Bureau d'économie théorique et appliquée (BETA)
UMR 7522

Documents de travail

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Document de Travail n° 2007–**26**

Juillet 2007

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Relative Performance Evaluation, Risk Aversion and Entry*

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June 28, 2007

Abstract

We study the relations between compensation schemes and risk aversion of managers in a strategic framework. We first show that the use of relative performance evaluation (RPE) in compensation contracts reduces the equilibrium profits of Cournot firms if managers are not too risk averse. Second, we introduce entry issues in our model. We then show that forbidding RPE can favour competition.

Key words: Executive Compensation, Relative Performance Evaluation, Moral Hazard, Market Structure
JEL Classification: D43, D82, D86

*We want to thank for their help Patrick Delamirande, Sandrine Spaeter and all seminar participants at the 46th SCSE congress, at the Journée du BETA and at the 55th AFSE annual congress. All errors are our own.
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1 Introduction

"In a setting with many interdependent principal-agent pairs, payments according to relative performance may therefore have strategic, as well as informational advantages." Vickers [1985], p.145.

In this article we study the effects of evaluating performance of managers on market equilibria. We consider two evaluation schemes: Relative Performance Evaluation (RPE) and Absolute Performance Evaluation (APE). By RPE we mean that a manager's compensation depends not only on the profit of his (or her) own firm, but on the profit of competitive firms as well.

The literature provides two arguments in favor of such compensation scheme. First, in the spirit of contract theory [Harris and Raviv, 1979, Holmstrom, 1982, Mookherjee, 1984], RPE increases the available information and hence improves the efficiency (from the point of view of the principal). The underlying intuition is straightforward; since the contract or the compensation scheme embeds more information, it is easier for a principal to induce the appropriate level of effort. It follows that RPE schemes tend to implement more efficient outcomes. Second, following Vickers [1985], another branch of the literature emphasises the strategic effect of the RPE. By introducing negatively the other firms' profits, this compensation scheme gives a strong incentive to the managers to choose the quantity that maximizes the firms' profits.

The theoretical effects of compensation and evaluation schemes on market equilibria have already been studied. Salas Fumás [1992] analyses the implications of RPE based compensation schemes.[1] He shows that, in Cournot competition, the two effects described above shape the compensation schemes in the same way. The effects induce firms to introduce a negative relation between the manager's compensation and the profit of the competitive firms. If firms compete through prices, the results are less clear. At equilibrium, compensation schemes may increase with the rival firm's profit. In that case, principals wish to curtail managers from competing aggressively.[2]

[1] Salas Fumás [1992] is our main reference. For other papers on incentives in firms, see Prendergast [1999].

[2] This result can be found both in Salas Fumás [1992] and in Aggarwal and Samwick [1999a].

These theoretical findings have been challenged in the empirical literature. Jensen and Murphy [1990], Barro and Barro [1990] Janakiraman et al. [1992], Joh [1999], Aggarwal and Samwick [1999b], Garvey and Milbourn [2003] either find no evidence, small evidences, or even the reverse relationship between compensation and competitors' performance. In contrast, Antle and Smith [1986], Gibbons and Murphy [1990], Murphy [1999], Bannister and Newman [2003] or Bannister et al. [2004] find some empirical evidence in favor of RPE. In a recent paper, Albuquerque [2006] argues that previous studies have failed to detect RPE because they relied on a misspecified peer group. She also provides convincing empirical arguments in favor of RPE.

In the rest of the paper we consider a simple setting in which RPE schemes are implemented at equilibrium. We argue that, from the point of view of the principals, these two effects then lead to an inefficient allocation. More precisely, if managers are not too much risk averse, the competing principals would be better off if RPE compensation schemes were forbidden.

We then apply the latter result to an extended version of the model in which we consider entry. We show that RPE schemes tend to reduce entry when the risk aversion of the managers is relatively low. If firms are allowed to use RPE compensation schemes, and if managers are not too risk averse, the equilibrium profits are low compared to profits when only APE schemes are allowed. Hence, under the same conditions, a firm will hesitate to enter a market if RPE compensation schemes are allowed, but it will enter if they are not.

