Cooperating firms in inventive and absorptive research

Ben Youssef, Slim and Breton, Michèle and Zaccour, Georges

Manouba University, ESC de Tunis and LAREQUAD, Tunisia, GERAD, HEC Montréal, Canada, GERAD, HEC Montréal, Canada

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Slim Ben Youssef · Michèle Breton · Georges Zaccour

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Abstract

We consider a duopoly competing in quantity, where firms can invest in both innovative and absorptive R&D to reduce their unit production cost, and where they benefit from free R&D spillovers between them. We analyze the case where firms act non cooperatively and the case where they cooperate by forming a research joint venture. We show that, in both modes of play, there exists a unique symmetric solution. We find that the investment in innovative R&D is always higher than in absorptive R&D. We also find that the value of the learning parameter has almost no impact on innovative R&D, firms profits, consumer's surplus and social welfare. Finally, differences in investment in absorptive research and social welfare under the two regimes are in opposite directions according to the importance of the free spillover.

Key Words: Innovative R&D · Absorptive R&D · Learning Parameter · Spillover · Research Joint Venture.

Slim Ben Youssef
Manouba University, ESC de Tunis and LAREQUAD, Tunisia

Michèle Breton
GERAD, HEC Montréal, Canada

Georges Zaccour (corr. author)
Chair in Game Theory and Management, GERAD, HEC Montréal, Canada
e-mail: georges.zaccour@gerad.ca

1 Introduction

In this paper, we consider a duopoly where firms can invest both in innovative (or original) and absorptive research and development (R&D) to reduce their unit production cost. We suppose the existence of free and exogenous R&D spillovers, that is, a firm cannot fully appropriate the knowledge developed in its laboratory. However, for a firm to benefit from rival's innovative R&D, it must invest in absorptive capacity, e.g., hire technical staff to adapt the rival's knowledge to its context. The duopoly game is played in two stages: In the first stage, firms choose their investment levels in R&D, and in the second stage they compete in quantity on the market. We consider two cases. In the first case, the firms act non-cooperatively, while in the second case, they cooperate in both types of research by forming a research joint venture (RJV). Interestingly, we show that under both modes of play, the sub-game perfect equilibrium is unique. We then characterize and compare the cooperative and non-cooperative R&D equilibrium strategies and outcomes.

The literature on process R&D can be schematically divided into three streams. The first stream has its root in the seminal paper by d'Aspremont and Jacquemin ([1], see also [2]), who considered a two-stage model where the firms invest in (innovative) R&D in the first stage and compete in quantities in the second stage, and where each firm benefits gratuitously from the research investment of the rival through research externalities. D'Aspremont and Jacquemin showed that cooperation in R&D through a RJV leads to higher investment in research and to higher production with respect to the non-cooperative outcome when the free spillover externality is high, while it is the reverse when the spillover is low. However, they did not explicitly determine whether cooperation in research is beneficial for firms, or socially desirable. Suzumura [3] showed that in the presence of sufficiently large R&D spillovers, neither noncooperative nor cooperative equilibria achieve even second-best R&D levels. However, in the absence of spillover effects, while the cooperative R&D level remains socially insufficient, the noncooperative level may overshoot first- and second-best levels of R&D. Salant and Shaffer [4] pointed out that asymmetric equilibria may exist for cooperating firm and showed that in that case a RJV can raise welfare, even when there are no free spillovers. Kamien, Muller and Zang [5] showed that creating an RJV increases firms' profits and social welfare. Amir and Wooders [6] showed that the symmetric equilibrium under R&D competition is sometimes unstable, in which case two asymmetric equilibria must also exist. For the latter, they found that total profits are sometimes higher with R&D competition than with RJV.

The above-mentioned references all assume that R&D spillovers are exogenous and cost less. A second stream of literature considers that, to benefit from the rival's R&D, a firm must acquire absorptive capacity. Cohen and Levinthal [7] were the first to introduce the concept of absorptive capacity in the R&D literature. They showed that investment in R&D develops the firm's ability to identify, assimilate, and exploit knowledge from the environment, which they termed "learning" or "absorptive" capacity. Poyago-Theotoky [8] showed that, when information spillovers are endogenized, non cooperating firms never disclose any of their knowledge, whereas they always share their full knowledge when they cooperate in R&D. Kamien and Zang [9] found that, when firms cooperate in R&D, they choose identical R&D approaches, while they choose firm-specific R&D approaches otherwise, unless there is no danger of exogenous spillovers. In contrast, Wiethaus [10] showed that competing firms do choose identical R&D approaches in order to maximize the flow of knowledge between them.

Grünfeld [11] showed that, in a small market, the highest welfare is reached when the learning parameter of absorptive capacity is large, while the opposite is true in a large market. Leahy and Neary [12], specifying a general model for the absorptive capacity process, showed that costly absorption raises the effectiveness of own R&D and lowers the effective spillover coefficient, thereby weakening the case for encouraging RJVs, even under total information sharing between firms. Kaiser [13] showed that cooperating firms invest more in R&D than non cooperating ones if spillovers are sufficiently large. Milliou [14] showed that the lack of full appropriability can lead to an increase in R&D investments.

