rivals 'overinvest' in R&D, diminishing their profits. If firms operate under moral hazard, they innovate less and thus price cutting as a market response becomes less profitable. As a result, risk-sharing can increase profits for both Bertrand and Cournot rivals.

A positive profit-risk relationship obtains only if firms compete simultaneously in both markets. In a sequential-move (contracting-R&D) game, the leader can solve the follower's problem and induce the follower to undertake the R&D level that maximizes the leader's profit. Consequently, the leader wishes to act under full information so as to effectively control the decisions taken by the agent and the follower.

It is also interesting to consider R&D incentives when the output shocks are correlated. Suppose that the correlation coefficient is $\rho = \frac{\sigma_{ij}}{\sigma^2}$ where $|\rho| \leq 1$. The variance of the agent i's compensation becomes

$$Var(w_i) = \left[(\beta_i + h\gamma_i)^2 + (h\beta_i + \gamma_i)^2 + 2\rho (\beta_i + h\gamma_i)(h\beta_i + \gamma_i) \right] \sigma^2.$$

In this model with two forms of interdependence between the agents' R&D-outputs, the optimal pay-for-rival performance parameter is $\gamma^{**} = -\frac{h+\rho}{1+\rho h}\beta^{**}$ where $\beta^{**} > 0$.

The optimal contract filters out both spillovers and the common shock from the agent's reward. If $\rho > 0$, the principal sets γ^{**} negative since the agent acts in a favorable environment, which increases her performance. If $\rho < 0$, the sign of γ^{**} depends on the relative intensity of the two forms of interdependence of R&D-outputs. As long as spillovers matter more in agents' evaluations, γ^{**} is negative. However, if $h < |\rho|$, setting γ^{**} positive is a plausible way to encourage effort exertion. A principal incentivizes an agent to innovate by making her suffer less from a 'bad' outcome. Her reward now increases with a rival's performance. If $h = \rho$, then z_i becomes a sufficient statistic of x_i and agent i's compensation depends only on her own performance. All results about the effect of risk on rivals' optimal profits also hold in this setting.

5 Conclusion

We examine researchers' incentives to carry out cost-reducing R&D in a setting with product market competition and R&D spillovers. Because R&D-inputs are not observable and the R&D process is subject to uncertainty over the R&D-outputs, moral hazard concerns and risk aversion of the agent become central in this analysis. A linear principal-agent model is employed where each principal is likely to offer a relative performance evaluation scheme. The performance measures are both own-firm and rival-firm cost reductions, since each agent appropriates some part of its rival's research. We show that compensation schemes based on explicit performance comparisons filter out spillovers from the reward packages by penalizing an agent when the rival performs better.

We highlight the positive effect of moral hazard on profits when firms compete in the product market. If R&D-efforts are strategic substitutes, then in highly competitive industries, firms innovate more in order to gain market share. If the cost of doing R&D is small, firms exert such a high level of effort that it decreases their profits. In such an environment, the existence of moral hazard can be profit-enhancing. In particular, the under-provision of incentives due to risk-sharing generates cost-savings and can increase firms' equilibrium profits. Thus, firms may prefer an organization structure where business and research teams are separated and agents abhor risk so as to use it as a collusive device that makes both firms better-off. Such results require research efforts to be strategic substitutes but can hold in both Cournot and Bertrand settings.

This analysis might be used to interpret some empirical evidence on the R&D performance of modern corporations in markets where innovation is rushed and knowledge is diffused. Science-based firms differ in behavior, management strategies, and responses to market changes. This model also suggests avenues for future empirical research. The strategic nature of delegation and the use of incentive pay are themselves empirically testable. One could examine whether the organization structure of the firms and the form of the R&D contracts depend on the R&D and product market characteristics. There is a strategic motive stemming from the product market competition and R&D interactions. In addition, one could study firms' incentives to collaborate in the R&D market by forming R&D alliances, R&D joint ventures, or by adopting any other form of collusive-like behavior in order to affect the intensity of competition in the downstream markets. Such decisions will differ for monopolists or less differentiated-product oligopolists. In high-tech industries where spillovers occur, firms' incentives will also depend on whether the R&D choices are strategic complements or substitutes.

