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

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Abstract

This paper studies incentive contracting in a market with R&D spillovers and Cournot competition. It examines the effect of spillovers on R&D incentives and addresses the question of whether the standard result that profits are higher under full information applies in this setting. This paper argues that, in highly competitive industries, rivals enter into a rat race and are driven by business stealing incentives. In turn, they exert a fairly high level of effort burning up their profits. Under-provision of incentives due to risk-sharing diminishes firms strategic and technological interactions. Thus, cost-savings by investing less in R&D due to moral hazard may generate gains for the rivals. Separation between the business and research units under asymmetric information can be used as a collusive device that makes firms better-off.

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

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1 Introduction

In knowledge-based industries, firms' interactions and technical advance favor an organizational structure that involves separation between the business units and the research teams. The owners of the firms appoint highly-skilled researchers or autonomous units to undertake efficiency-enhancing R&D projects. Thus, there is a division between ownership and control over the R&D-outputs. Managing scientific workers though and designing incentive schemes turn into a challenge. Innovation is usually subject to uncertainty about the R&D outcomes and R&D spillovers. In such markets, the incentive issue deserves special attention since knowledge is transmitted among product market competitors.[1] The R&D models based on D'Aspremont and Jacquemin (1988) and Kamien, Muller, and Zang (1992) evaluate the R&D performance of entrepreneurial firms competing in the product market while Holmstrom (1989) examines the innovation issue and incentive contracting when no spillovers occur. Thus, the R&D literature remains somewhat narrow in its focus on the effect of spillovers and risk on the principal-agent relationship and competitors' performance.

This paper extends this literature by analyzing how the contractual choices and R&D incentives depend on the intensity of knowledge externality and competition. It does so to examine whether the standard result that profits are higher under full information applies in this setting. It argues that the existence of the moral hazard problem may not necessarily contribute to decreasing profits. In particular, this paper claims that spillovers amplify efforts so that firms that are motivated by business stealing incentives may enter into a rat race burning up profits by doing so. Thus, cost-savings by exerting lower efforts due to risk-sharing in a world with information asymmetries may yield higher profits for competitors. Subject to competition in the product market, firms may be better-off by having less information on their agents' actions. This result indicates that firms do have incentives to collude. Delegating the R&D decisions could be used as a collusive device that generates benefits for the rivals. However, firms can never acquire these benefits, if the 'cost of information asymmetries' in terms of risk-premium is high.

The analysis is performed in a set-up where two risk-neutral firms conduct cost-reducing R&D and then, interact in a differentiated-product market. The owner of each firm (the principal) performs in the contracting and product market stage while the R&D decisions

[1] IBM, Apple, Intel and Motorola, for instance, employ closely related technologies for computer hardware; their patents reveal this fact. Their location in the product market though differs. As PC desktop producers, IBM and Apple compete in the product market while their competition with Intel and Motorola is less intensified. Last two firms mainly produce semi-conductor chips and compete with each other for market share. Differently, product market rivals may use quite different technologies. For instance, Phillips and Segway compete in the hard disk market. Segway employs magnetic technologies while Phillips products are based on holographic technology. Thus, innovation undertaken by Phillips may create a competitive advantage against Segway while spillovers are unlikely to improve Segway's technology. See Bloom, Schankerman, and Reenen (2007) for recent empirical research on the effect of spillovers and competition on R&D.

are delegated to a risk-averse researcher (the agent). Agents' efforts are unobservable and unverifiable to each other. In this framework, 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 (Holmstrom and Milgrom (1987)) and are contingent on marginal cost reduction. Cost-based schemes are consistent with real-world contracting practices. Scientists' rewards are typically based on measures such as operation costs.[2] In Germany, for instance, inventors' compensation schemes based on the expected value of the R&D-outputs have been established by law.[3]

This paper argues that, due to technological interactions between agents, each principal is likely to offer a *relative performance evaluation scheme*. The cost reduction realized by a firm is equal to the agent's effort as well as an 'unpaid appropriation' of some part of its rival's research output. The explicit comparisons of agents' R&D performance are the consequence of the efficient use of information conveyed by individual outputs about each agent's effort. The existing literature uses such contracts when the market shocks that hit agents' production are correlated (Holmstrom (1979), Holmstrom and Milgrom (1987), (1991)).[4,5] In this setting, individual outputs are correlated due to spillovers. Such contracts introduce 'competition' between agents and promote efficiency in incentive contracting. A negative weight is placed on rival-firm performance and thus, each agent is penalized if the rival does better. Such contracts can effectively be used as means of filtering out spillovers from agents' reward.

By changing the information structure of the model, this paper finds that firms' profits realized in an asymmetric information world may be greater than those experienced under full information. Thus, this paper argues that a positive profits-risk relationship may be realized and provides a simple reason why this might be the case. To intuitively interpret this result, it examines the effects of competition, spillovers and information on R&D incentives. The analysis performs a decomposition of R&D incentives and is focused on the underlying effects that arise due to competition in the product market. These are the strategic effect due to business stealing and the spillover effect due to knowledge transmission. The last effect is detrimental to the R&D-taking firm since spillovers enhance rival's efficiency making him tougher in the product market. In the regime where the strategic effect dominates the

[2] For more details, see, for instance, PatVal survey that examines the compensation and performance of the inventors of 9.017 European patents.

[3] It is the German Employees' Inventions Act passed in 1957.

[4] See Prendergast (1999) for a review in incentive contracts. For theoretical and empirical works on incentive contracting see also Baker (1992), Milgrom and Roberts (1990), Gibbons and Murphy (1992) among others. Shleifer and Vishny (1997) provide a survey on corporate governance.

[5] In a sense, spillovers induce the principals to consider the problem of designing the incentive scheme as a common agency problem, since (indirectly) each principal attempts to motivate the agents to take actions for his own interest; see Bernheim and Whinston (1986), Dixit, Grossman, and Helpman (1997).

spillover effect, effort are strategic substitutes. In this regime, the lower-cost firm can easier take away businesses from its rival. Thus, each principal wants to realize a slightly lower marginal cost from its competitor. Given that imperfect spillovers occur and both principals have the same incentives, firms enter into a rat race whose intensity increases with spillovers.[6]

This paper argues that, in highly competitive industries, firms, that compete for market share and are engaged into a prisoners-dilemma type of race, over-invest in R&D burning up profits by doing so.[7] Under moral hazard, the incentives-insurance trade-off mitigates rivals' incentives to conduct R&D. Under-provision of R&D due to risk-sharing diminishes the intensity of the race and rivals' strategic interactions. Cost-savings due to lower effort exertion may allow firms to realize higher profits. Firms may become better-off as risk increases. Thus, this paper is delving into firms' incentives to collude in R&D and even utilize the intra-firm conflicts of interests. R&D rivals do have incentives to separate the business and research units and thus, divide the ownership and control over the R&D-outputs as a self-commitment device that will generate profits for the rivals. Firms may even desire to appoint high risk-averse agents. However, we find that principals enjoy such benefits only if the cost of moral hazard in terms of the insurance an agent requires is relatively small. Otherwise, rivals' full information profits are higher. Thus, this result gives us an insight on the organizational structure firms may desire to adopt, given their location in the product and technology space.

The gains from risk-sharing are also studied in settings where firms' interactions differ. If firms compete à la Cournot and efforts are strategic complements, firms benefit more by undertaking research under full information since they enjoy gains mainly from efficiency enhancement. In contrast, Bertrand rivals will profit by exerting lower effort due to risk-sharing. It is so since price competition induces aggressive responses which are weakened under asymmetric information.

The presence of the moral hazard problem is no longer profitable when the R&D decisions are taken more centrally. This is the case in coordination games where firms reach collusive wage agreements while they compete in the product market. Government's profits are

[6]The result that spillovers stimulate R&D is in contrast to the main stream of theoretical studies based on D'Aspremont and Jacquemin (1988) and Kamien et al (1992). These works argue that efforts decrease with spillovers due to the "free-rider" problem. If spillovers are substantial, firms invest less in R&D since they can easily appropriate the results from rivals' research. Theoretical works that deal with the increase in R&D due to spillovers consider quite different settings from this paper such as vertical relations, learning and absorptive capacity (Cohen and Levinthal (1989)), product innovation or network externalities (Choi (1993)), complementarity in open source software (Henkel (2008)).

[7]Other works study the effect of competition on incentives using as measure of the degree of competition the number of competitors (Schmidt (1997)), the market size and the cost of entry (Raith (2003)). From an other perspective, Aggarwal and Samwick (1999) use relative-performance evaluation schemes to examine how the agents' incentives can influence the intensity of the strategic interaction between firms. See Nickell (1996), Schmidt (1997), Vickers (1995) for a review about the effect of competition on agent and firm incentives. See also Vives (2005) for a review about the effect of competition on innovation.

also higher under full information. However, social R&D incentives lead to over-investment inducing firms eventually to engage in the rat race.

The rest of the paper is organized as follows. Section 2 presents the set-up and section 3 solves the rivalry game backwards. The feasible set of the problem is determined and the optimal contractual parameters are calculated. In section 4, we comparatively evaluate firms' profits realized in a full and asymmetric information world. To intuitively interpret the results, the analysis is focused on the effects of competition, spillovers and information on R&D incentives. The use of delegation of R&D decisions under asymmetric information as a collusive devise is extensively discussed. In section 5, we examine our results under different modes of competition in the R&D and product market. Coordination games are solved in section 6. Section 7 contains the concluding remarks.

2 The set-up

The market is composed of two risk-neutral profit-seeking firms i and j where $i, j = 1, 2$ and $i \neq j$. Each firm is run by a principal whose task is to invest in process-improving R&D and then, make the output choices. To conduct R&D, each principal appoints a risk-averse researcher whose effort is unobservable and non-contractible. The principal's problem turns out to be the design of a contract based on contractible measures and compatible with agent's incentives to innovate. The players interact and play the two-period game described in Figure 1.

Period 1: Innovation → → Period 2: Production

Contracting stage:

Each principal i makes a take-it-or-leave-it offer to agent i; 'relative' performance evaluation schemes are provided.

R&D stage:

- If agent i accepts the offer, she chooses the effort level (x_i). Events beyond the agents' control occur, R&D-outputs are realized and the contracts are executed.
- If agent i rejects the offer, no innovation occurs.

Firms observe the R&D-outputs and compete à la Cournot in the product market. Profits are realized.

Figure 1. The timing of the game

Consumers' preferences. The market is populated by a continuum of consumers of the same type with mass equal to 1. Following Singh and Vives (1984), the representative consumer's preferences are described by the standard quadratic utility function $V(q_i, q_j) = A(q_i + q_j) - \left[\frac{1}{2}\left(q_i^2 + q_j^2\right) + dq_iq_j\right]$ where q_i is i's output, A is the market demand, $A > 0$, and d captures the degree of product substitutability, $d \in [0, 1]$.[8] When $d = 0$, firms have independent demands and behave as monopolists while, at the other extreme, $d = 1$, they

[8] Each consumer has a utility function separable and linear in the numeraire good. There are no income effects and thus, we can perform partial equilibrium analysis.

act as homogeneous-product duopolists. Higher values of d denote tougher competition in the product market. The inverse demands are linear of the form:

$$p_i(q_i, q_j) = A - q_i - dq_j \tag{1}$$

p_i is firm i's price, $p_i : R_+^2 \to R_+$.

R&D production. Each agent is engaged in a stochastic production process. She undertakes an efficiency-enhancing project that yields the R&D-output z_i. Thus, firm i's marginal cost has as

$$c_i = \overline{c} - z_i$$

where the initial marginal cost $\overline{c}$, $A > \overline{c} > 0$, is constant and identical for both firms. Agent i's R&D-output depends on her own effort, x_i, the size of the spillover, hz_j, and a random term, η_i:

$$z_i = x_i + hz_j + \eta_i,\ h \in \left[0, \overline{h}\right] \tag{2}$$

h stands for the degree of cross-agent R&D spillovers; i.e. the fraction of agent j's R&D-output that can be absorbed by agent i.[9] The spillover rate is assumed to be identical for all agents and independent of the actions undertaken; i.e. symmetric and exogenous. It lies in the range of $\left[0, \overline{h}\right]$ where the bound $\overline{h}$ is endogenously determined and less than unity, $\overline{h} < 1$, implying that the R&D-outputs are imperfectly appropriable. Thus, the own-action effect dominates the cross-action effect. The random term η_i follows a truncated normal distribution with zero mean, $E\left\{\eta_i\right\} = 0$, and finite variance, $Var\left\{\eta_i\right\} = \sigma^2$, and is independently and identically distributed across agents, $cov\left\{\eta_i, \eta_j\right\} = 0$. η_i lies in $\Theta \equiv [-\theta, \theta]$, $-\infty < -\theta < \theta < +\infty$. Substituting $z_j = x_j + hz_i + \eta_j$ into (2), we get

$$z_i = \frac{1}{1-h^2}\left(x_i + hx_j + \eta_i + h\eta_j\right) \tag{3}$$

The feasibility line $\overline{x_i}\left(x_j\right) = \left(1 - \overline{h}^2\right)\overline{c} - \overline{h}x_j - \left(1 - \overline{h}\right)\theta$ sets an upper bound on the effort choices and the parameter values such that the post-innovation marginal cost to be positive. Thus, agent i will commit to a level of cost-reducing effort $x_i \in X$ where $X \equiv \left[0, \left(1 - \overline{h}^2\right)\overline{c} - \left(1 + \overline{h}\right)\theta\right]$; θ and $\overline{h}$ are related to each other and both satisfy the assumptions (O.1) and (O.2) which are discussed in section 3.