All the above-mentioned papers consider that investments in R&D necessarily increase the absorptive ability of firms, and as such do not allow for distinguishing R&D investment decisions by type. A third stream of literature makes a distinction, in one way or another, between innovative and absorptive research. Frascatore [15] distinguished "basic research," which increases the firm's absorptive capacity, from "applied research," which reduces the firm's costs. The author showed that firms' expenditures in basic research can differ from what is socially optimal, and discussed policy responses that could bring firms' behavior in line with what is socially desirable. Jin and Troege [16] distinguished the innovative activity from the imitation activity, and obtained that asymmetric firms choose the same level of imitation expenditure, and the same ratio of innovative cost reduction to output. Hammerschmidt [17] considered a two-stage game in which R&D plays a dual role: first, it generates new knowledge; and second, it develops a firm's absorptive capacity. She found that firms invest more in R&D to strengthen their absorptive capacity when the spillover parameter is higher. Finally, Kannianinen and Stenbacka [18] showed that there is an under investment in imitation from a social point of view when imitation leads to sufficiently intense competition.

Our paper is principally related to this third stream of literature. We consider the investment in absorptive capacity as a decision separate from the investment in innovative R&D. The two decisions are however related, as investment in absorptive capacity allows the firms to increase the spillover from the rival's research. Our main contributions are the introduction of a free spillover parameter along with a learning (or absorptive) parameter, the comparison of non-cooperative and cooperative outcomes, and the analysis of the impact on firms profits and on social welfare of parameter values and modes of play.

More specifically, we address the following questions:

1. How do investment levels in innovative and absorptive research compare under cooperation and non-cooperation in R&D?

2. What is the impact of the free spillover and learning parameters on strategies and outcomes?

3. Does cooperation in R&D improve profits, consumers' surplus or welfare?

We obtain some new and non obvious results. Indeed, contrary to the results obtained when decisions in absorptive and innovative research are not dissociated, as in [11], we find that an increase in the efficiency of absorptive research investments has almost no impact on innovative R&D investments, firms' profits, consumers' surplus and social welfare. We also find that when the free spillover is low, investment in absorptive R&D, consumers' surplus and social welfare are higher under non-cooperation than under a RJV. This challenges a result in [4] stating that a RJV can raise welfare even in the absence of spillovers.

A third interesting result, in line with a finding of [17] in a non-cooperative setting, is that investment in innovative R&D is always higher than in absorptive R&D, in both the cooperative and non-cooperative cases, even when investment costs for innovation are much higher than for absorption capacity.

Finally, in our model, an increase in the free spillover leads to higher profits under the two regimes, and to higher social welfare and absorptive research investments in a RJV. This last result carries a priori a non-obvious message. Indeed, under cooperation, one could presume that when the free spillover decreases, firms are tempted to compensate by increasing their investment in absorption capacity, but our computations show that this is not the case.

The rest of the paper is organized as follows. Section 2 presents the basic model and Section 3 the market equilibrium. Section 4 characterizes the unique symmetric equilibrium in the non-cooperative case and Section 5 characterizes the unique equilibrium solution when the firms cooperate in R&D. Section 6 presents and discusses numerical illustrations and Section 7 briefly concludes.

2 The model

We consider a duopolistic industry producing a homogeneous good sold on a market having the following linear inverse demand function:

$$p(q_i, q_j) = \lambda - b(q_i + q_j),\ \ \lambda > 0, b > 0,\ \ i, j \in \{1, 2\}, j \neq i.$$

Firms are symmetrical and can invest in R&D to decrease their per-unit production cost. We distinguish between two types of R&D efforts, namely, innovative or original R&D, denoted y_i, which directly reduces production costs, and absorptive-capacity R&D, denoted a_i, which enables a firm to capture part of the original research developed by the rival, $i \in \{1, 2\}$. The total knowledge available (also referred to as the effective R&D level in the literature) to firm $i \in \{1, 2\}$ is:

$$y_i + (\beta + la_i)\, y_j, \qquad j \in \{1, 2\},\ j \neq i,$$

where $\beta \in [0, 1)$ is a parameter capturing the free and exogenous spillover and $l > 0$ is a learning or absorptive parameter. It is convenient to make a change of variable, defining $x_i \equiv \beta + la_i$, representing the effective spillover, that is, the fraction of knowledge developed by the rival firm which is captured by firm i, $i \in \{1, 2\}$. We assume that a firm cannot capture more than the knowledge developed by its competitor, so that $x_i \in [\beta, 1]$.

The above specification differs from that in d'Aspremont and Jacquemin [1] and in the first stream of literature mentioned in the introduction by the inclusion of a new spillover component that is not free, and that necessitates an investment in absorptive capacity. When $l = 0$, we obtain the corresponding R&D level in the d'Aspremont and Jacquemin model. Our specification also generalizes papers in the third stream of literature by considering a component β of free spillover that is independent of absorptive capacity.