We conclude that the shape of compensation schemes may have interesting implications in term of competition policy. By allowing or prohibiting RPE, a government may favor or deter competition.

The paper is organized as follows. In the next section we outline the model. In section 3 we study the game played by two firms. In section 4 we introduce entry issues into the model. Section 5 concludes. All proofs are presented in an appendix.

2 The Model

Our model is based on those proposed by Salas Fumás [1992] and Aggarwal and Samwick [1999a]. However we restrict attention to Cournot competition with homogeneous goods. These restrictions allow us to obtain closed form solutions from which we show the existence of an equilibrium.

We consider a game with four players, two firms and two managers.

Each firm (or principal) i ($i = 1,2$) hires exactly one manager (or agent). A manager, when employed by the firm i, chooses the quantity q_i and makes an effort e_i which is costly to him.

The gross profits of firm i are:

$$\pi_i = (1 - q_i - q_j)q_i + e_i + \varepsilon \qquad i \neq j \qquad i,j = 1,2 \tag{1}$$

where ε is a normally distributed random variable with expectation 0 and variance σ^2.

To simplify the analysis, we assume that the two firms are sufficiently similar to be affected in the same manner by the shock ε. Moreover, we assume that ε follows the standard normal law:

$$E(\varepsilon) = 0 \text{ and } \sigma = 1 \Rightarrow E(\pi_i) = (1 - q_i - q_j)q_i + e_i \text{ and } Var(\pi_i) = 1. \tag{2}$$

Finally, we assume that preferences of managers can be represented by an exponential utility function: $u(y_i, e_i) = -\exp^{-r[y_i - e_i^2/2]}$, where r is the absolute risk aversion, y_i is the compensation, and $e_i^2/2$ is the cost of an effort e_i. We assume that firms (more precisely the owners of the firms) have linear preferences, and hence are risk neutral.

3 Equilibrium Without Entry

Contracts are incomplete in two ways. First, the managers' efforts are unobserved, so that compensation schemes are not contingent on them. Second, quantities are not contractible. It follows that principals can only offer contracts contingent on the profits, which are assumed to be observed by all the players.

Following Salas Fumás [1992], we consider linear compensation schemes.[3] In formal terms:

$$y_i = \alpha_i + \beta_i(\pi_i + \mu_i \pi_j) \qquad i \neq j \qquad i, j = 1, 2 \tag{3}$$

where $\mu_i \in]-1, 0]$ is the weight of the profits of the competitive firm in the compenstion scheme.[4] The quantity $\pi_i + \mu_i \pi_j$ can be interpreted as the relative performance of the firm i. The variables α_i and β_i are two coefficients that complete the compensation scheme.

Principals, who are the owners of the firms, maximize the expected profit of the firm minus the compensation given to their own agent. In formal terms, principal i's program is:

$$\max_{q_i, e_i, \alpha_i, \beta_i, \mu_i} E(\pi_i - y_i), \tag{4}$$

with

$$(q_i, e_i) \in \arg\max_{q_i, e_i} E\left[-\exp^{-r\left[y_i - e_i^2/2\right]}\right], \tag{5}$$

and

$$E\left[-\exp^{-r\left[y_i - e_i^2/2\right]}\right] \geq -\exp^{-r\bar{y}}, \tag{6}$$

where $-\exp^{-r\bar{y}}$ is the reservation utility of an agent: $\bar{y}$ is the competitive market wage. Since the agent is free to participate, his/her expected utility must be at least equal to the utility that would obtained in the market. The participation constraint (6) ensures that this the case. Moreover, principal i does not observe the agent's effort e_i or the output q_i, so that these two quantities must be consistent with the agent's wishes, i.e. they must be incentive compatible. This requirement is formalized by the condition (5).

[3]Holmstrom and Milgrom [1987] argue in favor of linear contracts in a single-principal single-agent model.

[4]If we set endogenously $\mu_i = 0$, the compensation scheme is said to be an Absolute Performance Evaluation (APE).

The timing of the game is as follows. First, the two principals announce simultaneously and publicly their compensation schemes. Second, the agents choose non-cooperatively their effort e_i and the quantity q_i. Then the uncertainty is realized, and the players (principals and agents) get their payoffs.