Information asymmetries over the agents' effort matter for the link between the inputs in innovation process and the resulting output. Spillovers are positioned on rival's R&D-

[9] Researcher's (say) 'absorptive capacity' depends on the information control over the R&D outcomes, the amount of knowledge embodied in the R&D outputs, the degree of tacit knowledge required, the ease of imitation, the characteristics of R&D technologies, etc.

output since only observable measures can be appropriated.[10] In this R&D process, agent i's R&D-output spilled over increases agent j's R&D performance and, in turn, the increased R&D-output spilled over by j enhances i's performance further, and so on. There is a positive and "regenerative" feedback from the agents' efforts that leads to a self-amplifying sequence of R&D reactions. As an "echo chamber", information and ideas are reinforced by transmission inside an 'enclosed' R&D space. The spillover rate is the feedback factor. For higher h, the marginal contribution of i's effort on i's R&D production progressively increases; i.e. $\frac{\partial(\partial z_i/\partial x_i)}{\partial h} > 0$. This technology is convex in spillovers implying that an R&D-taking firm with cost-advantage keeps undertaking R&D projects and intensifies its own R&D activity. If both agents choose x, the derivative $\frac{\partial(\partial z/\partial x)}{\partial h} = \frac{1}{1-h}$ exceeds unity implying that spillovers drive all agents to exert higher efforts.

Innovation in science-based industries is an ongoing process and depends on the technological interactions among the research units. Empirical works, surveyed by Arthur (1994) and Feldman (1999), find that, in bioengineering and microelectronic-based industries, knowledge is transmitted within research networks and the feedback mechanism is self-reinforcing. R&D production exhibits speed-up of innovation and increasing returns to spillovers. For instance, pharmaceuticals exist within a network of academic departments, testing labs, hospitals and other organizations. Scientists appointed by these institutions observe some part of others' research outcomes due to lack of information control over their actions, embodiment of knowledge in chemical compounds and genetic sequences, or some special characteristics of R&D technologies. Thus, researchers learn more and improve their own research outcomes. As knowledge transmission within this network is intensified, the R&D process is reinforced. The production of micro-electronics devices and operating systems also displays 'dynamic learning'. This R&D process differs from those considered by D'Aspremont and Jacquemin (1988) and Kamien, Muller, and Zang (1992) in which there are no interactions during the R&D production. The latter technologies may discribe the R&D production in drug and material industries where innovation, once made, does not generate a sequence of discoveries.[11]

Firm profits and contracts. The principal is residual claimant on firm's net profits which are given by the Cournot profits, $\Pi_i = (p_i - c_i)q_i$, net the agent's compensation (the

[10] Few papers consider effort to be multi-dimensional: i.e. effort for applied and basic research (Lacetera and Zirulia (2008)). In such models, efforts are unobservable and unverifiable while effort for basic research is assumed to be diffused. The marginal cost is non-contractible and the contracts are contingent on verifiable signals of both types of efforts (i.e. patents, articles, publications). We consider a different framework where the principal-agent relationship is one-dimensional. The marginal cost is contractible and the R&D-outputs are observable and appropriable.

[11] Levin (1988) argues that there are inter-industry differences in the nature of technical advance. For instance, innovation in drug and material industries, once made, stands alone. A firm's innovation discourages the rival to innovate. In contrast, innovation in microelectronics industries is a dynamic process. The "building blocks" creating type of innovation is reinforced as more information is diffused.

cost of R&D incurred by the firm), w_i. Thus, i's net profits are $\pi_{net,i} = \Pi_i - w_i$. The principal invests w_i in the R&D process in order to reduce the initial marginal cost $\bar{c}$ by z_i.

Enforceable contracts are contingent on R&D-outputs. In particular, individual compensation is restricted to be linear to the weighted difference of both agents' R&D-outputs; i.e. $z_i - hz_j = x_i + \eta_i$ where $z_i - hz_j$ is a sufficient statistic of x_i (Holmstrom (1979), Mookherjee (1984)).[12,13] The weight which is put on rival performance is negative and equal to the spillover rate; i.e. the degree of correlation between agents' R&D-outputs. Following Holmstrom and Milgrom (1987), i's contract generates a payment

$$w_i = \alpha_i + \beta_i (z_i - hz_j) \tag{4}$$

α_i denotes the fixed salary component and β_i is the pay-for-performance parameter.[14] One could also interpret this compensation scheme as a 'spur' where an agent's incentives depend also on rival's success.

Such evaluation scheme can effectively be used as a mean of filtering out spillovers from agent's reward. The principal seems to anticipate the appropriability problem and penalizes the agent when the rival does better by reducing her own compensation. Due to spillovers, each agent acts in a favorable environment which should be discounted from her reward. In a sense, the principal induces the agent to be given a short position in rival's performance. Agent i is paid less the higher j's R&D-output.[15] Agent i experiences no increase in her own wage due to x_j since she pays nothing for exploiting the research outputs of this activity. Relative performance evaluations introduce 'competition' between agents and promote efficiency in designing incentives for a risk-averse agent. Comparing performance information provides a richer information base on which to write contracts (Holmstrom and Tirole (1989)) and allows the principal to better assess the effort level by looking at rival's performance. Thereby, such scheme improves the trade-off between incentives provision and insurance.

Agent's utility. Each agent has constant absolute risk-averse (CARA) preferences

[12] Following Holmstrom and Milgrom (1987), linear contracts are optimal in this setting.

[13] Alternatively, principals could offer forcing contracts where, in the good state, the agent will get (say) an R&D-output based reward while, in the bad state, she will earn nothing. Such contracts are mainly used in "the winner-takes-it-all" races or in rank-order tournaments. Uncertainty about the R&D outcomes though makes forcing contracts less appropriate.

[14] In practice, linear contracts (may) describe the form of the wages of researchers in modern corporations. The wages comprise bonus factors related to the performance and a base payment related to health insurance, family benefits, housing that (mainly) remain fixed throughout the duration of the contract.

[15] The performance measures satisfy the monotone likelihood ratio property (MLRP). This is, higher performance signals higher effort. Thus, under the optimal contract with relative performance appraisal, each agent should be paid less if the other's production is high.

described by the negative exponential utility function

$$U_i\left(w_i, x_i\right) = -exp\left\{-r\left[w_i - \psi(x_i)\right]\right\}$$

where r is the rate of risk aversion, $r > 0$, and $\psi(x_i)$ is the cost-of-effort function. This function is assumed to be quadratic, $\psi(x_i) = \frac{k}{2}x_i^2$, implying that there are diminishing returns to scale in the process of doing R&D. k stands for the agent's known ability to handle an R&D task successfully, $k > 1$. Higher values of k represent lower efficiency or productivity of the R&D technology.

Given that agents' performance is truncated normally distributed and incentive schemes are linear, the certain equivalent of U_i can be written in a mean-variance form:[16] i.e. $CE_i = E\left\{w_i\right\} - \frac{r}{2}var\left\{w_i\right\} - \frac{k}{2}x_i^2$; the first two moments of agent's utility function have a closed form solution and incentive parameters can be calculated. If agent rejects to enter the labor market, she picks the outside option which is normalized to zero.

3 The model

Firms compete in both the product and R&D markets and make their decisions simultaneously given their beliefs about the rival's actions. Under the silent assumption that all players are rational, such expectations are confirmed at the optimum. We solve the two-period R&D/output game backwards and restrict our attention to subgame-perfect equilibria.

3.1 Cournot competition

In period 2, each firm i observes the realization of both own and j's marginal cost and forms beliefs about j's output. Given that the wages are independent of second-period choices, firm i maximizes $\Pi_i(q_i, q_j;\, z_i, z_j) = \left[A - q_i - dq_j - \overline{c} + z_i\right] q_i$ where $q_i : X^2 \rightarrow R_+$ is a map from the pairs (c_i, c_j) to outputs. In equilibrium, firm i's output, price and Cournot profits have respectively as:

$$q_i^*\left(z_i, z_j\right) = \frac{A - \overline{c}}{2 + d} + \frac{2z_i - dz_j}{4 - d^2}\ ,\ \ p_i^* = c_i^* + q_i^*\ ,\ \ \Pi_i^* = q_i^{*2} \tag{5}$$

Note that firms may end up in an asymmetric equilibrium $\left(q_i^*, q_j^*\right)$ even if the R&D choices taken in first period are identical. It is so because firms may experience asymmetric marginal

[16] Agent's effort alters the first two moments of the distribution of R&D-output while higher moments remain unchanged. In appendix $A.2$, we prove that this property applies even if the performance measures follow a truncated normal distribution.

costs depending on how lucky the researchers were during the R&D process; the realizations of η_i, η_j may differ. Though, large marginal cost differences are unlikely to be realized since, by equation (5), optimal outputs require $(A-\overline{c})(2-d) > dz_j - 2z_i$. Implicitly, it is assumed that the variance of market shocks σ^2 is sufficiently small.[17]

3.2 Assumptions and effective action space

The expected output over η_i, η_j before the realization of marginal costs is given by:

$$E\left\{q_i^*\left(x_i,x_j\right)\right\} = \frac{A-\overline{c}}{2+d} + \frac{\left(2-dh\right)x_i + \left(2h-d\right)x_j}{\left(4-d^2\right)\left(1-h^2\right)} \tag{6}$$

To guarantee that there exists an interior solution in the delegation R&D game, the following Inada-type assumptions are imposed on the net profits function (Amir, Amir, and Jin (2000)):[18]

$$A\left(2-d\right) > 2\overline{c}\left(1-\overline{h}\right) + \frac{2\overline{h}-d}{1-\overline{h}}\theta \tag{O.1}$$

$$\frac{2\left(2-d\overline{h}\right)\left[\left(1-\overline{h}\right)A-\theta\right]}{\left(4-d^2\right)\left(2+d\right)\left(1-\overline{h}^2\right)\left(1-\overline{h}\right)} < w'\left\{\left(1-\overline{h}\right)\overline{c}-\theta\right\} \tag{O.2}$$

(O.1) requires merely that the market demand is high enough relative to the initial marginal cost such that each firm does have incentives to carry out some R&D projects regardless of the rival's R&D choice. In particular, the derivative of i's net profits with respect to i's effort at the point $(x_i, x_j) = (0, x_j)$ where $x_j \in X$ is assumed to be positive; i.e. $\frac{\partial \pi_{net,i}}{\partial x_i}\mid_{x_i=0,\ x_j\in X} > 0$. (O.2) serves to ensure that this derivative at the point where the firms' feasibility lines intersect is negative; i.e. $\frac{\partial \pi_{net,i}}{\partial x_i}\mid_{x_i=x_j=\left(1-\overline{h}\right)\overline{c}-\theta} < 0$.[19] (O.2) requires the unit cost of R&D to be large enough so as to moderate the R&D incentives and guarantee positive post-innovation marginal costs. $\overline{h}$ is the boundary spillover rate, $\overline{h} \in (0,1)$, which satisfies (O.2) for any unit cost of R&D. Assumptions (O.1) and (O.2) also bound the parameter space and guarantee that the optimal R&D efforts will lie in the interior of the jointly undominated effective strategy space Γ which is a subset of X^2:[20,21]

$$\Gamma \triangleq \left\{(x_1,x_2) : x_i \in \left[0, \left(1-\overline{h}^2\right)\overline{c} - \overline{h}x_j - \left(1+\overline{h}\right)\theta\right];\, i,j=1,2,\ i\neq j,\ h\in\left[0,\overline{h}\right],\ \eta_i,\eta_j\in\Theta\right\}$$

[17] Realized marginal cost far different from its mean can be ignored.

[18] See in Appendix $A.2$ how assumptions (O.1) and (O.2) are derived.