Before investing in R&D, the marginal cost of production of firms is $\in (0,)$, and it becomes after both types of investments:

$$C_i\left(y_i, x_i, y_j\right) = \theta - y_i - x_i y_j,\ i, j \in \{1, 2\}, j \neq i$$

with the condition $C_i\left(y_i, x_i, y_j\right) \geq 0$.

To accommodate for diminishing returns to scale of R&D, we let the cost of R&D activity be a convex increasing function that vanishes when there is no activity. For simplicity, we assume that the investment cost is additive and quadratic, so that the cost of original and absorptive R&D for firm $i \in \{1, 2\}$ is given by

$$\begin{aligned} A\left(y_i\right)^2 + D\left(a_i\right)^2 &= A\left(y_i\right)^2 + D\left(\frac{x_i - \beta}{l}\right)^2 \\ &= A\left(y_i\right)^2 + B\left(x_i - \beta\right)^2 \\ &\equiv I(y_i, x_i), \end{aligned}$$

where A and D are positive parameters and $B = \frac{D}{l^2}$. The profit of firm $i \in \{1, 2\}$ is then given by

$$\Pi_i(q_i, q_j, y_i, x_i, y_j) = \left(p(q_i, q_j) - C_i(y_i, x_i, y_j)\right) q_i - I(y_i, x_i),\ j \in \{1, 2\}, j \neq i.$$

As usual in the literature, the game is played in two stages; in the first stage, the firms decide on their investments in both types of R&D, and in the second stage they decide on their outputs. The sub-game perfect equilibrium is obtained by backward induction.

The consumers' surplus derived from the consumption of $q_i + q_j$ is:

$$CS(q_i, q_j) = \int_0^{q_i + q_j} p(u)du - p(q_i, q_j)(q_i + q_j) = \frac{b}{2}(q_i + q_j)^2,\ i, j \in \{1, 2\}, j \neq i.$$

The social welfare level is defined as the sum of the consumers' surplus and the profit of firms:

$$S(q_i, q_j, y_i, x_i, y_j, x_j) = CS\left(\cdot\right) + \Pi_i\left(\cdot\right) + \Pi_j\left(\cdot\right),\ i, j \in \{1, 2\}, j \neq i.$$

Without loss of generality, from now on we normalize the quantity and currency units so that $b = 1$ and $\lambda - \theta = 1$. The parameter set characterizing the game is then $\{A, B, \beta\}$. In the sequel, we however implicitly assume that solutions satisfy the constraints $C_i(y_i, x_i, y_j) \geq 0$, which depends on the value of θ.

3 Output game

In the second stage, for a given investment of each firm in original and absorptive research corresponding to (y_1, y_2, x_1, x_2), where $y_i \geq 0$ and $\beta \leq x_i \leq 1$, $i \in \{1, 2\}$, firms' profit functions are concave, and first-order conditions characterize the optimal reaction functions:

$$\begin{aligned} 1 - 2q_1 - q_2 + y_1 + y_2 x_1 &= 0 \\ 1 - 2q_2 - q_1 + y_2 + y_1 x_2 &= 0, \end{aligned}$$

provided that profits are non-negative. Simultaneous solution of the F.O.C. yields the equilibrium output as a function of R&D investments:

$$q_i^*(y_1, y_2, x_1, x_2) = \frac{1 + (2 - x_j)\, y_i + (2x_i - 1)\, y_j}{3},\ i, j \in \{1, 2\}, j \neq i.$$

To interpret the above equilibrium, we compute the partial derivatives of output decisions with respect to R&D efforts, to obtain:

$$\begin{array}{ll} \frac{\partial q_i^*}{\partial y_i} = \frac{2 - x_j}{3} > 0 & \frac{\partial q_i^*}{\partial x_i} = \frac{2y_j}{3} \geq 0 \\ \frac{\partial q_i^*}{\partial y_j} = \frac{2x_i - 1}{3} & \frac{\partial q_i^*}{\partial x_j} = -\frac{y_i}{3} \leq 0. \end{array}$$

When a firm increases its level of innovative or absorptive research, its marginal cost of production decreases, enabling it to expand its equilibrium production ($\frac{\partial q_i^*}{\partial y_i} > 0, \frac{\partial q_i^*}{\partial x_i} \geq 0$). On the other hand, when a competitor increases its investment in absorption, its marginal cost decreases, enabling it to expand its production, which in turn forces the other firm to reduce its production ($\frac{\partial q_i^*}{\partial x_j} \leq 0$). Consider now the derivative $\frac{\partial q_i^*}{\partial y_j}$. When the competing firm increases its innovative research, then this has two opposite effects on the firm's production, namely, (i) a positive effect on production due to the free R&D spillovers and absorptive capacity; and (ii) a negative effect due to competition between firms. When the proportion x_i of the captured knowledge is high enough (β and/or l are high enough), the first positive effect dominates and the production of the firm increases.

If $x_1 = x_2 = x$ and $y_1 = y_2 = y$, then

$$q_i^* (y, x) = \frac{1 + y (1 + x)}{3}, \ i \in \{1, 2\}.$$

4 Non-cooperative solution

In this section, we suppose that the two firms behave non-cooperatively in the first stage: each firm chooses its optimal levels of innovative and absorptive research independently, taking into account the equilibrium solution of the second stage game.