We solve the game backward, and characterize a sub-game perfect equilibrium. Hence we start at the last stage of the game, namely the game played by the agents.

The wage y_i follows a normal law, maximizing an exponential utility with a parameter r is equivalent to maximizing the linear Markowitz function with parameter $r/2$. In our case, this is equivalent to maximizing certainty equivalent, which is denoted:

$$C_i = E(y_i) - \frac{1}{2}e_i^2 - \frac{r}{2}Var(y_i). \tag{7}$$

From (2), we can deduce that:

$$E(y_i) = \alpha_i + \beta_i[(1 - q_i - q_j)q_i + e_i + \mu_i((1 - q_j - q_i)q_j + e_j)] \tag{8}$$

and

$$Var(y_i) = \beta_i^2(1 + \mu_i)^2. \tag{9}$$

As a consequence, the agent's program can be written as

$$\max_{q_i, e_i} \alpha_i + \beta_i[(1 - q_i - q_j)q_i + e_i + \mu_i(\left(1 - q_j - q_i\right) q_j + e_j)] - \frac{1}{2}e_i^2 - \frac{r}{2}\beta_i^2(1 + \mu_i)^2. \tag{10}$$

For this convex program, we can find explicit solutions for e_i and q_i:

$$q_i^* = \frac{1 - \mu_i}{4 - (1 + \mu_i)\left(1 + \mu_j\right)}, \tag{11}$$

$$e_i^* = \beta_i. \tag{12}$$

Since the parameter r enters expression (10) only in an additive term that is independent of e_i and q_i, the equilibrium quantities q_i^* and e_i^* are independent of r. Hence at this stage, the sub-game equilibrium would be exactly the same if the agents were risk neutral.

We now analyse the first stage of our game.

Each principal chooses a contract that gives no rent to its agent. In other words, each principal chooses a contract such that $E(y_i^*) - \frac{1}{2}e_i^{*2} - \frac{r}{2}Var(y_i^*) = \bar{y}$. The principals program can be written:

$$\max_{\beta_i,\mu_i}(1-q_i^*-q_j^*)q_i^*+e_i^*-\bar{y}-\frac{1}{2}e_i^{*2}-\frac{r}{2}\beta_i^2(1+\mu_i)^2, \tag{13}$$

and after some simplifications, this gives:

$$\max_{\beta_i,\mu_i}\frac{(\mu_i-1)(\mu_i\mu_j-1)}{(\mu_i\mu_j+\mu_i+\mu_j-3)^2}+\beta_i-\frac{\beta_i^2}{2}-\frac{r}{2}\beta_i^2(\mu_i+1)^2. \tag{14}$$

We solve this problem in two steps. First, the optimal value of β_i is obtained from the first order conditions. We obtain

$$\beta_i^* = \frac{1}{1+r(1+\mu_i)^2}. \tag{15}$$

Second, we plug the value of β_i^* into the objective function, which then depends only on μ_i and μ_j:

$$B_i = \frac{(\mu_i-1)(\mu_i\mu_j-1)}{(\mu_i\mu_j+\mu_i+\mu_j-3)^2}-\bar{y}+\frac{1}{2(1+r(1+\mu_i)^2)}. \tag{16}$$

The first order condition is

$$\frac{(\mu_j-1)\left(3\mu_i\mu_j-\mu_i-\mu_j-1\right)}{\left(\mu_i+\mu_j+\mu_i\mu_j-3\right)^3}-\frac{r(\mu_i+1)}{\left(r(\mu_i+1)^2+1\right)^2}=0. \tag{17}$$

Since the game is symmetric, we consider symmetric equilibria only. Hence, an equilibrium is characterized by

$$\frac{3\mu^*+1}{(\mu^*+3)^3(\mu^*-1)}-\frac{r(\mu^*+1)}{\left(r(1+\mu^*)^2+1\right)^2}=0. \tag{18}$$

Although r is expressed below as a function of μ^*, it would be necessary to solve a fifth degree polynomial equation to revert this relation.

This relationship is close to the one obtained by Aggarwal and Samwick [1999a]. Though we are able to infer a one-to-one relation between μ^* and r. This result allows us to show the existence and uniqueness of the symmetric Nash equilibrium. We believe this has not previously been proved in this class of models.