References

Aggarwal, R. K. & Samwick, A. A. (1999), 'Executive compensation, strategic competition and relative performance evaluation: Theory and evidence', *Journal of Finance* **54**, 1999–2043.

Aghion, P., Bloom, N., Blundell, R., Griffith, R. & Howitt, P. (2005), 'Competition and innovation: An inverted-U relationship', *Quarterly Journal of Economics* **120**(2), 701–728.

Aghion, P., Dewatripont, M. & Rey, P. (2004), 'Transferable control', *Journal of the European Economic Association* **2**(1), 115–138.

Aghion, P., Griffith, R. & Howitt, P. (2006), 'Vertical integration and competition', *American Economic Review* **96**(2), 97–102.

Alonso, R., Dessein, W. & Matouschek, N. (2008), 'When does coordination require centralization?', *American Economic Review* **98**(1), 145–179.

Amir, M., Amir, R. & Jin, J. Y. (2000), 'Sequencing R&D decisions in a two-period duopoly with spillovers', *Economic Theory* **15**(2), 297–317.

Baggs, J. & De Bettignies, J.-E. (2007), 'Product market competition and agency cost', *Journal of Industrial Economics* **55**(2), 289–323.

Bondt, R. D. (1997), 'Spillovers and innovative activity', *International Journal of Industrial Organization* **15**, 1–28.

Chiu, W. H., Eeckhoudt, L. & Rey, B. (2012), 'On relative and partial risk attitudes: theory and implications', *Economic Theory* **50**(1), 151–167.

D'Aspremont, C. & Jacquemin, A. (1990), 'Cooperative and noncooperative R&D in duopoly with spillovers', *American Economic Review* **80**(3), 641–642.

Fershtman, C. & Judd, K. L. (1987), 'Equilibrium incentives in oligopoly', *American Economic Review* **77**(5), 927–940.

Griffith, R. (2001), 'Product market competition, efficiency and agency cost: an empirical analysis', *Manuscript, Institute for Fiscal Studies* .

Hart, O. (1983), 'The market as an incentive mechanism', *Bell Journal of Economics* **14**(2), 366–382.

Hart, O. & Holmström, B. (2010), 'A theory of firm scope', *Quarterly Journal of Economics* **125**(2), 483–513.

Hermalin, B. E. (1992), 'The effects of competition on executive behavior', *RAND Journal of Economics* **23**(3), 305–327.

Holmström, B. (1979), 'Moral hazard and observability', *Bell Journal of Economics* **10**, 74–91.

Holmström, B. & Milgrom, P. (1987), 'Aggregation and linearity in the provision of intertemporal incentives', *Econometrica* **55**(2), 303–328.

Holmström, B. & Tirole, J. (1989), 'The theory of the firm', *in R. Schmalensee and R. D. Willig, Eds.: Handbook of industrial organization, Vol. 1, (North-Holland: Amsterdam)* pp. 61–133.

Itoh, H. (1991), 'Incentives to help in multi-agent situations', *Econometrica* **59**, 611–636.

Kamien, M., Muller, E. & Zang, I. (1992), 'Research joint ventures and R&D cartels', *American Economic Review* **85**(5), 1293–1306.

Lacetera, N. & Zirulia, L. (2012), 'Individual preferences, organization, and competition in a model of R&D incentive provision', *Journal of Economic Behavior & Organization* **84**(2), 550–570.

Lai, E. L.-C., Riezman, R. & Wang, P. (2009), 'Outsourcing of innovation', *Economic Theory* **38**(3), 485–515.

Levin, R. C. (1988), 'Appropriability, R&D spending, and technological performance', *American Economic Review* **78**(2), 424–428.