The profit function for firm i, given that the rival firm j chooses innovative R&D level y_j and absorptive capture level x_j is given by:

$$\begin{aligned}
&(p(q_1^* (y_1, y_2, x_1, x_2), q_2^* (y_1, y_2, x_1, x_2)) - C(y_i, x_i, y_j)) \\
&\qquad\qquad\qquad\qquad q_i^* (y_1, y_2, x_1, x_2) - I(y_i, x_i) \\
&= \frac{1}{9} (2y_i - y_j + 2x_i y_j - x_j y_i + 1)^2 - A (y_i)^2 - B (x_i - \beta)^2
\end{aligned}$$

and is positive when $y_i = 0$ and $x_i = \beta$. Assuming an interior solution, profit is positive and first order conditions yield

$$\begin{aligned}
x_i &= \frac{B\beta (9A - 4) - 2Ay_j (y_j - 1) + B\beta x_j (4 - x_j)}{A \left(9B - 4y_j^2\right) - B (2 - x_j)^2} \\
y_i &= B (2 - x_j) \frac{1 - y_j (1 - 2\beta)}{A \left(9B - 4y_j^2\right) - B (2 - x_j)^2},
\end{aligned}$$

which is the optimal investment decision pair for firm i if the following second order conditions are satisfied:

$$9A > (2 - x_j)^2 \quad (1)$$

$$9B > 4y_j^2 \quad (2)$$

$$A \left(9B - 4y_j^2\right) > B (2 - x_j)^2 . \quad (3)$$

The equilibrium solution is necessarily symmetric and is denoted (x^n, y^n); it satisfies:

$$\begin{aligned} 2y^n\left(y^n\left(x^n+1\right)+1\right)-9B\left(x^n-\beta\right) &= 0 \qquad (4) \\ \left(2-x^n\right)\left(y^n\left(x^n+1\right)+1\right)-9Ay^n &= 0 \qquad (5) \end{aligned}$$

or, equivalently,

$$\begin{aligned} x^n &= \frac{9B\beta+2y^n\left(y^n+1\right)}{9B-2\left(y^n\right)^2} \qquad (6) \\ y^n &= \frac{2-x^n}{9A-\left(x^n+1\right)\left(2-x^n\right)}. \qquad (7) \end{aligned}$$

Proposition 4.1 *If*

$$\begin{aligned} A &> \max\left[\frac{(2-\beta)^2}{9}, 0.25\right] \qquad (8) \\ B &> \frac{2A}{(1-\beta)\left(9A-2\right)^2}, \qquad (9) \end{aligned}$$

then there exists a unique symmetric non-cooperative equilibrium solution (x^n, y^n) *satisfying (6)-(7), with* $y^n > 0$ *and* $\beta < x^n < 1$.

Proof. We first show that under assumptions (8)-(9), there is a unique interior solution to (6)-(7), and that this solution satisfies the second order condition.

Consider (6) as a function $x^n(y)$, $y^2 \neq \frac{9B}{2}$. Differentiating with respect to y yields

$$2\frac{9B+2y^2+18By+18By\beta}{\left(9B-2y^2\right)^2} > 0 \text{ if } y \geq 0.$$

Therefore, x^n is an increasing function of y. Accordingly, $x^n(y) \in [\beta, 1]$ if $y \in \left[0, \frac{-1+\sqrt{1+36B(1-\beta)}}{4}\right]$.

Now consider (7) as a function $y^n(x)$, $(x+1)(2-x) \neq 9A$. Differentiating with respect to x yields

$$\frac{(2-x)^2-9A}{\left(9A-(x+1)(2-x)\right)^2} < 0.$$

Under assumption (8), $9A > (2-\beta)^2$. Therefore, y^n is decreasing in x for $x \in [\beta, 1]$. Moreover $y^n(x) > 0$ for $x \in [\beta, 1]$ if $9A > (x+1)(2-x) \geq 2.25$, which is satisfied under assumption (8). Accordingly, $y^n(x) \in \left[\frac{1}{9A-2}, \frac{2-\beta}{9A-(\beta+1)(2-\beta)}\right]$ if $x \in [\beta, 1]$.

Since x^n is increasing in y and y^n is decreasing in x, there is at most one intersection point of the two curves defined by (6)-(7). Since $y^n(\beta) > 0$, the intersection defines a unique interior solution with $x < 1$ if

$$\frac{1}{9A-2} < \frac{-1+\sqrt{1+36B\left(1-\beta\right)}}{4},$$

which is equivalent to Assumption (9).

It remains to check if this unique intersection point satisfies the second order conditions. Under Assumption (9), $\left(2-x^n\right)^2 < \left(2-\beta\right)^2 < 9A$ and condition (1) is satisfied.