Specifically, we have

$$r = F(\mu^*) = \frac{\mu^{*4} + 8\mu^{*3} + 12\mu^{*2} - 8\mu^* - 29 + G(\mu^*)}{2(3\mu^* + 1)(\mu^* + 1)^3}, \tag{19}$$

which can be written:

$$F(\mu^*) = \frac{2(3\mu^* + 1)}{(1 + \mu^*)(\mu^{*4} + 8\mu^{*3} + 12\mu^{*2} - 8\mu^* - 29 - G(\mu^*))}. \tag{20}$$

where

$$G(\mu^*) = \sqrt{(\mu^* - 1)(\mu^{*4} + 8\mu^{*3} + 6\mu^{*2} - 16\mu^* - 31)(\mu^* + 3)^3}. \tag{21}$$

Lemma 1 *The function $F(.)$ is continuous and decreasing over the set $[0, +\infty[$. Moreover, $F(0) = -1/3$ and $\lim_{\mu^* \to +\infty} F(\mu^*) = -1$.*

An immediate consequence of this lemma is that the function $F(.)$ is a bijection over the set $[0, +\infty[$. Hence, for any given risk aversion parameter r, there is only one possible candidate equilibrium. It follows that if a symmetric equilibrium exists, this equilibrium is unique.

To establish the existence of a (sub-game perfect) symmetric Nash equilibrium, we denote by $B(\mu_1)$ the net profit of the firm 1, when the firm 2 plays the equilibrium value μ^*:

$$B(\mu_1) = (-1 + \mu^*\mu_1)\frac{-1 + \mu_1}{(-3 + \mu_1 + \mu^* + \mu^*\mu_1)^2} - \bar{y} + \frac{1}{2(1 + r(1 + \mu_1)^2)}. \tag{22}$$

We now show that

$$\forall \mu_1 \in]-1,0],\, B(\mu_1) \leq B(\mu^*). \tag{23}$$

We need to show that $\mu_1 = \mu^*$ is a maximizer of B. First order conditions are not sufficient, since the function B is not concave.

Proposition 1 *There exists a unique symmetric Nash equilibrium in which both firms play μ^*. If managers are risk neutral, i.e. if $r = 0$, then $\mu^* = -\frac{1}{3}$. If managers are strictly risk averse then μ^* is a decreasing function of r, satisfying $\mu^{**} < -\frac{1}{3}$ and $\lim_{r \to +\infty} \mu^* = -1$.*

Proof. See appendix. ■

This proposition establishes that for every given level of risk aversion r there is a unique equilibrium contract. In other words, there is a one-to-one mapping between risk aversion and the equilibrium level of RPE μ^*.

When the managers are risk neutral, we have at equilibrium $\mu^* = -\frac{1}{3}$. For the principals there is not trade off between incentive and insurance. Hence the role of μ^* is to give the right incentive to choose the best quantity. Here, quantities are strategic substitutes in the sense of Bulow et al. [1985]. Thus firms have an incentive to be aggressive against their rival, since this strategy causes only a relatively weak reaction. This gives firms an incentive to choose μ^* different from zero (and of course negative). But firms do not set $\mu^* = -1$. Reducing μ^* has a cost for a firm. Equation (11) indicates that reducing μ_i increases the quantity q_i, which leads to lower prices and reduces the expected profits. Hence, when managers are risk neutral, it is never optimal for principals to set $\mu^* = -1$.

When managers are risk averse, there is a trade off between incentives and insurance. By decreasing μ_i a principal reduces this trade off. A lower μ_i gives more information to a principal, and hence reduces for the agent the possibility of "unfair punishments": If the agent experiences a low ε, his firm profit will be relatively low and as a consequence his compensation will be relatively low. But the profit of the other firm will be relatively low as well. If μ^* is negative, the agent's compensation increases. Thus, when r increases, μ^* decreases as well. This monotonic relationship accords with intuition (Salas Fumás's [1992] model has the same property).

Let us consider a game in which RPE compensation schemes are forbidden. In other words, we fix $\mu_i = 0$. The previous analysis then applies (except that we take μ_i and μ_j as exogenous).