[19] (O.2) is restrictive only if $h > \frac{d}{2}$ and, given that $A > \overline{c} > 0$, (O.1) plays a role only if $h < \frac{d}{2}$.

[20] Given that i's net profits function is concave in x_i, the action set X is compact and R&D reaction functions are single-valued and continuous, there exists an equilibrium in the interior of Γ.

[21] $\overline{h}$ increases with d, k, r, σ^2, $\overline{c}$, A and decreases with θ. θ is the boundary value of ηs and satisfies both assumptions. Thus, Θ is a compact set. Provided that (O.1), (O.2) hold for the extreme value θ, they will also do for ηs mean (their expected value).

3.3 Principals' problem and R&D rivalry

Each principal designs a piece rate contract (α_i, β_i) that maximizes his expected net profits and is compatible with agent's incentives to perform and to participate. Contracts are offered and efforts are exerted in an one-shot contracting/R&D game. Given the beliefs about the rival's effort level, principal i's problem becomes:

$$\max_{\alpha_i,\beta_i,x_i} E\left\{\pi_{net,i}(\beta_i, x_j)\right\} = \int_{-\theta}^{\theta}\int_{-\theta}^{\theta} \left\{\Pi_i - \alpha_i - \beta_i\left(z_i - hz_j\right)\right\} f\left(\eta_i, \eta_j\right) d\eta_j d\eta_i$$

$$\text{subject to} \quad x_i^* = \arg\max_{x_i} E\left[U_i\left(w_i, x_i\right)\right] \qquad (IC_i)$$

$$\text{and} \quad E\left[U_i\left(w_i, x_i\right)\right] \geq 0 \qquad (IR_i)$$

The incentive compatibility constraint (IC_i) guarantees that agent i will choose the expected utility-maximizing effort. The first-order condition of agent i's problem has as

$$x_i^* = \frac{1}{k}\beta_i \tag{7}$$

Optimal effort is linear in β^* whose marginal contribution on labor supply increases as R&D technology is more efficient. Given that the functions U_i and $\pi_{net,i}$ are strictly concave in x_i, we can use the first-order approach and replace the constraint IC_i in principal's problem with equation (7).[22]

The individual rationality constraint (IR_i) demonstrates that agent i will participate in the R&D process only if her expected utility of doing so exceeds her reservation utility which is normalized to zero. The constraint (IR_i) is binding at the optimum under the assumption that the labor markets are competitive and principals are endowed with the bargaining power. The fixed salary component α_i is such that induces agent participation at least cost. Solving this game (appendix $A.3$), i's R&D-reaction function is derived:

$$RF_i\left(x_j\right) = 2\left(2 - dh\right)\frac{\left(A - \overline{c}\right)\left(2 - d\right)\left(1 - h^2\right) + \left(2h - d\right)x_j}{\left(4 - d^2\right)^2\left(1 - h^2\right)^2 k_r - 2\left(2 - dh\right)^2} \tag{8}$$

where $k_r \equiv k\left(1 + kr\sigma^2\right)$. Given the concavity of firm i's net profits function, the denominator is positive and the slope of RF_i depends on the sign of $2h - d$.

[Figure 2 is about here]

If $h < \frac{d}{2}$, i's R&D reaction curve is downward sloping for all $x_j \in X$ and lies above the point

[22] It is $E\left\{\Pi_i\left(x_i, x_j\right)\right\} = \left[\frac{A-\overline{c}}{2+d} + \frac{(2-dh)x_i+(2h-d)x_j}{(4-d^2)(1-h^2)}\right]^2 + \frac{(2-dh)^2+(2h-d)^2}{(4-d^2)^2(1-h^2)^2}\sigma^2$; Principals like to act in a risky environment since the expected production profits increase with the variance of market shock, σ^2.

$(0, x_j)$. In the regime where $h > \frac{d}{2}$, this curve is strictly increasing in x_j until it intersects with the downward-sloping line $\overline{x_i}(x_j)$. Thus, RF_i lies below the point $(\overline{x_i}, \overline{x_j})$.[23] The rivals' R&D reaction curves will intersect somewhere in between the axis and the feasibility lines.

Proposition 1 (Optimal R&D incentives) *Under Assumptions (O.1) and (O.2), there exists a symmetric sub-game Nash equilibrium in performance-based parameter in which:*

$$\beta^* = \frac{2k}{\Omega}(A - \overline{c})(1-h)(2-dh)$$

where $\Omega \equiv (4-d^2)(2+d)(1-h^2)(1-h)k_r - 2(2-dh)$.

Proof. See appendix. ■

3.4 Contractual choices

The positive sign of β^* implies that higher 'net' performance is compensated with higher wage. We note that any compensation scheme that is linear transformation of this cost-based contract affects similarly agent's behavior. For instance, let agent i's reward be contingent on outputs. In such a case, agent i's payment will be $w_i = \alpha_i + \beta_i\left(q_i - \frac{2h-d}{2-dh}q_j\right)$. The degree of product market competition now plays a key role on the relationship between rivals' performance measures. If $h < \frac{d}{2}$, the agent is penalized if the rival firm realizes a lower marginal cost and can extend its businesses while, if $h > \frac{d}{2}$, agent gains by an increase in rival's output. However, both output-based and cost-based compensation schemes induce the same level of effort. Instead of designing a contract that compensates the agent for her higher performance relative to her rival's, equivalently, the principal can provide a two-piece rate contract. In such a case, the optimal pay-for-rival performance parameter is such that allows the contract to filter out the appropriability problem; i.e. given $w_i = \alpha_i + \beta_i z_i + \gamma_i z_j$, at the optimum, it is $\gamma^* = -h\beta^*$.[24]

One could also consider an agent's contract to be contingent only on own performance; i.e. $w_i = \widetilde{\alpha_i} + \widetilde{\beta}_i z_i$. In such a case, each agent chooses the effort level $\widetilde{x}_i^*$ where, for positive

[23] Given that the feasible set is descending in x_j, for higher x_j, RF_i coincides with $\overline{x_i}(x_j)$ and decreases.

[24] Let η_i, η_j be correlated; i.e. the correlation coefficient is $\rho = \frac{\sigma_{ij}}{\sigma^2}$, $|\rho| \leq 1$, $\sigma_{ij} < 1 + r\sigma^2$. In such a case, it is $w_i = \alpha_i + \beta_i\left(z_i - \frac{h+\rho}{1+\rho h}z_j\right)$. Positive correlation, $\rho > 0$, is an additional reason for rewarding agent i on how well she does relative to her rival and penalizing her for positive marketwide changes in innovative activity. If shocks are negatively correlated, $\rho < 0$, which is likely to occur when agents employ different R&D technologies, the 'compensation ratio' depends on the relative intensity of the correlation measures h, $|\rho|$. If $h < |\rho|$, setting the pay-for-rival weight positive is a plausible way to induce effort exertion. Principal encourages the agent to innovate by making her suffer less from a 'bad' outcome since her reward now increases with rival's performance. Such contracts can also filter out common risk from agents' reward. If $h + \rho = 0$, z_j ceases to convey information about x_i, and thus, i's contract is contingent only on i's performance.

spillovers, it is $\widetilde{x_i^*} < x_i^*$ and the unit cost of R&D is $\widetilde{k_r} \equiv k\left[1 + kr\sigma^2\left(1 + h^2\right)\right]$. Each principal seems to reward the agent for the own-firm efficiency enhancement, disregarding the effect of spillovers. A given reduction in initial marginal cost can be achieved by devoting lower efforts and thus, lower-power incentives are required. $\widetilde{k_r}$ is also sensitive to the degree of spillovers. h is multiplicative to $kr\sigma^2$ indicating that the agent is now exposed to higher risk. The agent requires more insurance which takes the form of a decrease in the slope of the optimal contract. Thus, by allowing performance comparisons, principals can better infer the level of agent's effort and agents find it easier to credibly commit to a given action. Such schemes, as means of gathering information on agents' actions, mute the distortion in R&D incentives.

[Figure 3 is about here]

Figure 3 shows the equilibria in the delegation R&D game where principals make use of two-piece and one-piece rate contracts. By using these two forms of compensation, principals seem to face the prisoners' dilemma into their contract decision. Best responses will induce both firms to condition each agent's reward on how well she does compared to another.

4 Full vs asymmetric information

We study the effect of information asymmetries on firms' net profits and argue that firms might enjoy higher profits under asymmetric information. To get a better insight into the equilibrium outcomes, we perform a comparative statics analysis to examine the intensify of R&D incentives given the degree of technological and strategic interactions.

4.1 Risk-profits relationship

In a world with full information, efficient incentives can (normally) be achieved and full insurance is entailed at the optimum. If the principal has complete bargaining power and can observe the agent's actions, he can extract the complete rents the agent would earn via the base payment. The principal's problem becomes:

$$\max_{x_i} E\left\{\pi_{net,i}(x_i, x_j)\right\} = \int_{-\theta}^{\theta}\int_{-\theta}^{\theta}\left\{\Pi_i - w_i\right\} f\left(\eta_i, \eta_j\right) d\eta_j d\eta_i$$

$$\text{subject to} \quad E\left[U_i\left(w_i, x_i\right)\right] \geq 0 \qquad (IR_i)$$

The principal rewards the agent by providing a lump-sum payment equal to the disutility of labor, $w_i^{FI} = \frac{k}{2}x_i^2$ and the optimal effort has as

$$x^{FI} = \frac{2}{\Omega_{FI}}\left(A - \bar{c}\right)\left(1-h\right)\left(2-dh\right)$$

where $\Omega_{FI} \equiv \left(4-d^2\right)\left(2+d\right)\left(1-h^2\right)\left(1-h\right)k - 2\left(2-dh\right)$.

Under asymmetric information, the agent's preferences towards risk matter for incentives provision. Risk-averse agents are unlikely to choose the profit-maximizing level of effort conflicting to principal's interests. Motivational deficiencies prevent them from doing so. In particular, risk-aversion of the part of the agent and uncertainty about the R&D-outcome induce each agent i to require insurance against low realizations of production. Risk-premium increases the marginal cost of inducing effort implying that effort falls short from its efficient level; i.e. $x^{FI} > x^*$ for all $x \in \Gamma$.[25,26] In other words, effort decreases with risk; i.e. $\frac{\partial x^*}{\partial k_r} < 0$ in all Γ. However, the comparison of firms' profits realized in worlds with different information structure is less clear cut. We fairly evaluate the effect of the unit cost of R&D on the optimal net profits, $\frac{\partial \pi^*_{net}}{\partial k_r}$;

$$\frac{\partial \Pi^*}{\partial k_r} = 2q^* \frac{1}{\left(2+d\right)\left(1-h\right)} \frac{\partial x^*}{\partial k_r} \text{ and } \frac{\partial w^*}{\partial k_r} = \frac{1}{2}x^{*2} + k_r x^* \frac{\partial x^*}{\partial k_r}$$

The production profits decrease with k_r: given that Π^* increases with efficiency-enhancing R&D and higher values of k_r distort effort downwards, lower production profits are realized as a result. The unit cost of R&D also affects the agent's compensation directly by decreasing the productivity of R&D process and indirectly through the R&D incentives. The indirect effect is related to the cost a firm saves by providing lower-power incentives in response to higher k_r.

We argue that there exists a regime where the relationship between risk and firm's net profits is positive. Net profits increase with k_r if, and only if, the indirect effect on the agent's payment dominates. In such a case, the gain in profits due to the cost a firm saves by exerting lower effort as risk increases exceeds the loss of profits due to lower market power a firm can possess. We argue that cost-savings by investing less in R&D due to risk-sharing may yield higher profits for rivals. In a sense, principals are better-off as the trade-off between effort provision and insurance is shifted towards the latter. That is, as principals appoint higher

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[25] At the optimum, the individual rationality constraint (IR) is binding implying that the agent earns nothing but the cost of effort and the risk premium. If $r > 0$ and the random terms vary around the mean, the risk premium increases with k, r, σ^2 and so does the difference between the optimal efforts exerted under full and asymmetric information.

[26] Setting the piece rates efficiently requires the marginal returns of R&D to be equal to the marginal cost of this activity from the principal's perspective. In this model, the marginal returns and costs of R&D have respectively as $\left(1 + kr\sigma^2\right)\beta^*$ and β^* implying inefficiency in the intra-firm incentives given $r > 0$.

risk-averse agents and as the market displays higher uncertainty. However, for this to be the case requires k_r to be positive but not too high. If k_r exceeds a threshold, the R&D process becomes too costly and higher risk yields to lower profits.[27]

Proposition 2 (Positive profits-risk relationship) *Under Assumptions (O.1) and (O.2), Cournot competitors realize higher profits under asymmetric information if, and only if,* $\widetilde{d} < d \leq 1$, *where* $\widetilde{d} \in \left(\frac{1}{2}, 1\right)$, *and* $k_r < \frac{2(2-dh)^2}{(4-d^2)(2+d)(1-h^2)(1-h)[2(1-d)+h(4-d)]}$.