Using (7) and the fact that $y^n(x)$ is decreasing,

$$\begin{aligned} 4\left(y^n\right)^2 &= 4\left(\frac{\left(2-x^n\right)}{9A-\left(x^n+1\right)\left(2-x^n\right)}\right)^2 \\ &< 4\left(\frac{\left(2-1\right)}{9A-\left(1+1\right)\left(2-1\right)}\right)^2 = \frac{4}{\left(9A-2\right)^2} \end{aligned}$$

and using Assumption (9),

$$9B > \frac{18A}{\left(9A-2\right)^2\left(1-\beta\right)} > \frac{18A}{\left(9A-2\right)^2}$$

and Condition (2) is satisfied if $18A > 4$, which is the case under Assumption (8).

Finally, using (4)-(5),

$$\begin{aligned} B &= 2\frac{y^n}{9\left(x^*-\beta\right)}\left(y^n\left(x^n+1\right)+1\right) \\ A &= \frac{1}{9y}\left(y^n\left(x^n+1\right)+1\right)\left(2-x^n\right) \end{aligned}$$

so that

$$\begin{aligned} & A\left(9B-4\left(y^n\right)^2\right)-B\left(2-x^n\right)^2 \\ = \; & \frac{2}{9}\frac{\left(2-x^n\right)\left(y^n\left(x^n+1\right)+1\right)}{x^n-\beta}\left(y^n\left(2\beta-1\right)+1\right) \end{aligned}$$

which is positive if $y^n\left(2\beta-1\right)+1 > 0$. Now, this is always the case if $\beta \geq 0.5$.

If on the other hand $\beta < 0.5$, then

$$\begin{aligned} y &\leq \frac{2-\beta}{9A-(\beta+1)(2-\beta)} \\ &< \frac{2-\beta}{(2-\beta)^2-(\beta+1)(2-\beta)} = \frac{1}{1-2\beta} \end{aligned}$$

and $y^n(2\beta-1)+1>0$.

We now show that there are no other possible (non interior) equilibrium points. Indeed, according to the values of x_2 and y_2, the optimal solution for Player 1 could be either

$x_1=\beta$, $y_1=\max\left[0,\frac{(2-x_2)(y_2(2\beta-1)+1)}{9A-(x_2-2)^2}\right]$, with a candidate equilibrium point at $\left(\beta,\frac{2-\beta}{9A-(\beta+1)(2-\beta)}\right)$

$x_1=1$, $y_1=\max\left[0,\frac{2y_2(2-x_2)+(y_2-1)(x_2-2)}{9A-(x_2-2)^2}\right]$, with a candidate equilibrium point at $\left(1,y=\frac{1}{9A-2}\right)$

1. If $x_2=\beta$ and $y_2=\frac{2-\beta}{9A-(\beta+1)(2-\beta)}$, the profit function of Player 1 is

$$\begin{aligned} &\frac{1}{9}\left(2y_1-\frac{2-\beta}{9A-(\beta+1)(2-\beta)}+2x_1\frac{2-\beta}{9A-(\beta+1)(2-\beta)}-\beta y_1+1\right)^2 \\ &-A(y_1)^2-B(x_1-\beta)^2. \end{aligned}$$

   Differentiating with respect to x_1 and evaluating the derivative at $x_1=\beta$ and $y_1=\frac{2-\beta}{9A-(\beta+1)(2-\beta)}$ yields

$$4A\frac{2-\beta}{(9A-(\beta+1)(2-\beta))^2}>0$$

   which implies that $\left(\beta,\frac{2-\beta}{9A-(\beta+1)(2-\beta)}\right)$ cannot be an equilibrium solution.

2. If $x_2=1$ and $y_2=\frac{1}{9A-2}$, the profit function of Player 1 is

$$\frac{1}{9}\left(y_1-\frac{1}{9A-2}+2x_1\frac{1}{9A-2}+1\right)^2-A(y_1)^2-B(x_1-\beta)^2.$$

   Differentiating with respect to x_1 and evaluating the derivative at $x_1=1$

and $y_1 = \frac{1}{9A-2}$ yields

$$\begin{aligned} & -\frac{2}{9}\frac{9B\left(9A-2\right)^2\left(1-\beta\right)-18A}{\left(9A-2\right)^2} \\ < \quad & -\frac{2}{9}\frac{9\frac{2A}{(9A-2)^2(1-\beta)}\left(9A-2\right)^2\left(1-\beta\right)-18A}{\left(9A-2\right)^2} = 0 \end{aligned}$$

which implies that $\left(1, \frac{1}{9A-2}\right)$ cannot be an equilibrium solution.

■

Recall that we discarded as non interesting the case where the cost parameter θ is smaller than $y^n(x^n+1)$, meaning that the firms can eliminate their production costs at equilibrium. This could also happen, irrespective of the value of θ, for low values of A; For instance, when $9A < 1$,the profit function of Player 1 becomes convex in y_1 for all $x_2 \leq 1$, and it is optimal for players to invest in both types of R&D until production costs vanish.

Finally notice that when Assumption (8) is satisfied, but Assumption (9) is not, it is straightforward to show, using the arguments in the proof of Proposition 4.1, that the unique equilibrium is at $x = 1$, $y = \frac{1}{9A-2}$. Figure 1 illustrates the space of parameter values yielding interior equilibrium solutions.