The firms' profit therefore:

$$B_0(r) = \frac{1}{9} - \bar{y} + \frac{1}{2(1+r)}, \tag{24}$$

and productions and efforts are:

$$q_i^* = \frac{1}{3} \tag{25}$$

$$e_i^* = \beta_i^* = \frac{1}{1+r}. \tag{26}$$

Upon comparing effort and quantities under RPE and APE, we see that they are both lower under APE than under RPE:

$$\frac{1}{1+r} \leq \frac{1}{1+r(1+\mu_i)^2}, \tag{27}$$

$$\frac{1-\mu_i}{4-(1+\mu_i)\left(1+\mu_j\right)} \leq \frac{1}{3}. \tag{28}$$

This is consistent with our preceding results: the risk sharing effect and the strategic effect go in the same direction. RPE schemes give more incentive to managers and then reduce moral hazard. They also induce managers to produce more.

We can compare B_0 and $B(\mu^*)$, which are two functions of r. For small values of r, the firms would have greater profits under APE (i.e. if RPE is not allowed) than under RPE. This is stated formally in the following proposition.

Proposition 2 *There exists a unique threshold value $r = \bar{r} > 0$ such that profits are equal under RPE and APE. If the managers' risk aversion is smaller (greater) than $\bar{r}$, firms' profits are greater (smaller) under APE than RPE.*

Proof. See appendix. ■

This proposition shows clearly that, for the principals, the RPE compensation schemes are not efficient when r is sufficiently small. They would be better off if RPE were forbidden. By itself, the fact that an equilibrium is not efficient is not surprising, especially if we restrict attention to two players only.

APE schemes would be particularly desirable when r is small. If r is small, managers are not (or almost not) risk averse, and moral hazard plays a little role. In a single-principal single-agent model, a principal would be able to implement a fully efficient (or almost efficient) allocation. The choice of μ_i is then driven by the strategic effect. When r increases, the choice of μ_i is also a way to insure the agents, so that RPE schemes become progressively efficient.

In the next section we apply our results to entry issues.

4 Equilibrium with Entry

We consider the same game: the same players, and almost the same timing. We now assume that there is an incumbent firm (firm 1) and a potential challenger (firm 2). To enter into the market, firm 2 has to pay a fixed cost f. If it enters, the firms play the game described in the previous sections. If firm 2 decides not to enter, it pays no cost and its profit is zero.

We study two cases. First, firms are allowed to use any kind of compensation scheme. In the second case, they are allowed to use APE schemes only.

If RPE schemes are allowed, firm 2 anticipates that its expected profit is

$$\left(-1+\mu^{*2}\right)\frac{-1+\mu^*}{\left(-3+\mu^*+\mu^*+\mu^{*2}\right)^2}-\bar{y}+\frac{1}{2(1+r\,(1+\mu^*)^2)}. \qquad (29)$$

From equation (19), we derive the equilibrium profit as a function of r only. We can then conclude that the firm enters if and only if:

$$B\left(\mu^*\left(r\right)\right)=\frac{1+F^{-1}(r)}{\left(3+F^{-1}(r)\right)^2}-\bar{y}+\frac{1}{2\left(1+r\left(1+F^{-1}(r)\right)^2\right)}\geq f. \qquad (30)$$

If RPE schemes are not allowed, then firm 2 enters if and only if:

$$B_0(r) = \frac{1}{9} - \bar{y} + \frac{1}{2(1+r)} \geq f. \quad (31)$$

In any case, managers' risk aversion reduces the firm 2's expected profits if it enters. Entry is more likely if managers are not too risk averse. In our last proposition, we specify the relation between entry and the risk aversion r.