Proof. See appendix. ■

This paper provides a simple reason why there might be a positive relationship between insurance and profits which counters the prediction of the principal-agent theory.

4.2 Slutsky-like decomposition of R&D

To intuitively interpret proposition 2, we decompose the R&D incentives and consider the underlying effects. The direct effect of effort comes through marginal cost reduction; the more a firm produces at a more efficient scale, the more it profits. This is the so called *efficiency effect* which is positive. Indirect effects on revenues due to firms' interactions in the product market are also at work. First, it is the *strategic effect* which is also positive: 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, it is the negative *spillover effect*: agent's effort also reduces the rival's initial marginal cost due to spillovers which is detrimental to the R&D-taking firm. The derivative $\frac{\partial \pi_{net,i}}{\partial x_i}$ shows the trade-off among all these effects against the increase in agent's compensation. We consider R&D as a technology that reduces the marginal cost at the expense of the fixed cost;[28]

$$\frac{\partial \pi_{net,i}}{\partial x_i} = \underbrace{\frac{\partial \Pi_i}{\partial q_j} \frac{1}{\Lambda(1-h^2)} \frac{\partial p_j}{\partial q_i}}_{\substack{\text{strategic effect} \\ = \frac{d^2}{(1-h^2)(4-d^2)} q_i}} + \underbrace{\left(-\frac{\partial \Pi_i}{\partial q_j} \frac{2h}{\Lambda(1-h^2)} \frac{\partial p_i}{\partial q_i}\right)}_{\substack{\text{spillover effect} \\ = -\frac{2dh}{(1-h^2)(4-d^2)} q_i}} + \underbrace{\frac{\partial \Pi_i}{\partial c_i} \frac{\partial c_i}{\partial x_i}}_{\substack{\text{efficiency effect} \\ = \frac{1}{1-h^2} q_i}} - w'(x_i) \quad (9)$$

where $\Lambda \equiv 4 \frac{\partial p_i}{\partial q_i} \frac{\partial p_j}{\partial q_j} - \frac{\partial p_j}{\partial q_i} \frac{\partial p_i}{\partial q_j}$ comes from the stability condition. Note that for positive d and h, R&D best-responses depend on the relative intensity of strategic and spillover effect. If $h < \frac{d}{2}$,

[27] Each principal commits himself to a certain information structure by making the delegation decision before the contracting stage takes place.

[28] In appendix $A.2$, see how the forms of the effects are obtained; it is $\frac{\partial \pi_{net,i}}{\partial x_i} = \frac{\partial \Pi_i}{\partial q_i} \frac{\partial q_i}{\partial x_i} + \frac{\partial \Pi_i}{\partial q_j} \frac{\partial q_j}{\partial x_i} + \frac{\partial \Pi_i}{\partial c_i} \frac{\partial c_i}{\partial x_i} - w_i'$. The term $\frac{\partial \Pi_i}{\partial q_i} \frac{\partial q_i}{\partial x_i}$ can be decomposed to $(p_i - c_i) \frac{\partial q_i}{\partial x_i}$ and $q_i \frac{\partial q_i}{\partial x_i}$. These two effects cancel each other out due to Cournot competition in the product market where the output level is equal to the price-cost margin (equation (5)). Thus, we focus our analysis on the three effects that drive the results.

the strategic effect dominates and efforts become strategic substitutes. The R&D-taking firm with cost-advantage can steal businesses from its rival and serve a larger market share.[29] In turn, the rival reduces its own R&D production. If $h > \frac{d}{2}$, the opposite holds. Notably, the conditions stated in proposition 2 can be satisfied and thus, a positive relationship between risk and profits can be realized only in the regime where efforts are strategic substitutes. Thus, for the rest of section 4, the analysis is focused on the corresponding parameter space.

Differentiating equation (9) with respect to h gives

$$\frac{d\left(\partial \pi_{net,i}/\partial x_i\right)}{dh} = 0 \quad \text{or} \quad \frac{\partial\left(\partial \pi_{net,i}/\partial x_i\right)}{\partial h} + \frac{\partial^2 \pi_{net,i}}{\partial x_i^2}\frac{dx_i}{dh} = 0$$

This Slutsky-like decomposition sheds light on the effect of spillovers on agent's behavior. Given the concavity in x_i of the net profits function, $\frac{\partial^2 \pi_{net,i}}{\partial x_i^2} < 0$, the optimal effort changes with spillovers as the marginal profitability of effort does. The sign of $\frac{\partial(\partial \pi_{net,i}/\partial x_i)}{\partial h}$ is ambiguous and depends on the 'relative severity' of the strategic, spillover and efficiency effects. In particular, all these effects are intensified with h; remember that the spillover effect is negative.[30]

Corollary 3 (Effort & spillovers) *Under Assumptions (O.1) and (O.2), the optimal effort x^* increases with spillovers if, and only if, both conditions $h < \frac{2-\left(4-d^2\right)^{1/2}}{d}$ & $k_r > \frac{2(2-dh)^2}{(4-d^2)(2+d)(1-h)^2(d-4h+dh^2)}$ do not apply simultaneously.*

Proof. See appendix. ■

[Figure $4a$ is about here]

In contrast to the literature based in AJ and KMZ models that consider the free-rider problem, corollary 3 states that spillovers can stimulate the R&D activity. It is so when spillovers make the positive strategic and efficiency effects relatively more severe compared to the negative spillover effect. The intuition of this result is as follows. If efforts are strategic substitutes, by undertaking R&D, a firm realizes lower marginal cost and can easier extent its businesses at the expense of its rival's. Thus, each principal wants to experience a slightly lower marginal cost from its competitor. Given that the own-action effect dominates the cross-action effect and both principals have the same incentives, they enter into a *rat race.* As spillovers increase, higher-power incentives provide firms that are involved in this type of race. Nevertheless, R&D incentives are reversed if the R&D process is relatively too costly. In such a case, principals seem to be unwilling to bear high R&D costs and find it

[29] In the knife-edge case where $h = \frac{d}{2}$, each firm has a dominant strategy on R&D.

[30] It is $\frac{\partial x^*}{\partial h} = \frac{2(A-c)}{\Omega^2}\left[2\left(2-dh\right)^2 + \left(2-d\right)\left(2+d\right)^2\left(1-h\right)^2\left(4h-d-dh^2\right)k_r\right]$.

best to exert lower efforts as spillovers increase. For high unit cost of R&D, the spillover effect becomes relatively more severe and drives the result. In figure $4a$, the derivative $\frac{\partial x^*}{\partial h}$ is negative for those d and h in the left hand side of the lines that have been drawn for different values of k_r.

Spillovers also play a key role in the relationship between effort and competition. Competition intensifies the strategic and spillover effect while weakens the efficiency effect.

Corollary 4 (Effort & competition) *Under Assumptions (O.1) and (O.2), the optimal effort x^* increases with competition if, and only if,* $d > \frac{3+h-\left(9-2h-7h^2\right)^{1/2}}{2h}$.

Proof. See appendix. ■

[Figure $4b$ is about here]

In the literature with exogenous market structure, it is pretty common this relationship to be U-shaped; for low values of d, the derivative $\frac{\partial x^*}{\partial d}$ is negative while it progressively increases and becomes positive as d approaches 1.[31] To interpret this relationship, we first examine the sign of $\frac{\partial(\partial \pi_{net,i}/\partial x_i)}{\partial d}$. On the one hand, competition decreases the efficiency effect.[32] As demand becomes more elastic, the willingness to pay for firms' goods decreases implying lower prices. In turn, a drop in output is required to compensate the fall in profits. The marginal profitability of R&D decreases and principals provide lower-power incentives. On the other hand, competition increases the strategic effect. As d increases, a firm with cost-advantage is better able to take away businesses from its rival. Thus, each firm has incentives to exert higher effort in order to become tougher in the product market. In the absence of spillovers, it is $\frac{\partial x^*}{\partial d} > 0$ if, and only if, $d > \frac{2}{3}$ where the strategic effect becomes more severe compared to the efficiency effect (i.e. Hermalin (1992)). If spillovers occur, competition also intensifies the (negative) spillover effect. For a more elastic demand, a reduction in rival's marginal cost due to spillovers harms the R&D-taking firm since the rival becomes more aggressive in the product market. Lower prices and profits yield as a result. Given h, the strategic effect becomes more severe and dominates for high values of d. Thus, competition speeds up R&D efforts when the business stealing incentives are intensive.

Corollary 5 (Reinforcing R&D) *In the regime where efforts are strategic substitutes, R&D activity is amplified when firms are engaged in a rat race due to the technological interactions and are driven by business-stealing incentives due to the strategic interactions.*

[31] Empirical works also report a U-shaped relationship between competition and incentives; i.e. Aghion, Bloom, Blundell, Griffith, and Hawitt (2005), Scherer and Ross (1990) among others. Griffith (2001), Baggs and de Bettignies (2006) study the effect of effort on the intensity of the moral hazard problem.

[32] It is $\frac{\partial x^*}{\partial d} = -\frac{4k_r}{\Omega^2}(A-c)(1-h)^2\left(1-h^2\right)\left[2-3d+\left(2-d+d^2\right)h\right]$; competition intensifies the strategic and the (negative) spillover effect and decreases the efficiency effect.

4.3 Delegation as a collusive device

This paper argues that, in highly competitive industries where firms are driven by business-stealing incentives and are involved in a rat race, they exert a fairly high level of R&D efforts burning up profits by doing so. Higher risk-premiums diminish principals' appetite for innovation. The contractual components are such that weaken the R&D incentives. Risk-sharing mutes the effect of spillovers and competition on agents' behavior. In turn, lower efforts mitigate the intensity of the race and the strategic interactions. Thus, cost-savings by exerting lower effort due to the trade-off between effort provision and insurance may yield higher profits for rivals. This result is, to the best of our knowledge, novel since, in the linear principal-agent models, firms wish to have full information so as to perfectly monitor the agent and achieve the optimal allocation of effort from the principal's perspective. This result also indicates the desirability of the R&D duopolists to collude so as to soften the intensity of the strategic interactions and internalize the knowledge externality. Separation between the business and research units under asymmetric information can be used as a collusive device that raises profits for both rivals. In a sense, delegation in R&D under moral hazard can serve as a self-commitment device that makes firms' interactions less intensive.

Corollary 6 (Collusive device) *The division between ownership and control of R&D outputs under asymmetric information can be used as a collusive device that diminishes the intensity of the rat race and weakens the business-stealing incentives generating profits for the rivals.*

This analysis gives us an new insight into firms' organizational structure. For instance, delegation in R&D under asymmetric information and, thus, much of the use of incentive pay should be in volatile industries, such as in high-tech industries and the financial sector, if the unit cost of R&D is not too high. On the other hand, low-competitive firms desire to have full information about the agents' actions so as to effectively manage the innovation process.

4.4 Agency cost & spillovers

One could also examine the effect of spillovers on the intensity of the principal-agent conflicts. The agency cost can be represented by the ratio $\frac{x^*}{x^{FI}}$. As effort x^* deviates more from its full information level, this ratio will be less than unity and decreasing implying higher agency costs. It is equal to unity only if the intra-firm incentives are efficient.[33] The agency cost can be considered as a function of the severity of the moral hazard problem and the underlying R&D technology. Given the value of d, in the absence of spillovers, $h = 0$, the agency cost represents the cost of information asymmetries which increases with r and σ^2. If $h > 0$, the agency cost also incorporates the cost of externality which increases progressively with h; i.e. $\frac{\partial^2 x^{FI}}{\partial h^2} > \frac{\partial^2 x^*}{\partial h^2}$ in Γ.

Proposition 7 (Agency cost) *Under assumptions (O.1) and (O.2), spillovers intensify the agency cost in the entire parameter space; i.e.* $\frac{\partial \left(x^*/x^{FI}\right)}{\partial h} < 0$ *in* Γ.