Milliou, C. & Petrakis, E. (2011), 'Timing of technology adoption and product market competition', *International Journal of Industrial Organization* **29**, 513–523.

Mirrlees, J. & Raimondo, R. C. (2013), 'Strategies in the principal-agent model', *Economic Theory* **53**(3), 605–656.

Nickell, S. (1996), 'Competition and corporate performance', *Journal of Political Economy* **104**, 724–746.

Piccolo, S., D'Amato, M. & Martina, M. (2008), 'Product market competition and organizational slack under profit-target contracts', *International Journal of Industrial Organization* **26**, 1389–1406.

Prendergast, C. (1999), 'The provision of incentives in firms', *Journal of Economic Literature* **37**, 7–63.

Qiu, L. (1997), 'On the dynamic efficiency of Bertrand and Cournot equilibria', *Journal of Economic Theory* **75**(1), 213–229.

Raith, M. (2003), 'Competition, risk and managerial incentives', *American Economic Review* **93**, 1425–1436.

Rockett, K. (2012), 'Perspectives on the knowledge-based society: An introduction to the special issue', *Economics: The Open-Access, Open-Assessment E-Journal* **6**(2012-35), 1–22.

Schmidt, K. M. (1997), 'Managerial incentives and product market competition', *Review of Economic Studies* **64**(2), 191–213.

Serfes, K. (2005), 'Risk sharing vs. incentives: Contract design under two-sided heterogeneity', *Economics Letters* **88**(3), 343–349.

Serfes, K. (2008), 'Endogenous matching in a market with heterogeneous principals and agents', *International Journal of Game Theory* **36**, 587–619.

Singh, N. & Vives, X. (1984), 'Price and quantity competition in a differentiated duopoly', *RAND Journal of Economics* **15**(4), 546–554.

Sklivas, S. D. (1987), 'The strategic choice of managerial incentives', *RAND Journal of Economics* **18**(3), 452–458.

Vickers, J. (1995), 'Concepts of competition', *Oxford Economic Papers* **47**, 1–23.

Vives, X. (2008), 'Innovation and competitive pressure', *Journal of Industrial Economics* **56**(3), 419–469.

A APPENDIX

A.1 Proof of lemma 1

By equations (1) and (2), agent i's expected utility is[24]

$$E\left\{U_i\left(w_i, x_i\right) \mid \varepsilon_i \in \Theta\right\} = -e^{-r[\alpha_i+\beta_i x_i-\psi(x_i)]} E\left\{e^{-r\beta_i\varepsilon_i} \mid \varepsilon_i \in \Theta\right\}. \tag{13}$$

The conditional density of ε_i is

$$f\left(\varepsilon_i \mid \Theta\right) = \frac{\frac{1}{\sigma}\phi\left(\frac{\varepsilon_i}{\sigma}\right)}{\Phi\left(\frac{\theta}{\sigma}\right) - \Phi\left(\frac{-\theta}{\sigma}\right)}, \; -\theta \leq \varepsilon_i \leq \theta \text{ where } \phi\left(\frac{\varepsilon_i}{\sigma}\right) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_i}{\sigma}\right)^2}. \tag{14}$$

[24] It is also assumed that a positive constant term is added to the agent's utility which moves this function upwards so that $E\left\{U_i\left(w_i, x_i\right) \mid \varepsilon_i \in \Theta\right\} \geq 0$.

By equation (13) and (14), and letting $\widehat{r}=-r$, we have

$$\int_{-\theta}^{\theta} e^{\widehat{r}\beta_i\varepsilon_i} f\left(\varepsilon_i\right) d\varepsilon_i=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta} e^{\widehat{r}\beta_i\varepsilon_i} e^{-\frac{1}{2}\left(\frac{\varepsilon_i}{\sigma}\right)^2} d\varepsilon_i=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta} e^{-\frac{\left(\varepsilon_i^2-2\sigma^2\widehat{r}\beta_i\varepsilon_i\right)}{2\sigma^2}} d\varepsilon_i=$$