Proposition 3 *Consider the decreasing function F defined by (20).*

For $r < \bar{r}$:

If $f < B(F^{-1}(r))$ *then entry is profitable under APE and under RPE.*

If $f \in [B(F^{-1}(r)), B_0(r)]$ *then entry is profitable under APE but not under RPE.*

If $f > B_0(r)$ *then entry is never profitable.*

For $r > \bar{r}$:

If $f < B_0(r)$ *then entry is profitable under APE and RPE.*

If $f \in [B_0(r), B(F^{-1}(r))]$ *then entry is profitable under RPE but not under APE.*

If $f > B\left(F^{-1}(r)\right)$ *then entry is never profitable.*

Proof. See appendix. ■

The intuition underlying this last proposition follows from the meaning of proposition 2. If r is low, firms are more profitable under APE than under RPE. Hence entry is more likely under APE. The reverse is true when r is relatively high. Hence, when a firm wishes to enter a market, knowledge of the compensation rules allowed can be crucial.

5 Conclusion

This work involves both contract theory and oligopoly theory. We have considered a model which allows us to study two effects of RPE based compensation schemes: an information effect and a strategic effect.

We have demonstrated two related things. First, we have shown that a close link exists between risk aversion and RPE. If managers are risk averse, principals will tend to use more RPE. Such compensation schemes allow principals to use more information, and implicitly to insure the manager more. From the point of view of the principals the effect leads to an inefficient allocation. The resulting RPE compensation schemes give too much incentive to managers to increase the production.

Second, we compare in terms of output, effort and efficiency (for the principals) the consequences of the adoption of APE schemes rather than RPE schemes. This has not been done before. We show that when the managers' risk aversion is low, an RPE scheme may reduce entry, since it reduces the equilibrium profits. The converse applies when the managers' risk aversion is sufficiently high.

Our last finding has an interesting implication for competition policy. By changing the law on compensation, for example by forbidding RPE schemes, a government can favour or deter entry and competition on markets.

A Proof of proposition 1

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Lemma 2 *Let μ_c be defined by the equality $3r\,(1+\mu_c)^2 = 1$. Then the function $B\,(\mu_1)$ is strictly concave for all μ_1 in $]-1,\mu_c]$, in particular $\mu_1 = \mu^*$ since $\mu^* \in\,]-1,\mu_c]$.*

Proof.

Suppose that μ^* is given. We denote $B(\mu_1)$ the net profit of the firm 1. B is the sum of two functions:

$$B_1(\mu_1) = \frac{(-1+\mu^*\mu_1)\,(-1+\mu_1)}{(-3+\mu_1+\mu^*+\mu^*\mu_1)^2} \tag{32}$$

and

$$B_2(\mu_1) = -\bar{y} + \frac{1}{2(1+r\,(1+\mu_1)^2)}. \tag{33}$$

First, we show that B_1 is strictly concave over $]-1,0]$. To do this we study the function B_1''.

$$B_1''(\mu_1) = -2\,(-1+\mu^*)\,\frac{-3\mu^{*2}+3\mu^{*2}\mu_1+2\mu^*+2\mu^*\mu_1-3-\mu_1}{(-3+\mu_1+\mu^*+\mu^*\mu_1)^4}, \quad \mu_1 \in]-1,0] \tag{34}$$

B_1'' is a decreasing function since B_1''' is negative.

$$\begin{aligned} B_1'''(\mu_1) &= 6\,(-1+\mu^*)\,(\mu^*+1)\,\frac{-5\mu^{*2}+3\mu^{*2}\mu_1+6\mu^*+2\mu^*\mu_1-5-\mu_1}{(-3+\mu_1+\mu^*+\mu^*\mu_1)^5} \\ &= 6\,(1+\mu^*)\,(-1+\mu^*)\,\frac{\big(3(1+\mu^*)^2-4(1+\mu^*)\big)(1+\mu_1)-16+20(1+\mu^*)-8(1+\mu^*)^2}{(-4+(1+\mu^*)(1+\mu_1))^5} \end{aligned} \tag{35}$$

Let us remark that $X = (1+\mu^*) \in]0,\frac{2}{3}]$ implies that $3X^2-4X \leq 0$ and $-16+20X-8X^2 \leq 0$.