The full and asymmetric information effort levels differ more as spillovers increase. It is so because risk-sharing makes the principal less able to exploit the knowledge externality and thus, x^* is less responsive to spillovers. Thus, spillovers force firms away from the efficient level of R&D. As h increases, the efficiency of monitoring and control the agent's actions progressively diminishes implying that there is far more distortion in R&D incentives. From an other perspective, the marginal contribution of spillovers on the marginal returns of R&D diminishes with k_r yielding lower benefits from absorption. The effect of an increase in the unit cost of R&D on the agent's behavior is twofold. On the one hand, it is the bargaining game; higher unit costs of inducing effort lead to a lower increase in incentives. On the other hand, it is the effect of spillovers on the agent's behavior; higher values of k_r make the agent willing to respond to spillovers by innovating less. Thus, the trade-off between insurance and incentives is shifted towards the former as the contract is 'rewritten' to accommodate increased spillovers. Spillovers worsen the agency problems within a firm. Under-provision of R&D incentives also implies that some productive opportunities remain unexploited giving rise to 'X-inefficiency' - loss of output, given inputs, due to inadequate 'motivation'.[34] Given information asymmetries, the total cost of production (including the agent's payment as the fixed cost) is not minimized.

5 Different modes of competition

We examine the commitment value of delegation under different modes of R&D and product market competition. We discuss the case where firms compete à la Cournot and

[33] Prendergast (2002) extensively discusses empirical studies about the effect of risk on incentives and concludes that most studies find this effect to be positive or insignificant. Raith (2003) argues that agent's incentives decrease with the risk in production, as it is standard in the literature, while they increase with the firm risk. Thus, the measure of risk used in empirical studies plays a key role for the empirical analysis. Jensen and Meckling (1976) test empirically the concept of agency cost and the ownership structure.

[34] Leibenstein (1966) is referred to X-efficiency; principals are able to control a given set of inputs and combine them in such a way so as to reach the ultimate limit of output. Incomplete contracts, asymmetric information about (at least) one factor of production, uncertainty and interdependence of inputs are the main cause for X-inefficiency to exist.

R&D efforts are strategic complements, and the Bertrand case.

5.1 Strategic complementarity in R&D

Efforts become strategic complements in the regime where the spillover effect on the marginal productivity of R&D (equation (9)) dominates the strategic effect. That is for $h > \frac{d}{2}$. For instance, if firms act in different industries and spillovers occur, $d = 0$ and $h > 0$, monopolist j's R&D-output spilled over increases the marginal productivity of i's research. Firm i responds by increasing its own effort and so on. Complementarities in R&D allow firms to exploit the causation causality between the agents' actions mainly for efficiency enhancing reasons. Higher spillovers also boost R&D. In the monopoly case, only the efficiency effect is at work. Spillovers increase the return to cost reduction, $\frac{\partial^2 \pi_{net,i}}{\partial c_i \partial h} < 0$, and thus, the efficiency in production by exerting higher effort. Monopolists gain from mutual beneficial R&D. That is why under-provision of R&D due to risk-sharing decreases the optimal profits. The moral hazard problem distorts the R&D decisions downwards making a firm less able to exploit the benefits of other's research and knowledge externality. The full-information profits are always higher for a monopolist. Delegation of R&D as a collusive device is no longer profitable. Less distorted decisions enhance profits.

5.2 Bertrand competition

In the Bertrand case, the benefits of moral hazard are considerable and even greater than those in the Cournot setting. Bertrand competitors are much more aggressive implying that under-investment in R&D due to the incentives-insurance trade-off generates profits for the rivals. In particular, each firm i faces the direct demand function $q_i = A - p_i + dp_j$. We solve the period-2 game backwards and derive the expected price before the realizations of (c_i, c_j):

$$E\{p_i\} = \frac{A - \bar{c}}{2 - d} - \frac{(2 + dh)\, x_i + (2h + d)\, x_j}{(4 - d^2)(1 - h^2)}$$

The expected Bertrand profits are given by $E\left\{\Pi_i^B\right\} = E\left\{q_i^2\right\}$. Note that individual R&D allows both rivals to set lower prices. Given though that R&D increases the price-cost margin and the own-action effect dominates the cross-action effect, each principal does have incentives to conduct some R&D. By doing so, she is better able to exercise its market power over its price. Lower spillovers and less product substitutability yield to higher expected markups. In period 1, given equations (4) and (7), the optimal piece-rate has as[35]

$$\beta^B = \frac{2k}{\Omega_B}\left[A - \overline{c}\,(1-d)\right](1-h)\left[2 - d\,(d+h)\right]$$

where $\Omega_B \equiv (4-d^2)\,(2-d)\,(1-h^2)\,(1-h)\,k_r - 2\,(1-d)\left[2-d\,(d+h)\right]$.

The R&D rivalry of the two modes of product market competition differs mainly in that: under Bertrand competition, the strategic effect is negative; i.e. $\frac{\partial \Pi_i}{\partial p_j}\frac{1}{\Lambda(1-h^2)}\frac{\partial q_j}{\partial p_i} = -\frac{d^2}{(1-h^2)(4-d^2)}q_i^B$. It is so because cost-reducing R&D allows the R&D-taking firm to set lower price. Competing for market share, the rival responds by cutting its own price as well implying lower profits for the innovator.[36] The strategic and technological interactions drive Bertrand rivals to innovate and produce less compared to what Cournot firms do, $x^* > x^B$. However, what burns up their profits is the intensive price competition between them. Firms are involved into a (say) price war and end up cutting their prices so that yields in profits loss. In such a case, information asymmetries over the agents' efforts may operate as a cost-saving device that mitigates the intensity of Bertrand interactions. Due to risk-sharing, optimal efforts and marginal cost reduction are lower and, in turn, price cutting as a market response is less profitable. Firms experience a less sever price war. Bertrand rivals are more aggressive than the Cournot ones implying that cost-savings due to under-provision of incentives yield substantial gains. The marginal profitability of risk is greater in a Bertrand world and profits increase with risk in a greater parameter space. Thus, firms' incentive to collude are strong.

6 Coordination in R&D

This section provides a discussion of R&D games where the choices are taken centrally. We examine the intention of individual firms to form an R&D cooperative by reaching 'collusive' wage agreements and the government's R&D incentives.

[35] We make similar assumptions as (O.1) and (O.2) so as to guarantee positive R&D-efforts and post-innovation marginal costs,

[36] Both higher spillovers and competition increase the severity of the Bertrand strategic effect. In particular, rival's response in the product market weakens firm's ability to retain her market power measured by the price-cost margin. Higher spillovers make it even harder and decrease the marginal contribution of R&D in raising profits. Thus, given that the spillover and efficiency effects change similarly with d and h as in the Cournot case, effort decreases with h in a greater parameter space and increases only if h exceeds a threshold where gains in efficiency enhancement are sufficiency high. As goods become less differentiated, high price is also less likely to sustain. Each firm faces a more elastic demand and sets lower price inflicting loss in profits. The marginal profitability of R&D and thus, optimal effort decrease with d in the entire parameter space.

6.1 Coordinated decisions

We consider firms to coordinate their R&D actions by providing 'collusive' contracts to their agents. By doing so, spillovers are internalized and the duplication of effort is eliminated. In period 2, firms compete in quantities in the product market for market share; optimal output and Cournot profits are as in subsection 3.1. In period 1, they form an R&D cooperative and design contracts that maximize the joint net profits

$$E\left\{\pi_{net,i}+\pi_{net,j}\right\}=\int_{-\theta}^{\theta}\int_{-\theta}^{\theta}\left\{\Pi_i+\Pi_j-(\alpha_i+\alpha_j)-\beta_i\left(z_i-hz_j\right)-\beta_j\left(z_j-hz_i\right)\right\}f\left(\eta_i,\eta_j\right)d\eta_j d\eta_i$$

subject to the constraints faced by both agents. This peculiar 'R&D cartel' can be considered as a monopolist who has two stores and sets the contractual parameters such that maximize the 'monopoly' profits. Principals solve the coordination R&D game and, given equation (7), they set the pay-for-performance parameter as

$$\beta^c=\frac{2k}{\Omega_c}\left(A-\overline{c}\right)(1-h)$$

where $\Omega_c=(2+d)^2(1-h)^2k_r-2$; the script c denotes 'coordination' in R&D.

Each collusive firm seems to enjoy lower marginal returns of R&D and exert lower effort than R&D competitors, if efforts are strategic substitutes;

$$x^c<x^*,\text{ if }\ h<\frac{d}{2}$$

To interpret this result, we consider coordination as a common agency problem. Agent's opportunity cost of devoting extra effort to the R&D process is higher for R&D cooperatives since now each agent is subject to both principals' appraisal. In turn, more R&D is conducted in markets with R&D rivalry. Moreover, the *cross-profit* effect also holds: firm i's R&D also affects firm j's profits; i.e. $\frac{\partial\pi_{net,j}}{\partial x_i}=\frac{2(2h-d)q_j}{(1-h^2)(4-d^2)}$.[37,38] For low spillovers, the cross-profit effect is negative while it becomes positive when $h>\frac{d}{2}$. Negative cross-profit effect implies that the increase in profits due to greater marginal cost reduction is lower than the loss of profits due to a decline in the market share of the 'higher-cost' rival. R&D duopolists ignore this effect and exert higher R&D efforts than the R&D cooperative due to either the rat race or the strategic interactions. In this regime, the benefits from business expansion shape firm's incentives to innovate. This result is in line with the argument that firms do have incentives to collude so as to mitigate the intensity of profit-burning strategic interactions.

Corollary 8 (Profits of R&D cooperative & risk) *Under Assumptions (O.1) and (O.2),*

[37] The 'cross-profits' effect is identical to the 'combined-profits' effect in Kamien et al (1992).

[38] In appendix $A.1$, the form of the 'cross-profit' effect is obtained analytically.

net profits of each 'collusive' firm decrease with risk; i.e. $\frac{\partial \pi^*_{net,i}}{\partial k_r} < 0$ *in* Γ_c.

Under full information, an R&D cooperative can better manipulate the agents' behavior and exploit the benefits from technological interactions. Once the collusive agreement has been reached, higher risk contributes only to decreasing profits.[39]

6.2 Government's R&D

Subject to Cournot competition in the product market, the government maximizes the sum of the utilities of all agents been involved in the economy. The government's objective function is the unweighted sum of the firms' net profits, $\sum_{i=1}^{2} \pi_{net,i}$, agents' utilities, $\sum_{i=1}^{2} U_i$, and the consumer surplus, $CS = V(q_i, q_j) - p_i q_i - p_j q_j$. Simplifying things, the authorities maximise the social function:

$$E\{W\} = E\left\{V(q_i, q_j) - \sum_{i=1}^{2} [(c - z_i) q_i + w_i] + \sum_{i=1}^{2} U_i\right\} \tag{10}$$

subject to agents' constraints to perform and participate. Given the equations (5) and (7), the government sets the incentive parameters as

$$\beta^g = \frac{k}{\Omega_g} (A - c)(1 - h)(3 + d) \tag{11}$$

where $\Omega_g = (2 + d)^2 (1 - h)^2 k_r - (3 + d)$.[40]

Social incentives lead to over-investment in R&D compared to what R&D rivals do, $x^g > x^*$. It is so because the government takes into account the cross-profit effect as well as the effect over the consumer surplus. The social gains from the R&D activity are twofold. On the one hand, the 'production inefficiencies' are reduced: R&D efforts allow firms to produce more at lower cost moving the economy towards its production possibility curve. On the other hand, it is the effect on the consumer surplus: an R&D-taking firm is better able to allocate its resources in accordance with the wishes of consumers. By doing R&D, more output can be offered at a lower price making consumers better-off. Thus, the intensity of R&D activity undertaken by individual firms does matter for social welfare. As mentioned above, an R&D cooperative softens firms' interactions and increases the net profits of each member by preventing firms to get involved in the race. The value of coordination can

[39] If agents also coordinate their actions, they chooce effort i and j by maximizing the sum of the utilities. They choose lower effort than x^* and x^c in the entire paremeter space. Higher profits are realized for each collusive firm.

[40] At the optimum, the consumer and total surplus have respectively as $CS = (1 + d)(q^g)^2$ and $W^g = \frac{k_r}{\Omega_g} (A - c)^2 (3 + d)(1 - h)^2$.

be measured in terms of the elimination of resources wasted in this process. However, social incentives lead to over-investment in R&D even if efforts are strategic substitutes and enduce firms eventually to engage in this race; i.e. $x^g > x^* > x^c$ if $h < \frac{d}{2}$. The government seems to put a greater weight on the efficiency and consumer-surplus effects in order to induce price cutting in the product market, despite the fact that firms' strategic benefits from coordination remain unexploited.

7 Conclusion

Agent' incentives to carry out cost-reducing R&D are examined in a setting with R&D spillovers and product market competition. Moral hazard problems and risk-aversion of the part of the agent are at the heart of this analysis. R&D process is subject to uncertainty over the R&D-outputs and, thus, information asymmetries over the R&D-inputs exist. A linear principal-agent model is employed in which each principal is likely to offer a relative performance evaluation scheme whose performance measures are both own- and rival- firm cost reductions; each agent 'appropriates' some part of its rival's research. This paper argues that compensation schemes based on explicit performance comparisons filter out spillovers from the reward packages by penalizing an agent when the rival does better.