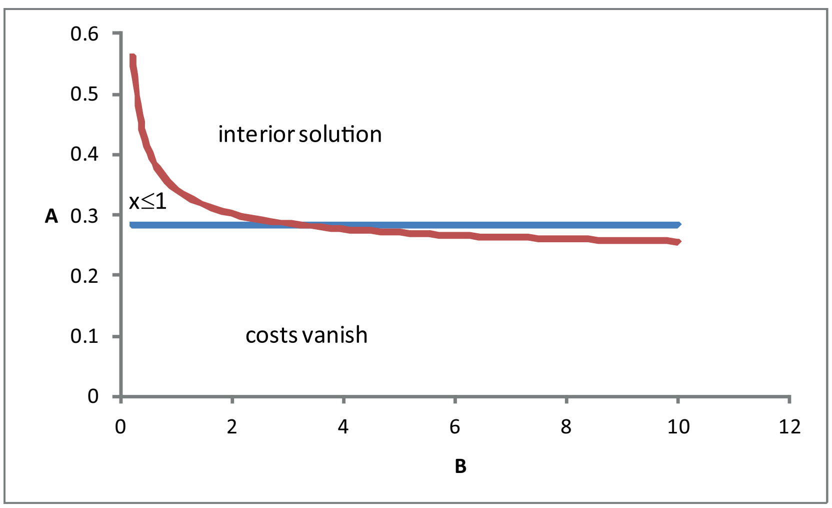

Figure 1: Solution regions according to parameter values for $\beta = 0.4$.

5 Cooperation in research

In this section, firms cooperate in both types of research in the first stage by creating a Research Joint Venture, and compete in the second stage of production. Thus, the solution of the second stage is the same as in Section (3). The total profit function is then

$$\begin{aligned}\Pi(x_1,x_2,y_1,y_2) =& \frac{1}{9}\Big((2y_1 - y_2 + 2x_1y_2 - x_2y_1 + 1)^2 \\ &+ (2y_2 - y_1 + 2x_2y_1 - x_1y_2 + 1)^2 \Big) \\ &- A\left(y_1^2 + y_2^2\right) - B\left((x_1-\beta)^2 + (x_2-\beta)^2\right).\end{aligned}$$

As in [[1]], we look for a symmetric equilibrium, which can be motivated by the fact there are no side-payments between firms, who only agree in coordinating their R&D investments; the total profit function becomes

$$\Pi(x,y) = \frac{2}{9}(y + xy + 1)^2 - 2A(y)^2 - 2B(x-\beta)^2$$

where x and y represent the knowledge captured and the investment in original research, for both firms in the RJV. Total profit is positive when $y = 0$ and $x = \beta$. Moreover, at $y = 0$,

$$\Pi'_y(x,0) = \frac{4}{9}(x+1) > 0,$$

implying that the maximizing y is strictly positive, and, at $x = \beta$,

$$\Pi'_x(\beta,y) = \frac{4}{9}y(y + y\beta + 1) > 0,$$

implying that the maximizing x is strictly greater than β.

Assuming an interior solution, denoted by (y^c, x^c), profit is positive and first order conditions yield

$$\begin{aligned} y^c(y^c + x^cy^c + 1) - 9B(x^c - \beta) &= 0 \\ (x^c+1)(y^c + x^cy^c + 1) - 9Ay^c &= 0 \end{aligned}$$

or, equivalently,

$$x^c = \frac{9B\beta + y^c + (y^c)^2}{9B - (y^c)^2} \tag{10}$$

$$y^c = \frac{x^c + 1}{9A - (x^c + 1)^2}. \tag{11}$$

which is optimal if the following second order conditions are satisfied:

$$9A > (x^c + 1)^2 \tag{12}$$

$$9B > (y^c)^2 \tag{13}$$

$$\left(9B - (y^c)^2\right)\left(9A - (x^c + 1)^2\right) > (2y^c + 2x^c y^c + 1)^2. \tag{14}$$

Proposition 5.1 *If*

$$A > \frac{4}{9} \tag{15}$$

$$B > \frac{2A}{(1-\beta)(9A-4)^2}, \tag{16}$$

then there exists a unique optimal solution (x^c, y^c) *satisfying (10)-(11), with* $y^c > 0$ *and* $\beta < x^c < 1$.

Proof. We first show that there is a unique interior solution to (10)-(11).

Consider (10) as a function $x^c(y)$, $y^2 \neq 9B$. Differentiating with respect to y yields

$$\frac{9B + 18By + y^2 + 18By\beta}{(9B - y^2)^2} > 0 \text{ if } y \geq 0.$$

Therefore, x^c is an increasing function of y. Accordingly, $x^c(y) \in [\beta, 1]$ if $y \in \left[0, \frac{\sqrt{72B(1-\beta)+1}-1}{4}\right]$, where $\frac{\sqrt{72B(1-\beta)+1}-1}{4} < 9B$. Moreover, the second derivative of $x^c(y)$ is

$$2\frac{27By^2 + 81B^2\beta + 27By + 81B^2 + y^3 + 27By^2\beta}{(9B - y^2)^3},$$

implying that this function is convex for $0 \leq y^2 < 9B$, so that $[x^c]^{-1}(x)$ is concave on the corresponding domain.