Finally:

$$\sup_{\mu_1 \in]-1,0]} B_1''(\mu_1) = B_1''(-1) = \frac{1}{64}\,(\mu^*-1)\left(1+3\mu^{*2}\right) < 0. \tag{36}$$

Then we can show that $B_2''(\mu^*) < 0$. It is enough to compute

$$B_2''(\mu_1) = r\frac{3r(1+\mu_1)^2-1}{(1+r(1+\mu_1)^2)^3}, \tag{37}$$

and to observe that $3r(1+\mu^*)^2-1<0$; accordingly (21) is equivalent to

$$3\frac{\mu^{*4}+8\mu^{*3}+12\mu^{*2}-8\mu^*-29+G(\mu^*)}{2(3\mu^*+1)(\mu^*+1)}-1<0, \tag{38}$$

which is always satisfied.

We write $\mu_c = -1+\sqrt{\frac{1}{3r}}$.

As a result, the expression for B_2'' shows that B_2 is strictly concave over $]-1,\mu_c[$ and as a consequently that B is strictly concave over $]-1,\mu_c[$, since it is a sum of two strictly concave functions. ■

Obviously, from this lemma one cannot deduce straightforwardly that for all $\mu_1 \in]-1,0]$, we have $B(\mu_1) \leq B(\mu^*)$. In the next proposition we show that, even if μ^* is characterized through first order conditions only, it is a maximizer and hence an equilibrium.

Let μ^* be the unique solution of the equation $r = F(\mu^*)$, where F is defined by the equation (20). Simple computations show that $r=0$ and $\mu^* = \frac{-1}{3}$ and if $r>0$ then $\mu^* \in]-1,-1/3]$.

To prove our result, we have to show that:

$$\forall \mu_1 \in]-1,0], B(\mu_1) \leq B(\mu^*). \tag{39}$$

However, we have just shown that $B(\mu^*)$ is a local maximum of B.

Now B is strictly concave over the set $]-1,\mu_c]$, where μ_c is defined by

$$\mu_c = -1+\sqrt{\frac{1}{3r}}. \tag{40}$$

We denote by μ_0 the maximizer of the concave function B_1 as defined by (32)

$$\mu_0 = \frac{\mu^*+1}{3\mu^*-1}, \tag{41}$$

Let us assume that $\mu_1 > \mu_c$.

If $\mu_0 \leq \mu_c$, B_2 is a decreasing function, then

$$\forall \mu_1 > \mu_c \geq \mu_0, \quad B(\mu_1) = B_1(\mu_1) + B_2(\mu_1) \leq B_1(\mu_0) + B_2(\mu_0) = B(\mu_0) \leq B(\mu^*). \quad (42)$$

$B(\mu^*)$ is a maximum of B over the set $]-1, \mu_c]$, and μ_0 belongs to $]-1, \mu_c]$.

If $\mu_0 > \mu_c$ then two cases are possible, $\mu_1 \in [\mu_c, \mu_0]$ or $\mu_1 \geq \mu_0$. In the second case, since B_1, B_2, and B are now decreasing functions on this set, we conclude that

$$B(\mu_1) = B_1(\mu_1) + B_2(\mu_1) \leq B_1(\mu_0) + B_2(\mu_0) = B(\mu_0) \leq B(\mu_c) \leq B(\mu^*). \quad (43)$$

Let us now consider the case $\mu_1 \in [\mu_c, \mu_0]$.

$$\begin{aligned} B(\mu_1) - B(\mu^*) \quad = \quad & \frac{(-1+\mu^*\mu_1)(-1+\mu_1)}{(-3+\mu_1+\mu^*+\mu^*\mu_1)^2} \\ & + \frac{1}{2\left(1+r(\mu_1+1)^2\right)} - \left[\frac{\mu^*+1}{(\mu^*+3)^2} + \frac{1}{2\left(1+r(\mu^*+1)^2\right)}\right] \end{aligned} \quad (44)$$

Since B_1 is increasing over $[\mu_c, \mu_0]$ and B_2 is a decreasing function over the same set,

$$\begin{aligned} B(\mu_1) - B(\mu^*) \quad \leq \quad & \frac{(-1+\mu^*\mu_0)(-1+\mu_0)}{(-3+\mu_0+\mu^*+\mu^*\mu_0)^2} \\ & + \frac{1}{2\left(1+r(\mu_c+1)^2\right)} - \left[\frac{\mu^*+1}{(\mu^*+3)^2} + \frac{1}{2\left(1+r(\mu^*+1)^2\right)}\right] \end{aligned} \quad (45)$$