$$=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta} e^{-\frac{\left[\varepsilon_i^2-2\varepsilon_i\left(\sigma^2\widehat{r}\beta_i\right)+\left(\sigma^2\widehat{r}\beta_i\right)^2-\left(\sigma^2\widehat{r}\beta_i\right)^2\right]}{2\sigma^2}} d\varepsilon_i=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta} e^{-\frac{\left(\varepsilon_i-\sigma^2\widehat{r}\beta_i\right)^2}{2\sigma^2}} e^{\frac{\left(\sigma^2\widehat{r}\beta_i\right)^2}{2\sigma^2}} d\varepsilon_i=$$

$$=e^{\frac{\widehat{r}^2\beta_i^2\sigma^2}{2}}\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta} e^{-\frac{1}{2}\left(\frac{\varepsilon_i-\sigma^2\widehat{r}\beta_i}{\sigma}\right)^2} d\varepsilon_i=e^{\frac{\widehat{r}^2\beta_i^2\sigma^2}{2}}\int_{-\theta}^{\theta}\frac{1}{\sigma}\phi\left(\frac{\varepsilon_i-\sigma^2\widehat{r}\beta_i}{\sigma}\right) d\varepsilon_i=$$

$$=e^{\frac{\widehat{r}^2\beta_i^2\sigma^2}{2}}\left[\Phi\left(\frac{\theta-\sigma^2\widehat{r}\beta_i}{\sigma}\right)-\Phi\left(\frac{-\theta-\sigma^2\widehat{r}\beta_i}{\sigma}\right)\right].$$

Thus, $E\left\{e^{\widehat{r}\beta_i\varepsilon_i}\mid\varepsilon_i\in\Theta\right\}=\dfrac{\int_{-\theta}^{\theta} e^{\widehat{r}\beta_i\varepsilon_i} f\left(\varepsilon_i\right) d\varepsilon_i}{\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)}=e^{\frac{\widehat{r}^2\beta_i^2\sigma^2}{2}}\dfrac{\Phi\left(\frac{\theta-\sigma^2\widehat{r}\beta_i}{\sigma}\right)-\Phi\left(\frac{-\theta-\sigma^2\widehat{r}\beta_i}{\sigma}\right)}{\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)}=e^{\frac{\widehat{r}^2\beta_i^2\sigma^2}{2}}\Omega_i,$

where $\Omega_i=\frac{\Phi\left(\frac{\theta-\sigma^2\widehat{r}\beta_i}{\sigma}\right)-\Phi\left(\frac{-\theta-\sigma^2\widehat{r}\beta_i}{\sigma}\right)}{\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)}$. By (13), we get

$$E\left\{U_i\left(w_i,x_i\right)\mid\varepsilon_i\in\Theta\right\}=-\Omega_i e^{-r\left[\alpha_i+\beta_i x_i-\psi(x_i)\right]} e^{\frac{r^2\beta_i^2\sigma^2}{2}}=-\Omega_i e^{-r\left[\alpha_i+\beta_i x_i-\frac{r}{2}\beta_i^2\sigma^2-\psi(x_i)\right]}.$$

Given that Ω_i is positive and independent of x_i, agent i's optimization problem is equivalent to choosing

$$x_i\in\arg\max\widetilde{U}_i\left(x_i\right)\equiv\alpha_i+\beta_i x_i-\frac{r}{2}\beta_i^2\sigma^2-\psi(x_i),$$

where $\widetilde{U}_i\left(x_i\right)$ is the certainty equivalent of agent i's utility. Thus, given CARA preferences and linear contracts, agent i's problem has a closed form solution even if ε_i follows a *truncated* normal distribution, which is symmetric around the mean.