Now consider (11) as a function $y^c(x)$, $(x+1)^2 \neq 9A$. Differentiating with respect to x yields

$$\frac{9A + (x+1)^2}{\left(9A - (x+1)^2\right)^2} > 0,$$

so that y^c is decreasing in x, implying that $y^c(x) \in \left[\frac{\beta+1}{9A-(\beta+1)^2}, \frac{2}{9A-4}\right]$ for $x \in [\beta, 1]$ where $\frac{\beta+1}{9A-(\beta+1)^2} > 0$ under Assumption (15). Moreover, the second derivative of $y^c(x)$ is

$$2(x+1)\frac{27A + (x+1)^2}{\left(9A - (x+1)^2\right)^3} > 0,$$

implying that this function is convex for $x \in [\beta, 1]$.

Now consider $[x^c]^{-1}(\beta) = 0 < \frac{\beta+1}{9A-(\beta+1)^2} = y^c(\beta)$. Since $[x^c]^{-1}$ is concave and y^c is convex, there is a unique intersection point of the two curves defined by (10)-(11) in $(\beta, 1)$ if $[x^c]^{-1}(1) > y^c(1)$, which translates to the condition

$$\frac{\sqrt{72B(1-\beta)+1} - 1}{4} > \frac{2}{9A-4},$$

corresponding to Assumption (16).

We now show that (x^c, y^c) maximizes the profit function. Second order conditions (12) and (13) are readily verified if $x^c \in (\beta, 1)$:

$$\begin{aligned} (x^c+1)^2 &< 4 < 9A \\ (y^c)^2 &< \frac{\sqrt{72B(1-\beta)+1} - 1}{4} < 9B, \end{aligned}$$

but Condition (14) cannot be checked analytically. To prove that (x^c, y^c) is indeed a maximum, consider the partial derivative of the profit function with respect to the variable y on $x \in [\beta, 1], y \geq 0$:

$$\begin{aligned} \Pi'_y(x,y) &= \frac{4}{9}(x+1)(y + xy + 1) - 4Ay \\ &\leq \frac{8}{9}(2y+1) - 4Ay \end{aligned}$$

and notice that this derivative is negative for all $y > \frac{2}{9A-4}$. As a consequence, we can restrict the optimization domain to the compact set $[\beta, 1] \times \left[0, \frac{2}{9A-4}\right]$, and since the profit function is continuous, it admits a maximum in this set which is either the unique stationary point (x^c, y^c) or a boundary point. We already know that investment in both types of research are strictly positive at optimality. At $x=1$,

$$\begin{aligned}\Pi'_x(1,y) &= \frac{4}{9}y\left(2y+1\right)-4B\left(1-\beta\right) \\ &\leq 8\frac{A}{\left(9A-4\right)^2}-4B\left(1-\beta\right)<0,\end{aligned}$$

implying that the interior stationary point (x^c, y^c) is optimal.

Again, we assume that $\theta \geq y^c(x^c+1)$. When Assumption (15) is not satisfied, the objective function is convex in y at $x=1$, therefore unbounded if y can take arbitrarily large values, and it is optimal for firms to invest in both types of R&D until production costs vanish. On the other hand, if Assumption (15) is satisfied, but Assumption (16) is not, one can show that either there exist no intersection point of $x^c(y)$ and $y^c(x)$, and the optimal solution is then at $\left(x=1, y=\frac{2}{9A-4}\right)$, or there are two intersection points, one of which is a saddle point. ∎

6 Numerical Results

As it is not possible to have explicit closed-form solutions, we resort to numerical experiments to gain some qualitative insight into the (fully analytically) characterized equilibria. In particular, we are interested in assessing the impact of key model parameters on strategies and outcomes, and in comparing profits, consumers' surplus and total welfare under the two modes of play, i.e., non-cooperative and cooperative R&D. Note that in the sequel, we retain the restrictions on parameter values derived for the cooperative solution, which are more stringent than their non-cooperative counterparts.

The parameter set characterizing the game is $\{A, B, \beta\}$, with $B=\frac{D}{l^2}$. As we are interested in highlighting, among other things, the impact of the learning parameter, we shall present the results in terms of the parameters A, D, β and l. Recall that $A>0$ and $D>0$ are the coefficients of the investment cost function in innovative and absorptive research, that $\beta \in [0,1)$ is a parameter capturing the free and exogenous spillover, and that $l>0$ is a learning or absorptive parameter. The first step is to define the space of feasible parameter values and to discretize it using some suitable step sizes for the various parameters. In our context, as three out of the four parameters of interest, namely, A, D and l, do not have any natural upper bounds, the definition of a numerical grid is somewhat arbitrary, as long as the combination of values remains in the feasible region. For the sake of parsimony, we let l vary in the same way as β, i.e., in the interval $[0.1, 1]$.[1] For the cost parameters, we arbitrarily assume that $A, D \in [1, 5]$, that is, the largest value for each of them can be up to 5 times the lowest one.[2]