To understand the agent's behavior, we decompose the R&D incentives into three effects: the strategic, spillover and efficiency effect. The relative severity of these effects determines the agent's responses to the degree of spillovers and competition. This paper argues that, if agents' R&D efforts are strategic substitutes and the innovation process is not too costly, as spillovers increase, firms enter into a rat race. Thus, in highly competitive industries where firms intent to steal businesses from their rival and are engaged into the race, a fairly high level of effort is exerted burning up firms' profits. Cost-savings due to under-provision of incentives under information asymmetries may make firms better-off. In a sense, by delegating the R&D decisions in an asymmetric information world and even appointing high risk-averse agents, firms can committe themselves and change rival's responces in the proceeding stages of the game. Delegation can be used as a collusive device that mitigates the intensity of the race and strategic interactions.

Delegation as a self-commitment device is also valuable for Bertrand competitors. In Bertrand setting, firms respond aggressively to rival's action and thus, price competition is much more intensive than Cournot competition. Such firms may prefer an organization structure where the business and research teams are separated and agents abhor risk.

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A APPENDIX

A.1 Decomposition of R&D

■ **Unilateral decisions:** Firm i's net profits function has as $\pi_{net,i} = (p_i - c_i)\, q_i - w_i$ where $p_i\,(q_i, q_j)$ is the inverse demand function in the general case. The derivative of net profits with respect to own effort is given by

$$\frac{\partial \pi_{net,i}}{\partial x_i} = \frac{\partial \Pi_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \frac{\partial \Pi_i}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \Pi_i}{\partial c_i}\frac{\partial c_i}{\partial x_i} - w_i' \tag{12}$$

where

$$\frac{\partial \Pi_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} = \frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} q_i + (p_i - c_i)\,\frac{\partial q_i}{\partial x_i}$$

Given that the first-order condition of firm i's problem in the production stage has as $p_i + \frac{\partial p_i}{\partial q_i} q_i - c_i = 0$, the effects $(p_i - c_i)\,\frac{\partial q_i}{\partial x_i}$ and $\frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial x_i} q_i$ cancel each other out. Thus, our analysis is focused on the other effects of effort that drive the results.

To derive the form of $\frac{\partial q_j}{\partial x_i}$, we differentiate the first order conditions of both firms with respect to x_i and get the two-by-two system of equations:

$$\begin{pmatrix} 2\frac{\partial p_i}{\partial q_i} & \frac{\partial p_i}{\partial q_j} \\ \frac{\partial p_j}{\partial q_i} & 2\frac{\partial p_j}{\partial q_j} \end{pmatrix} \begin{pmatrix} \frac{\partial q_i}{\partial x_i} \\ \frac{\partial q_j}{\partial x_i} \end{pmatrix} = \begin{pmatrix} -\frac{1}{1-h^2} \\ -\frac{h}{1-h^2} \end{pmatrix}$$

Solving this system, it obtains:

$$\frac{\partial q_j}{\partial x_i} = \frac{1}{\Lambda\,(1-h^2)}\left(\frac{\partial p_j}{\partial q_i} - 2h\frac{\partial p_i}{\partial q_i}\right) \quad \text{and} \quad \frac{\partial q_i}{\partial x_i} = \frac{1}{\Lambda\,(1-h^2)}\left(h\frac{\partial p_i}{\partial q_j} - 2\frac{\partial p_j}{\partial q_j}\right)$$

where $\Lambda = 4\frac{\partial p_i}{\partial q_i}\frac{\partial p_j}{\partial q_j} - \frac{\partial p_j}{\partial q_i}\frac{\partial p_i}{\partial q_j}$. Hence, the decomposition in (12) can be rewritten as that in (9).

For a linear demand function, it is $\frac{\partial p_i}{\partial q_i} = -1$, $\frac{\partial p_j}{\partial q_i} = -d$, $\Lambda = 4 - d^2$. Given that $\frac{\partial \Pi_i}{\partial q_j} = -dq_i$ and $\frac{\partial \Pi_i}{\partial c_i} = -q_i$, the strategic, spillover and efficiency effect have respectively as

$$\frac{\partial \Pi_i}{\partial q_j}\frac{1}{\Lambda(1-h^2)}\frac{\partial p_j}{\partial q_i} = \frac{d^2 q_i}{(1-h^2)(4-d^2)}, -\frac{\partial \Pi_i}{\partial q_j}\frac{2h}{\Lambda(1-h^2)}\frac{\partial p_i}{\partial q_i} = \frac{-2dhq_i}{(1-h^2)(4-d^2)}, \frac{\partial \Pi_i}{\partial c_i}\frac{\partial c_i}{\partial x_i} = \frac{q_i}{1-h^2}$$

■ **Coordination in R&D:** When firms coordinate their actions, they consider the effect of effort on joint net profits, $\frac{\partial(\pi_{net,i}+\pi_{net,j})}{\partial x_i}$. Each firm i takes into account the three effects analyzed in the competitive case as well as the effect agent i's effort brings on firm j's profits:

$$\frac{\partial \pi_{net,j}}{\partial x_i} = \frac{\partial \Pi_j}{\partial q_j}\frac{\partial q_j}{\partial x_i} + \frac{\partial \Pi_j}{\partial q_i}\frac{\partial q_i}{\partial x_i} + \frac{\partial \Pi_j}{\partial c_j}\frac{\partial c_j}{\partial x_i}$$

As above, by choosing the the profit-maximizing level of output in the product market, the effect $\frac{\partial \Pi_j}{\partial q_j}\frac{\partial q_j}{\partial x_i}$ vanishes. Thus, for linear demand, the cross-profit effect has as:

$$\begin{aligned}\frac{\partial \pi_{net,j}}{\partial x_i} &= -\frac{\partial \Pi_j}{\partial q_i}\frac{2}{\Lambda(1-h^2)}\frac{\partial p_j}{\partial q_j} + \frac{\partial \Pi_j}{\partial q_i}\frac{h}{\Lambda(1-h^2)}\frac{\partial p_i}{\partial q_j} + \frac{\partial \Pi_j}{\partial c_j}\frac{\partial c_j}{\partial x_i} \\ &= \frac{2(2h-d)q_j}{(1-h^2)(4-d^2)}\end{aligned}$$

This effect is negative if, and only if, efforts are strategic substitutes, $h < \frac{d}{2}$.

A.2 Certain equivalent utility: truncated normal distribution

To keep things more general, we rearrange the terms of agent i's compensation (equation (4)) and denote as φ_{ii}, φ_{ij} the coefficients of $x_i + \eta_i$, $x_j + \eta_j$ respectively. The expected wage, then, becomes $w_i = \alpha_i + \varphi_{ii}x_i + \varphi_{ij}x_j$ and the agent's expected utility takes the form:

$$\begin{aligned}E\left\{U_i(w_i, x_i) \mid \eta_i, \eta_j \in \Theta\right\} &= E\left\{-e^{-r[w_i - \psi(x_i)]} \mid \eta_i, \eta_j \in \Theta\right\} \\ &= -e^{-r\left[\alpha_i + \varphi_{ii}x_i + \varphi_{ij}x_j - \psi(x_i)\right]} E\left\{e^{-r\left[\varphi_{ii}\eta_i + \varphi_{ij}\eta_j\right]} \mid \eta_i, \eta_j \in \Theta\right\} \\ &= -e^{-r\left[\alpha_i + \varphi_{ii}x_i + \varphi_{ij}x_j - \psi(x_i)\right]} E\left\{e^{-r\varphi_{ii}\eta_i} \mid \eta_i \in \Theta\right\} E\left\{e^{-r\varphi_{ij}\eta_j} \mid \eta_j \in \Theta\right\}\end{aligned}$$

given that η_i, η_j are independently distributed. It is also silently assumed that a constant term μ (> 0) is added at the agent's utility and moves the utility curve upward such that $E\left\{U_i(w_i, x_i) \mid \eta_i, \eta_j \in \Theta\right\} \geq 0$; the agent's reservation utility is normalized to zero.

It is $\eta \sim N(0, \sigma^2)$ where $\eta \in \Theta \equiv [-\theta, \theta]$, $-\infty < -\theta < \theta < +\infty$. The conditional density of η_i ,$\eta_i \sim N(0, \sigma^2)$, has as

$$f(\eta_i \mid \Theta) = \frac{\frac{1}{\sigma}\phi\left(\frac{\eta_i}{\sigma}\right)}{\Phi\left(\frac{\theta}{\sigma}\right) - \Phi\left(\frac{-\theta}{\sigma}\right)}, -\theta \leq \eta_i \leq \theta \text{ where } \phi\left(\frac{\eta_i}{\sigma}\right) = \frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{\eta_i}{\sigma}\right)^2} \quad (13)$$

$\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)$ is the probability of η_i falling into the internal $[-\theta,\theta]$, $-\infty<-\theta<\theta<+\infty$. The (unconditional) density of the random vector $\eta'=\begin{pmatrix}\eta_i & \eta_j\end{pmatrix}$ which follows a bivariate normal distribution takes the form:

$$f\left(\eta_i,\eta_j\right)=\frac{1}{\sigma}\phi\left(\frac{\eta}{\sigma}\right)\ =\frac{1}{2\pi\sigma^2}e^{-\frac{1}{2}\left[\left(\frac{\eta_i}{\sigma}\right)^2+\left(\frac{\eta_j}{\sigma}\right)^2\right]} \tag{14}$$

By the equations (13) and (14) and letting $\widehat{r}=-r$, we get:

$$\int_{-\theta}^{\theta}e^{\widehat{r}\varphi_{ii}\eta_i}f\left(\eta_i\right)d\eta_i=$$

$$\begin{aligned}
&= \frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta}e^{\widehat{r}\varphi_{ii}\eta_i}e^{-\frac{1}{2}\left(\frac{\eta_i}{\sigma}\right)^2}d\eta_i=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta}e^{-\frac{\left(\eta_i^2-2\sigma^2\widehat{r}\varphi_{ii}\eta_i\right)}{2\sigma^2}}d\eta_i=\\
&= \frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta}e^{-\frac{\left[\eta_i^2-2\eta_i\left(\sigma^2\widehat{r}\varphi_{ii}\right)+\left(\sigma^2\widehat{r}\varphi_{ii}\right)^2-\left(\sigma^2\widehat{r}\varphi_{ii}\right)^2\right]}{2\sigma^2}}d\eta_i=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta}e^{-\frac{\left(\eta-\sigma^2\widehat{r}\varphi_{ii}\right)^2}{2\sigma^2}}e^{\frac{\left(\sigma^2\widehat{r}\varphi_{ii}\right)^2}{2\sigma^2}}d\eta_i=\\
&= e^{\frac{\widehat{r}^2\varphi_{ii}^2\sigma^2}{2}}\frac{1}{\sigma\sqrt{2\pi}}\int_{-\theta}^{\theta}e^{-\frac{\left(\eta_i-\sigma^2\widehat{r}\varphi_{ii}\right)^2}{2\sigma^2}}d\eta_i=e^{\frac{\widehat{r}^2\varphi_{ii}^2\sigma^2}{2}}\int_{-\theta}^{\theta}\frac{1}{\sigma}\phi\left(\frac{\eta_i-\sigma^2\widehat{r}\varphi_{ii}}{\sigma}\right)d\eta_i=\\
&= e^{\frac{\widehat{r}^2\varphi_{ii}^2\sigma^2}{2}}\left[\Phi\left(\frac{\theta-\sigma^2\widehat{r}\varphi_{ii}}{\sigma}\right)-\Phi\left(\frac{-\theta-\sigma^2\widehat{r}\varphi_{ii}}{\sigma}\right)\right]
\end{aligned}$$

and

$$E\left\{e^{r\varphi_{ii}\eta_i}\mid\eta_i\in\Theta\right\}=\frac{\int_{-\theta}^{\theta}e^{r\varphi_{ii}\eta_i}f\left(\eta_i\right)d\eta}{\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)}=e^{\frac{r^2\varphi_{ii}^2\sigma^2}{2}}\frac{\Phi\left(\frac{\theta-\sigma^2r\varphi_{ii}}{\sigma}\right)-\Phi\left(\frac{-\theta-\sigma^2r\varphi_{ii}}{\sigma}\right)}{\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)}=e^{\frac{r^2\varphi_{ii}^2\sigma^2}{2}}\Phi_{\varphi_{ii}}$$

where $\Phi_{\varphi_{ii}}=\frac{\Phi\left(\frac{\theta-\sigma^2\widehat{r}\varphi_{ii}}{\sigma}\right)-\Phi\left(\frac{-\theta-\sigma^2\widehat{r}\varphi_{ii}}{\sigma}\right)}{\Phi\left(\frac{\theta}{\sigma}\right)-\Phi\left(\frac{-\theta}{\sigma}\right)}$.