A.2 Proof of lemma 2

The existence of an equilibrium in R&D requires showing that each firm's R&D reaction function - denoted by $r_i\left(x_j\right)$ for any i and j - is a (monotone) contraction, and then applying the Contraction Mapping Theorem. Assumption $(A.2)$ suffices to guarantee that π_i is strictly concave in x_i, and thus $r_i\left(x_j\right)$ is single-valued and continuous. Given that the action set X is compact, an equilibrium exists. The interiority of this equilibrium requires π_i to be strictly increasing when $x_i=0$ for all $x_j\in X$; i.e., $\frac{\partial\pi_i(0,x_j)}{\partial x_i}=\frac{4}{(4-b^2)(2+b)}\left[A-\overline{c}-\frac{bx_j}{2-b}\right]-\left[1+r\sigma^2\psi''\left(0\right)\right]\psi'\left(0\right)>0$. Given that $\psi'(0)=0$ and $\frac{\partial\pi_i(0,x_j)}{\partial x_i}$ decreases with x_j, if the latter inequality holds for $x_j=\overline{c}+\theta$, it will also hold for all $x_j\in X$, which is guaranteed by assumption $(A.1)$. Firm i's reaction function, $r_i\left(x_j\right)$, must also be strictly decreasing. Let

$$H\equiv\frac{\partial^2\pi_i\left(r_i\left(x_j\right),x_j\right)}{\partial x_i^2}=\frac{8}{\left(4-b^2\right)^2}-\left[1+r\sigma^2\psi''\left(x_i\right)\right]\psi''\left(x_i\right), \tag{15}$$

which is negative by assumption $(A.2)$. We have $\frac{d(\partial\pi_i/\partial x_i)}{dx_j} = 0 \Leftrightarrow \frac{\partial^2\pi_i(r_i(x_j),x_j)}{\partial x_i \partial x_j} + \frac{\partial^2\pi_i(r_i(x_j),x_j)}{\partial x_i^2} r_i'(x_j) = 0$ implying

$$r_i'(x_j) = -\frac{\frac{\partial^2\pi_i(r_i(x_j),x_j)}{\partial x_i \partial x_j}}{\frac{\partial^2\pi_i(r_i(x_j),x_j)}{\partial x_i^2}} = \frac{4b}{(4-b^2)^2 H}, \tag{16}$$

which is also negative for any $b > 0$ since $H < 0$.

The uniqueness of this equilibrium requires $-1 < r_i'(x_j) < 1$ for all $x_j \in X$. Given that $r_i'(x_j) < 0$, it suffices to show that $-1 < r_i'(x_j)$ which is also implied by assumption $(A.2)$. Therefore, given that the game in the product market has a unique equilibrium, the subgame perfect equilibrium of the overall game is also unique.

A.3 Proof of proposition 1

We first need to examine how the optimal effort x^* changes with $r\sigma^2$. We have

$$\frac{d(\partial\pi_i/\partial x_i)}{d(r\sigma^2)} = 0 \Leftrightarrow \frac{\partial(\partial\pi_i/\partial x_i)}{\partial(r\sigma^2)} + \frac{\partial^2\pi_i}{\partial x_i^2}\frac{\partial x^*}{\partial(r\sigma^2)} = 0. \tag{17}$$

To find the effect of $r\sigma^2$ on the marginal profitability of R&D, we take the derivative $\frac{\partial\pi_i}{\partial x_i}$ and substitute x_j with the optimal value x^* getting $\frac{4}{(4-b^2)(2+b)}\left[A - \bar{c} + \frac{2x_i - bx^*}{2-b}\right] - \left[1 + r\sigma^2\psi''(x_i)\right]\psi'(x_i)$. Then, we differentiate with respect to $r\sigma^2$, taking x_i as constant, and obtain

$$\frac{\partial(\partial\pi_i/\partial x_i)}{\partial(r\sigma^2)} = -\frac{4b}{(4-b^2)^2}\frac{\partial x^*}{\partial(r\sigma^2)} - \psi''(x^*)\psi'(x^*). \tag{18}$$