From (41), we obtain:

$$\begin{aligned} B(\mu_1) - B(\mu^*) \quad \leq \quad & \frac{\left(-1+\mu^*\frac{\mu^*+1}{3\mu^*-1}\right)\left(-1+\frac{\mu^*+1}{3\mu^*-1}\right)}{\left(-3+\frac{\mu^*+1}{3\mu^*-1}+\mu^*+\mu^*\frac{\mu^*+1}{3\mu^*-1}\right)^2} \\ & + \frac{1}{2\left(1+\frac{1}{3}\right)} - \left[\frac{\mu^*+1}{(\mu^*+3)^2} + \frac{1}{2\left(1+r(\mu^*+1)^2\right)}\right] \end{aligned} \quad (46)$$

or

$$B(\mu_1) - B(\mu^*) \leq \frac{1}{8}\frac{3\mu^*-4}{\mu^*-1} - \frac{\mu^*+1}{(\mu^*+3)^2} - \frac{1}{2+2r(\mu^*+1)^2} = w(\mu^*). \quad (47)$$

From (20), the function w is always negative over the set $]-1, -\frac{1}{3}]$.

$$w(\mu^*) = \frac{3\mu^{*3}+6\mu^{*2}+3\mu^*-28}{8(\mu^*-1)(\mu^*+3)^2} - \frac{(3\mu^*+1)(\mu^*+1)}{18\mu^{*2}-27+\mu^{*4}+8\mu^{*3}+G(\mu^*)} \leq 0, \tag{48}$$

which completes the proof. ■

B Proof of proposition 2

For a given value of r, let us consider

$$\Delta B = B(\mu^*) - B_0 = \frac{1+\mu^*}{(\mu^*+3)^2} + \frac{1}{2}\frac{1}{1+r(1+\mu^*)^2} - \left(\frac{1}{9}+\frac{1}{2}\frac{1}{1+r}\right) \tag{49}$$

If $r=0$ then $\mu^* = -\frac{1}{3}$, and $\Delta B = \frac{1-\frac{1}{3}}{\left(-\frac{1}{3}+3\right)^2} + \frac{1}{2} - \left(\frac{1}{9}+\frac{1}{2}\right) = -\frac{5}{288}$ is negative.

In the same way, if $r \to +\infty$ then $\mu^* \to -1$ and, from (20),

$$\begin{aligned} & \lim_{\mu^* \to -1} r(1+\mu^*)^2 \\ = & \lim_{\mu^* \to -1} \frac{2(1+\mu^*)(3\mu^*+1)}{\left(\mu^{*4}+8\mu^{*3}+12\mu^{*2}-8\mu^*-29-G(\mu^*)\right)} \\ = & \ 0. \end{aligned} \tag{50}$$

If $\mu^* \to -1$, then $\Delta B \to \frac{7}{18} > 0$. There exists a $\bar{r}$ such that $\Delta B = 0$.

■

C Proof of proposition 3

From proposition 2, if $r < \bar{r}$ then $\Delta B = B(\mu^*) - B_0 < 0$. As a consequence, the fixed costs f, expressed as $f = B(\mu^*) - k\Delta B$ with $0 \leq k \leq 1$, satisfy the following conditions

$$\left\{ B_0 - f = B_0 - (B(\mu^*) - k(B(\mu^*) - B_0)) = -(1-k)(-\Delta B) > 0 B(\mu^*) - f = k\Delta B < 0. \right. \tag{51}$$

Then $f = B(\mu^*) - k\Delta B$ with $0 \leq k \leq 1$, i.e., $f \in [B(F^{-1}(r)), B_0(r)]$, entry is profitable under APE but unprofitable under RPE.

If $r > \bar{r}$ then profits under RPE are strictly greater than profit under APE: $\Delta B = B(\mu^*) - B_0 > 0$. Hence all fixed costs f having the form $f = B(\mu^*) + k\Delta B$ with $0 \leq k \leq 1$ satisfy $\begin{cases} B_0 - f < 0 \\ \text{and} \\ B(\mu^*) - f > 0. \end{cases}$ Entry is profitable under RPE and unprofitable under APE.

All other cases are trivial. ■

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