The agent's utility becomes:

$$E\left\{U_i\left(w_i,x_i\right)\mid\eta_i,\eta_j\in\Theta\right\}=-\Phi_{\varphi_{ii}}\Phi_{\varphi_{ij}}e^{-r\left[\alpha_i+\varphi_{ii}x_i+\varphi_{ij}x_j-\frac{r}{2}\left(\varphi_{ii}^2+\varphi_{ij}^2\right)\sigma^2-\psi(x_i)\right]}=-\Phi_{\varphi_{ii}}\Phi_{\varphi_{ij}}e^{-r\left[\widehat{w}(x_i)\right]}$$

where $\widehat{w}\left(x_i\right)$ is the certain equivalent of agent's utility. Given that $\Phi_{\varphi_{ii}}$ and $\Phi_{\varphi_{ij}}$ are positive, agent i's optimization problem is equivalent to choose $x_i\in\arg\max\widehat{w}\left(x_i\right)$. Thus, the desired property of an exponential utility function that the incentive parameters of a linear contract can be calculated applies even if η_i,η_j follow a truncated normal distribution.

A.3 Proof of proposition 1: Solution of the delegation R&D-game

■ The certain equivalent of agent i's utility takes the mean-variance form

$$E\left[U_i\left(w_i,x_i\right)\right]=\alpha_i+\beta_ix_i-\frac{1}{2}r\beta_i^2\sigma^2-\frac{k}{2}x_i^2 \tag{15}$$

and the optimal effort is

$$x_i = \frac{\beta_i}{k} \tag{16}$$

Given that the agent's problem is strictly concave in x_i, we can use the first-order approach and replace the constraint IC_i in the principals' problem with equation (16).

■ We solve the delegation R&D-game by considering corner and interior solutions. No or some R&D might be an optimal choice. The first-order condition of the agent i's problem can be written as

$$x_i \left(\frac{\beta_i}{k} - x_i \right) = 0 \tag{17}$$

where $\frac{\varphi_{ii}}{k} \geq x_i \geq 0$, and the Lagrange function of principal i's problem becomes

$$L_i = \Pi_i - (\alpha_i + \beta_i x_i) + \lambda_i \left\{ x_i \left(\frac{\beta_i}{k} - x_i \right) \right\} + \mu_i \left(\alpha_i + \beta_i x_i - \frac{1}{2} r \beta_i^2 \sigma^2 - \frac{k}{2} x_i^2 \right) \tag{18}$$

Omitting details, the condition with respect to α_i gives:

$$-1 + \mu_i = 0 \tag{19}$$

or $\mu_i = 1$. It implies that the individual rationality constraint (IR_i) is binding at the optimum. The fixed salary component α_i is such that induces agent participation at least cost; setting the equation (**??**) equal to zero, α_i is derived. For a given level of w_i, lower base payments have to be compensated with higher variable parts of the wage. Putting all things together, the agent's payment takes the form $w_i(\beta_i) = \frac{1}{2} r \beta_i^2 \sigma^2 + \frac{k}{2} x_i^2$ implying that each agent is rewarded for the cost-of-effort she incurs and the risks she bears. Thus, the Kuhn-Tucker conditions of i's and j's problem with respect to x_i and x_j have respectively as

$$\frac{\partial L_i}{\partial x_i} \leq 0 \Rightarrow 2q_i \frac{\partial q_i}{\partial x_i} + \lambda_i \left(\frac{\beta_i}{k} - x_i \right) - \lambda_i x_i - k x_i \leq 0 \tag{20}$$

$$\frac{\partial L_j}{\partial x_j} \leq 0 \Rightarrow 2q_j \frac{\partial q_j}{\partial x_j} + \lambda_j \left(\frac{\beta_j}{k} - x_j \right) - \lambda_j x_j - k x_j \leq 0 \tag{21}$$

No innovation is not a solution. If no R&D efforts are exerted, equation (20) at $(x_i, x_j) = (0, 0)$ yields

$$2q_i \frac{\partial q_i}{\partial x_i} + \lambda_i \frac{\beta_i}{k} \leq 0$$

which is not true since $q_i(0,0) > 0$, $\frac{\partial q_i}{\partial x_i} > 0$ at $(x_i, x_j) = (0, 0)$, $\lambda_i \geq 0$ and $\beta_i \geq 0$.

Innovation by only one firm is not a solution. Let us assume that only j does some R&D; i.e. $x_i = 0$, $x_j > 0$. It implies that $\beta_i = 0$ since no incentives are provided. If j invests in R&D, $x_j > 0$, by equation (17), it is $\frac{\beta_j}{k} - x_j = 0$. Thus, equations (20) and (21) become respectively

$$2q_i \frac{\partial q_i}{\partial x_i} \leq 0 \Rightarrow 2(2-dh) \frac{(A-\overline{c})(2-d)(1-h^2)+(2h-d)x_j}{(4-d^2)^2(1-h^2)^2} \leq 0 \tag{22}$$

$$2q_j \frac{\partial q_j}{\partial x_j} - (k+\lambda_j)x_j = 0 \tag{23}$$

If $h > \frac{d}{2}$, equation (22) is violated. If $h < \frac{d}{2}$, it suffices to show that equation (22) is not valid when x_j takes its highest value, $x_j = \left(1-\overline{h}^2\right)\overline{c}$:

$$2(2-dh)\frac{(A-\overline{c})(2-d)+(2h-d)\overline{c}}{(4-d^2)^2(1-h^2)} \leq 0 \Rightarrow A(2-d) \leq 2\overline{c}(1-h)$$

Assumption (O.1), in expected terms, guarantees that this inequality can not hold.

One could also check the following. Given that $\lambda_j = kr\sigma^2\beta_j$ or $\lambda_j = k^2r\sigma^2x_i$ in this case, equation (23) implies

$$x_j = \frac{2(A-\overline{c})(2-d)(1-h^2)(2-dh)}{(4-d^2)^2(1-h^2)^2k_r - 2(2-dh)^2}$$

Substituting x_j into (22), we have

$$1 \leq \frac{2(d-2h)(2-dh)}{(4-d^2)^2(1-h^2)^2k_r - 2(2-dh)^2} \Rightarrow k_r \leq \frac{2(2-dh)}{(4-d^2)(2+d)(1-h^2)(1-h)}$$

This inequality can not hold given assumption (O.2).

Unique interior solution in Γ. If both firms innovate, $x_i > 0$ and $x_j > 0$, by equations (20) and (21), we haveN

$$2q_j \frac{\partial q_j}{\partial x_j} - (k+\lambda_j)x_j = 0 \tag{24}$$

In addition, the Kuhn-Tucker conditions of i's problem with respect to β_i and λ_i are respectively

$$\frac{\lambda_i}{k} - r\beta_i\sigma^2 = 0 \tag{25}$$

$$\frac{\beta_i}{k} - x_i = 0 \tag{26}$$

Due to moral hazard and agents' risk-aversion, the modified Borch rule applies, yielding $\lambda > 0$ and equation (26) is binding. It denotes that the optimal insurance is distorted and there is a trade-off between effort provision and risk.[41] Given the equations (**??**), (26) and (**??**), each principal anticipates the rival's actions and derives the optimal incentive

[41] If $\lambda = 0$, the risk-averse agents would be fully insured under the first-best contracts; optimal coinsurance (Borch) rule.

parameters as in Proposition 1.

This solution is also the unique equilibrium of the delegation R&D game. It suffices to show that the slope of i's R&D-reaction function lies in the range $(-1, 1)$ for all $x_j \in \left[0, \left(1-\overline{h}^2\right)\overline{c}\right]$. By equation (8), we have

$$RF_i'(x_j) = \frac{2(2-dh)(2h-d)}{(4-d^2)^2(1-h^2)^2 k_r - 2(2-dh)^2}$$

Thus, uniqueness of equilibrium requires

$$\frac{2(2-dh)}{(4-d^2)^2(1-h^2)^2}[2-dh+|d-2h|] < k_r$$

Assumption (O.2) guarantees that the above inequality will be satisfied in the entire parameter space.

A.4 Proof of proposition 2

The effect of the unit cost of R&D over the optimal net profits, $\frac{\partial \pi^*_{net}}{\partial k_r}$, has as:

$$\frac{\partial \Pi^*}{\partial k_r} = 2q^* \frac{1}{(2+d)(1-h)} \frac{\partial x^*}{\partial k_r} \quad \text{and} \quad \frac{\partial w^*}{\partial k_r} = \frac{1}{2}x^{*2} + k_r x^* \frac{\partial x^*}{\partial k_r}$$

Given that the relationship between effort and risk is negative, $\frac{\partial x^*}{\partial k_r} < 0$, the equilibrium production profits decrease with k_r, $\frac{\partial \Pi^*}{\partial k_r} < 0$. The effect of k_r on the optimal wage though is ambiguous. The direct effect over the agent's payment is positive, $\frac{1}{2}x^{*2}$, while the indirect effect is negative, $k_r x^* \frac{\partial x^*}{\partial k_r} < 0$. Under Assumptions (O.1) and (O.2), it is $\frac{\partial \pi^*_{net}}{\partial k_r} > 0$ if, and only if, $\frac{\partial \Pi^*}{\partial k_r} - \frac{1}{2}x^{*2} < -\left(k_r x^* \frac{\partial x^*}{\partial k_r}\right)$. It is so if, and only if,

$$k_r < \frac{2(2-dh)^2}{\xi(1+h)[2(1-d)+h(4-d)]}; \tag{27}$$

where

$$\xi \equiv \left(4-d^2\right)(2+d)(1-h)^2$$

It is

$$\frac{\partial \pi^*_{net}}{\partial k_r} = \frac{2(A-\overline{c})^2(1-h)^2(2-dh)}{\Omega^3}\left[2(2-dh)^2 - \xi(1+h)[2(1-d)+h(4-d)]k_r\right]$$

Note that if $h > \frac{d}{2}$, the term in the right hand side of condition (27) is less than unity, implying that (27) is violated and $\frac{\partial \pi^*_{net}}{\partial k_r} < 0$. (27) holds only in the regime where $h < \frac{d}{2}$: by assumption (O.2), it must be $\frac{A}{\overline{c}}\frac{2(2-dh)}{\xi(1+h)} < \frac{2(2-dh)^2}{\xi(1+h)[2(1-d)+h(4-d)]}$ or $\frac{A}{\overline{c}} < \frac{2-dh}{2(1-d)+h(4-d)}$. Using (O.1), by transitivity, we have: $\frac{2(1-h)}{2-d} < \frac{2-dh}{2(1-d)+h(4-d)}$ or $(2h-d)[2-(4-d)h] < 0$ which holds only if efforts are strategic substitutes, $h < \frac{d}{2}$. In the regime where (27) is satisfied, firms prefer to act under information asymmetries.