By (15) and (18), equation (17) gives

$$\frac{\partial x^*}{\partial(r\sigma^2)} = \frac{\psi''(x^*)\psi'(x^*)}{H - \frac{4b}{(4-b^2)^2}}, \tag{19}$$

which is negative since $H < 0$ and $\psi(.)$ is convex; i.e., $\frac{\partial x^*}{\partial(r\sigma^2)} < 0$ for all $x_i \in X$. By (7), π^* increases with $r\sigma^2$ if and only if

$$\frac{2}{(2+b)^2}(A - \bar{c} + x^*)\frac{\partial x^*}{\partial(r\sigma^2)} > \left[\frac{1}{2}\psi'(x^*) + r\sigma^2\frac{\partial\psi'(x^*)}{\partial(r\sigma^2)} + \frac{\partial x^*}{\partial(r\sigma^2)}\right]\psi'(x^*). \tag{20}$$

Since $\frac{\partial\psi'(x^*)}{\partial(r\sigma^2)} = \psi''(x^*)\frac{\partial x^*}{\partial(r\sigma^2)}$ and equation (6) gives $\frac{2}{(2+b)^2}(A - \bar{c} + x^*) = \frac{2-b}{2}\left[1 + r\sigma^2\psi''(x^*)\right]\psi'(x^*)$, inequality (20) becomes

$$-\frac{b}{2}\left[1 + r\sigma^2\psi''(x^*)\right]\frac{\partial x^*}{\partial(r\sigma^2)} > \frac{1}{2}\psi'(x^*). \tag{21}$$

We substitute $\frac{\partial x^*}{\partial(r\sigma^2)}$ with (19) in (21) and given (15), we obtain $\frac{4}{(4-b^2)(2+b)(1-b)} > \left[1 + r\sigma^2\psi''(x^*)\right]\psi''(x^*)$.

A.4 Proof of proposition 2

The interiority of the equilibrium requires, if efforts are strategic substitutes, $h < \frac{b}{2}$, π_i to be strictly increasing when $x_i = 0$; i.e., $\frac{\partial\pi_i(0,x_j)}{\partial x_i} = \frac{2(2-bh)}{(4-b^2)(2+b)}\left[A - \bar{c} + \frac{(2h-b)x_j}{2-b}\right] > 0$. If this inequality holds for $x_j = \bar{c} + \theta$, it will also hold for all $x_j \in [0, \bar{c} - \varepsilon_i]$ since $h < \frac{b}{2}$. This is guaranteed by assumption $(A.3)$. If $h > \frac{b}{2}$, $\frac{\partial \pi_i(0,x_j)}{\partial x_i}$ is always positive. The uniqueness of the equilibrium requires $-1 < r_i'(x_j) < 1$. Let

$$M \equiv \frac{\partial^2 \pi_i (r_i(x_j), x_j)}{\partial x_i^2} = \frac{2(2-bh)^2}{(4-b^2)^2} - \left[1 + r\sigma^2 \psi''(x_i)\right] \psi''(x_i), \tag{22}$$

which is negative by assumption $(A.4)$. The slope of firm i's reaction function, $r_i(x_j)$, similarly to (16), is $r_i'(x_j) = \frac{2(2-bh)(2h-b)}{(4-b^2)^2 M}$. If $h < \frac{b}{2}$, given that $M < 0$ and thus $r_i'(x_j) < 0$, it suffices to show that $r_i'(x_j) > -1$. This requires $\frac{2(2-bh)[2-bh-b+2h]}{(4-b^2)^2} < [1 + r\sigma^2\psi''(x_i)]\psi''(x_i)$ which is implied by assumption $(A.4)$. If $h > \frac{b}{2}$, given that $r_i'(x_j) > 0$, it suffices to show that $r_i'(x_j) < 1$. This requires $\frac{2(2-bh)[2-bh-2h+b]}{(4-b^2)^2} < [1 + r\sigma^2\psi''(x_i)]\psi''(x_i)$ which is also implied by assumption $(A.4)$. Thus, a unique interior equilibrium exists.