A.5 Proof of corollary 3

Effects of h on x^*. Differentiating equation (9) with respect to h, we get:

$$\frac{d\left(\partial \pi_{net,i}/\partial x_i\right)}{dh} = 0 \;\Rightarrow\; \frac{\partial\left(\partial \pi_{net,i}/\partial x_i\right)}{\partial h} + \frac{\partial^2 \pi_{net,i}}{\partial x_i^2}\frac{dx_i}{dh} = 0 \tag{28}$$

where

$$\frac{\partial^2 \pi_{net,i}}{\partial x_i^2} = -\frac{B}{\left(4-d^2\right)^2\left(1-h^2\right)^2} \tag{29}$$

and $B \equiv \left(4-d^2\right)^2\left(1-h^2\right)^2 k_r - 2\left(2-dh\right)^2$. $(A.2)$ guarantees that B is positive and net profits function is concave in x_i, $\frac{\partial^2 \pi_{net,i}}{\partial x_i^2} < 0$. Hence, the derivative $\frac{dx_i}{dh}$ depends exclusively on the sign of $\frac{\partial(\partial \pi_{net,i}/\partial x_i)}{\partial h}$. To calculate this term, we substitute x_j in equation (9) with the optimal value x^*, differentiate with respect to h and then, substitute x_i with x^* resulting in

$$\frac{\partial\left(\partial \pi_{net,i}/\partial x_i\right)}{\partial h} = \frac{2\left(A-\bar{c}\right)B\left[2\left(2-dh\right)^2 + \xi\left(-d+4h-dh^2\right)k_r\right]}{\left(4-d^2\right)^2\left(1-h^2\right)^2\Omega^2} \tag{30}$$

The term $\frac{\partial(\partial \pi_{net,i}/\partial x_i)}{\partial h}$ shows the changes in the marginal profitability of effort due to h. Spillovers intensify all the effects: i.e. the strategic effect: $\frac{d^2}{(4-d^2)(1-h^2)}\left(\frac{2h}{1-h^2}q_i + \frac{\partial q_i}{\partial h}\right) > 0$, the spillovers effect: $\left|\frac{-2d}{(4-d^2)(1-h^2)}\left(\frac{1+h^2}{1-h^2}q_i - h\frac{\partial q_i}{\partial h}\right)\right| > 0$, the efficiency effect: $\frac{1}{1-h^2}\left(\frac{2h}{1-h^2}q_i + \frac{\partial q_i}{\partial h}\right) > 0$ since $\frac{\partial q_i}{\partial h} > 0$. By equations (28), (29) and (30), we get:

$$\frac{dx_i}{dh} = \frac{2\left(A-\bar{c}\right)}{\Omega^2}\left[2\left(2-dh\right)^2 - \xi\left(-d+4h-dh^2\right)k_r\right]$$

The optimal effort level increases with h, $\frac{\partial x^*}{\partial h} < 0$, in the regime where the spillover effect becomes relatively more severe compared to the strategic and efficiency effects due to h. It is so if, and only if,

$$h < \frac{2-\left(4-d^2\right)^{1/2}}{d} \tag{31}$$

and

$$\frac{2\left(2-dh\right)^2}{\xi\left(-d+4h-dh^2\right)} < k_r \tag{32}$$

do *not* apply. Note that conditions (31), (32) can be satisfied only in the parameter space where efforts are strategic substitutes since $\frac{2-\left(4-d^2\right)^{1/2}}{d} < \frac{d}{2}$ for all $d \in (0,1]$. As d approaches zero, given that $h \geq 0$, by the l'Hôpital rule, we have $\lim_{d\to 0^+}\left\{\frac{2-\left(4-d^2\right)^{1/2}}{d}\right\} = \lim_{d\to 0^+}\left\{\frac{d}{\left(4-d^2\right)^{1/2}}\right\} = 0$ implying that (31) is violated. Both assumptions should also be satisfied. (O.2) (in expected terms) implies that $\frac{A}{\bar{c}}\frac{2(2-dh)}{\xi(1+h)} < k_r$; this is the lower bound for the unit cost of R&D which guarantees that the post-innovation costs will be positive. For

(32) to be valid requires $\frac{A}{\bar{c}}\frac{2(2-dh)}{\xi(1+h)} < \frac{2(2-dh)^2}{\xi(-d+4h-dh^2)}$ or $\frac{A}{\bar{c}} < \frac{(2-dh)(1+h)}{d-4h+dh^2}$. (O.1) also states that $\frac{2(1-h)}{2-d} < \frac{A}{\bar{c}}$. By transitivity, it is $\frac{2(1-h)}{2-d} < \frac{(2-dh)(1+h)}{d-4h+dh^2}$ which holds for all $d \in (0,1]$ and those h that satisfy (31).

A.6 Proof of corollary 4

Effects of d on x^*. Similarly, we derive the form:

$$\frac{\partial\left(\partial\pi_{net,i}/\partial x_i\right)}{\partial d} = -\frac{4\left(A-\bar{c}\right)\left(1-h\right)B\left[2-3d+\left(2-d+d^2\right)h\right]k_r}{\left(4-d^2\right)\left(2-d\right)\left(1+h\right)\Omega^2} \tag{33}$$

The term $\frac{\partial(\partial\pi_{net,i}/\partial x_i)}{\partial d}$ shows the changes in the effects due to d. Competition intensifies the strategic effect, $\frac{d}{(4-d^2)(1-h^2)}\left(\frac{8}{4-d^2}q_i + d\frac{\partial q_i}{\partial d}\right) > 0$, and the spillover effect, $\left|\frac{-2h}{(4-d^2)(1-h^2)}\left(\frac{4+d^2}{4-d^2}q_i + d\frac{\partial q_i}{\partial d}\right)\right| > 0$, while mitigates the efficiency effect, $\frac{1}{(1-h^2)}\frac{\partial q_i}{\partial d} < 0$, since $\frac{\partial q_i}{\partial d} < 0$ and $q_i > \left|\frac{\partial q_i}{\partial d}\right|$. Thus, the derivative $\frac{dx^*}{dd}$ increases in the regime where the strategic effect becomes relatively more severe compared to the spillover and efficiency effects. By equations (28), (29) and (33), the derivative of x_i, at the optimum, with respect to d has as:

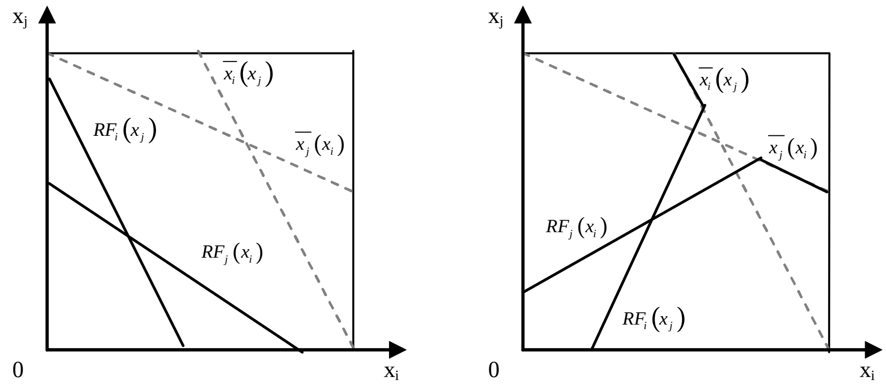
$$\frac{\partial x_i}{\partial d} = -\frac{4k_r}{\Omega^2}\left(A-\bar{c}\right)\left(2+d\right)\left(1-h\right)^2\left(1-h^2\right)\left[2-3d+\left(2-d+d^2\right)h\right]$$

Effort increases with d, $\frac{\partial x_i}{\partial d} > 0$, if, and only if, $2-3d+\left(2-d+d^2\right)h < 0$ or

$$d > \frac{3+h-\left(9-2h-7h^2\right)^{1/2}}{2h} \tag{34}$$

Note that if no spillovers occur, $h=0$, it is $\frac{\partial x_i}{\partial d} > 0$ if, and only if, $d > \frac{2}{3}$; by the l'Hôpital rule, it is $\lim_{h\to 0^+}\left\{\frac{3+h-\left(9-2h-7h^2\right)^{1/2}}{2h}\right\} = \lim_{h\to 0^+}\left\{\frac{1}{2}\left(1+\frac{1+7h}{\left[(1-h)(9+7h)\right]^{1/2}}\right)\right\} = \frac{2}{3}$. For $h>0$, the derivative $\frac{\partial x_i}{\partial d}$ can be positive only if efforts are strategic substitutes, $2h < d$. This claim requires $\frac{3+h-\left(9-2h-7h^2\right)^{1/2}}{2h} > 2h$ or $\frac{3+h-\left(9-2h-7h^2\right)^{1/2}-4h^2}{2h} > 0$ which is true for all $h \in \left(0,\overline{h}\right)$ and $\lim_{h\to 0^+}\left\{\frac{3+h-\left(9-2h-7h^2\right)^{1/2}-4h^2}{2h}\right\} = \lim_{h\to 0^+}\left\{\frac{1}{2}\left(1-2h+\frac{1+7h}{\left[(1-h)(9+7h)\right]^{1/2}}\right)\right\} = \frac{2}{3}$.

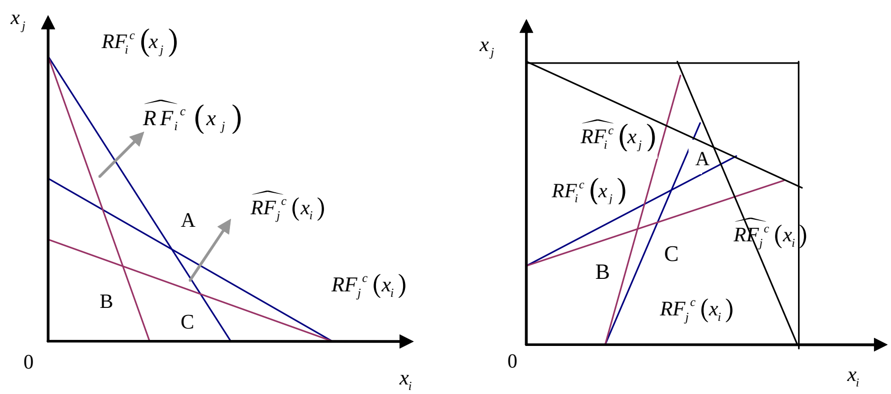
Figure 2. Reaction functions & feasibility lines



$2a$ $2b$

Figures $2a$ and $2b$ show the reaction functions, $RF_i\left(x_j\right)$, $RF_j\left(x_i\right)$, and the feasibility lines, $\overline{x_i}\left(x_j\right)$, $\overline{x_i}\left(x_j\right)$, when efforts are strategic substitutes and strategic complements respectively. The feasibility lines bound the action space.

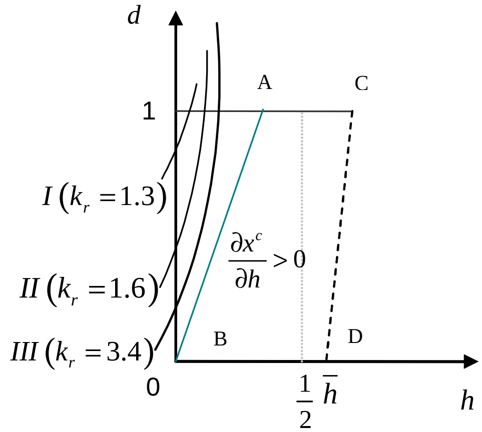
Figures $3a, 3b$. Reaction functions; performance vs relative performance evaluations

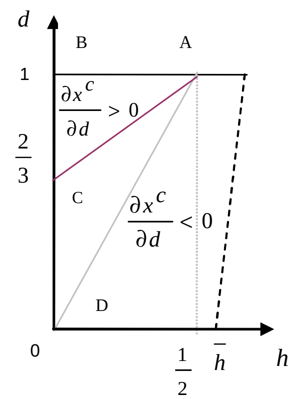


Figures $3a$ and $3b$ show the R&D-reaction functions and the equilibrium outcomes of the delegation R&D game when principals make use of two-piece and one-piece rate contract. $RF_i\left(x_j\right)$ and $RF_j\left(x_i\right)$ present the reaction functions when principals use relative performance evaluation. Best responses lead to point A. When principals use performance evaluation, their reaction functions are $\widehat{RF}_i\left(x_j\right)$ and $\widehat{RF}_j\left(x_i\right)$ whose intersection is at point B. The effort levels that correspond to point C will be chosen, if principal j uses performance evaluation and principal i uses relative performance evaluation. If efforts are strategic complements (Figure $3a$), best-responses lead both firms to use relative performance evaluations (point A) and neither firm has incentives to deviate. By imposing some rivalry in compensation, higher profits are obtained for both firms. Figure $3b$ shows the R&D-reaction curves when efforts are strategic substitutes.

By using these two forms of compensation, principals seem to face the prisoners' dilemma in the delegation R&D game. If principal j compensates the agent with a performance evaluation scheme, i's best response is to use a relative performance evaluation scheme (point C). By doing so, firm i exploits the information conveyed by both performance measures and can better monitor the agent. However, firms' strategies lead them to stand at point A that corresponds to the equilibrium where each agent's reward is conditioned on how well she performs compared to another.

Figure $4a$. The effect of h on x^* Figure $4b$. The effect of d on x^*





Figures $4a$ and $4b$ show the parameter space where the optimal effort level increases with h, $\frac{\partial x^*}{\partial h}$, and d, $\frac{\partial x^*}{\partial d}$, respectively. Figure $4a$: Efforts increase with h in the (d, h) space at the right hand side of the lines I, II, III that have been drawn for different values of k_r such that to satisfy the equation $k_r = \frac{2(2-dh)^2}{(4-d^2)(2+d)(1-h)^2(d-4h+dh^2)}$; Line AB: $\frac{4h}{1+h^2} = d$. Figure $4b$: Efforts increase with d in the space ABC; Line AC: $h = \frac{3d-2}{2-d+d^2}$; Line AD: $h = \frac{d}{2}$.