Given (10) and (11), to find the optimal R&D incentives and effort, we consider the Lagrange function of principal i's problem:

$$\begin{aligned} L_i &= E\left\{(q_i^*)^2 - \alpha_i - \beta_i z_i - \gamma_i z_j \mid \varepsilon_i, \varepsilon_j \in \Theta\right\} + \lambda_i\left[\beta_i + h\gamma_i - \psi'(x_i)\right] \\ &\quad + \mu_i\left[E\left\{\alpha_i + \beta_i z_i + \gamma_i z_j \mid \varepsilon_i, \varepsilon_j \in \Theta\right\} - \psi(x_i) - \frac{r}{2}\left[(\beta_i + h\gamma_i)^2 + (h\beta_i + \gamma_i)^2\right]\sigma^2\right], \end{aligned} \tag{23}$$

where z_i is given by (8) and $E\{q_i^* \mid \varepsilon_i, \varepsilon_j \in \Theta\}$ by (12). Omitting details, the Kuhn-Tucker condition with respect to α_i gives $-1 + \mu_i = 0 \Leftrightarrow \mu_i = 1$, implying that the (IR_i) constraint binds at the optimum. Given also that the equilibrium is interior, the profit-maximizing conditions are

$$\frac{\partial L_i}{\partial \lambda_i} = \beta_i + h\gamma_i - \psi'(x_i) = 0, \ \forall i \tag{24}$$

$$\frac{\partial L_i}{\partial \beta_i} = -r\left[\beta_i + h\gamma_i + h(h\beta_i + \gamma_i)\right]\sigma^2 + \lambda_i = 0, \ \forall i \tag{25}$$

$$\frac{\partial L_i}{\partial \gamma_i} = -r\left[h(\beta_i + h\gamma_i) + h\beta_i + \gamma_i\right]\sigma^2 + h\lambda_i = 0, \ \forall i \tag{26}$$

$$\frac{\partial L_i}{\partial x_i} = \frac{2(2-bh)}{(4-b^2)(2+b)}\left[(A - \bar{c}) + \frac{(2-bh)x_i - (b-2h)x_j}{2-b}\right] - \lambda_i\psi''(x_i) - \psi'(x_i) = 0, \ \forall i \tag{27}$$

By (25) and (26), we have

$$\frac{\beta_i + h\gamma_i + h(h\beta_i + \gamma_i)}{h(\beta_i + h\gamma_i) + h\beta_i + \gamma_i} = \frac{1}{h}. \tag{28}$$

Solving with respect to γ_i, we obtain $\gamma_i^* = -h\beta_i^*$. Equation (24) gives $(1-h^2)\beta_i^* = \psi'(x_i^*)$. Since $\lambda_i = r\sigma^2\psi'(x_i)$ by equation (25), the optimal effort level x^* solves equation (27) which implies the form in proposition 2.

A.5 Effect of competition on optimal effort

The effects of b on the marginal profitability of R&D are given by

$$\frac{\partial\left(\partial\pi_i/\partial x_i\right)}{\partial b}=\frac{2\left[4b-h\left(4+b^2\right)\right]}{\left(4-b^2\right)^2\left(2+b\right)}\left[A-\overline{c}+\left(1+h\right)x^*\right]+\frac{2\left(2-bh\right)}{4-b^2}\left[\frac{2h-b}{4-b^2}\frac{\partial x^*}{\partial b}-\frac{A-\overline{c}}{\left(2+b\right)^2}-\frac{1+h}{\left(2+b\right)^2}x^*\right].$$

Given also (22), the decomposition $\frac{\partial(\partial\pi_i/\partial x_i)}{\partial b}+\frac{\partial^2\pi_i}{\partial x_i^2}\frac{\partial x^*}{\partial b}=0$ implies

$$\frac{\partial x^*}{\partial b}=\left(\frac{4}{4-b^2}\right)\frac{\left[3b-2-\left(2-b+b^2\right)h\right]\left[A-\overline{c}+\left(1+h\right)x^*\right]}{\left(4-b^2\right)\left(2+b\right)\left[1+r\sigma^2\psi''\left(x^*\right)\right]\psi''\left(x^*\right)-2\left(2-bh\right)\left(1+h\right)}.$$

The denominator is positive by assumption $(A.4)$. Thus, the derivative $\frac{\partial x^*}{\partial b}$ is positive if and only if $3b-2-\left(2-b+b^2\right)h>0\Leftrightarrow b>\frac{3+h-\left(9-2h-7h^2\right)^{1/2}}{2h}$. By L'Hôpital's rule, it is $\lim_{h\to 0^+}\left\{\frac{3+h-\left(9-2h-7h^2\right)^{1/2}}{2h}\right\}=\lim_{h\to 0^+}\left\{\frac{1}{2}\left(1+\frac{1+7h}{\left[(1-h)(9+7h)\right]^{1/2}}\right)\right\}=\frac{2}{3}$.

A.6 Effect of spillovers on optimal effort

Given (22) and that

$$\frac{\partial\left(\partial\pi_i/\partial x_i\right)}{\partial h}=-\frac{2b}{\left(4-b^2\right)\left(2+b\right)}\left[A-\overline{c}+\left(1+h\right)x^*\right]+\frac{2\left(2-bh\right)}{4-b^2}\left[\frac{2h-b}{4-b^2}\frac{\partial x^*}{\partial h}+\frac{1}{2+b}x^*\right],$$

the decomposition of the effect of spillovers on effort implies

$$\frac{\partial x^*}{\partial h}=2\frac{\left[2-b\left(1+2h\right)\right]x^*-b\left(A-\overline{c}\right)}{\left(4-b^2\right)\left(2+b\right)\left[1+r\sigma^2\psi''\left(x^*\right)\right]\psi''\left(x^*\right)-2\left(2-bh\right)\left(1+h\right)}\tag{29}$$

where x^* satisfies proposition 2. The denominator in (29) is positive by assumption $(A.4)$. Thus, spillovers increase the optimal effort, $\frac{\partial x^*}{\partial h}>0$, only if $h<\frac{2-b}{2b}$ and $\frac{b(A-\overline{c})}{2-b(1+2h)}<x^*$. By proposition 2, the latter inequality becomes $\frac{2(2-bh)^2(A-\overline{c})}{[2-b(1+2h)](4-b^2)(2+b)}<\left[1+r\sigma^2\psi''\left(x^*\right)\right]\psi'\left(x^*\right)$.

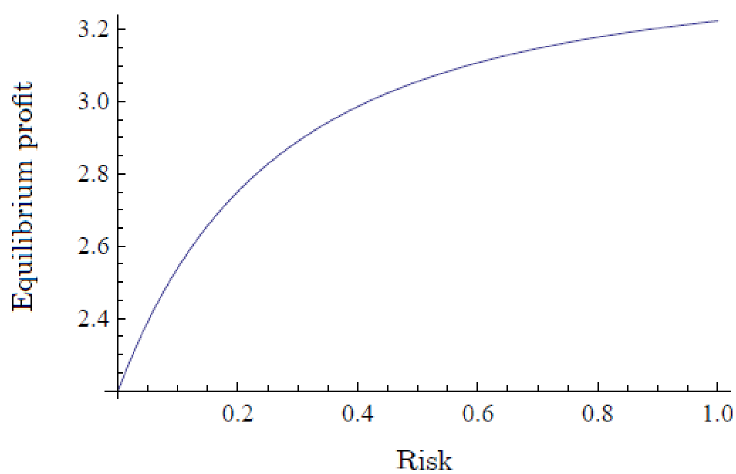

Figure 2 shows the profits-risk relationship when $\psi(x_i)=\dfrac{k}{2}x_i^2$, $A=10$, $\overline{c}=4.5$, $b=1$ and $k=1.2$.