The results are reported in six series of figures. In each series, we show three values for β, namely, a low (0.1), medium (0.5), and a high value (0.9), and vary the value of l in the interval $[0.1, 1]$. In each series, the first two rows report the results for equal innovative and absorptive costs, while the last two rows show the results for asymmetric costs. In this way, we can immediately see (i) the impact of increasing both costs (by comparing row 1 to row 2), (ii) the impact of increasing absorptive research cost (by comparing row 1 to row 3), and (iii) the impact of increasing innovative research cost (by comparing row 1 to row 4). We emphasize that the results presented here represent a very small subset of the total number of conducted experiments.[3]

We summarize our findings in seven claims. Claims 1-3 assess the impact of varying the parameter values on R&D equilibrium strategies. Claim 4 compares investment strategies under non-cooperative R&D and RJV. Claim 5 compares the investment levels in innovative and absorptive research, and Claims 6-7 relate to the outcomes (profits, consumers' surplus and welfare).

Claim 6.1 ***Impact of cost parameters on strategies.*** *Increasing the cost of any type of R&D activity, leads to*

1. *lower* ***investment*** *in that research activity (see Figures 2-4);*
2. *lower profits and* ***consumers' surplus****, and consequently to lower* ***welfare*** *(see Figures 5-7).*

The above results are expected. Indeed, a higher investment cost in R&D means lower investment and higher production cost, which implies a higher price to consumer and lower demand for the product. Consequently, profits and consumers' surplus are lower, and so is total welfare.

Claim 6.2 ***Impact of spillover parameter on strategies.*** *For any cost configuration and any given l, increasing β leads to*

[1] We exclude zero as a lower bound because the characterization of the solutions was made under the assumption that $l > 0$.

[2] Actually, we compared the results obtained with values of A as high as 50 times the lowest value (similarly for D) and the conclusions remain qualitatively the same.

[3] Results for other parameters' value are available from the authors upon request.

1. *higher (lower) investments in* ***innovative research*** *when the firms cooperate (do not cooperate) in R&D (Figure 2);*

2. *higher (lower) investments in* ***absorptive research*** *when the firms cooperate (do not cooperate) in R&D (Figure 3);*

3. *higher (lower)* ***total knowledge*** *(effective R&D) when the firms cooperate (do not cooperate) in R&D (Figure 4).*

The result that firms increase their investments in innovative R&D when they cooperate (item 1), can be explained by the fact that cooperating firms internalize the free spillover; thus, increasing the latter makes the investment in innovative R&D more efficient and results in a higher investment. However, when β is increased in the non-cooperative case, firms are incited to invest less in innovative research and to profit from this increasing gratuitous research spillover. The result in item 2 is of interest in view of its newness to the literature, and because it carries a priori a non-obvious message. Indeed, under cooperation, one could presume that when the free spillover decreases, firms are tempted to compensate by increasing their investment in absorption capacity, but our computations show that this is not the case. The explanation is that when the free spillover decreases, cooperating firms reduce their innovative research, which incite them to invest less in absorptive research. On the other hand, non-cooperating firms invest less in absorptive R&D when the free spillover increases, because the reduction in the investment in innovative research renders the former less efficient. The result in the third item is a consequence of the first two.

Recall that the results obtained in [15], [16] and [17] are not comparable to ours because there is no free spillover in their model of absorptive research. On the other hand, although the existence of a free R&D spillover has been assumed in many studies (e.g., [1], [2], [4], [5], [8], [9],[10], [11], [13], [14]), none of them assessed the impact of varying this parameter on R&D levels. In this sense, the results in Claim 2 are new, and cannot be compared to the literature.

Claim 6.3 ***Impact of learning parameter on strategies.*** *Under both cooperation and non-cooperation in R&D, for any cost configuration and any given β, increasing l leads to*

1. *almost no change in investments in* ***innovative research*** *(Figure 2);*

2. *higher investments in* ***absorptive research*** *(Figure 3);*

3. *higher **total knowledge** or effective R&D (Figure 4).*

Contrary to what we found when varying the spillover parameter, here the direction of change is the same under both cooperative and non-cooperative R&D. Interestingly, a higher value for the learning parameter increases the efficiency of the investment in absorption, and that is why the investment in absorptive R&D increases with the learning parameter. This is similar to the result found in the non-cooperative case by Hammerschmidt ([17]).

Our results show that l does not have any significant impact on investment in innovative research. Indeed, even when we multiply the value of l by ten, that is, we consider the two extreme values of $l = 0.1$ and $l = 1.0$, we obtain a variation of less than 10% in individual investments in innovative R&D. As explained above, a greater value for the learning parameter increases the investment in absorptive R&D, which may discourage the investment in innovative R&D. On the other hand, a higher learning ability increases the efficiency of innovative research, and therefore we could a priori expect it to increase. It seems that these two opposite effects neutralize. This interesting result is different from the one found by Hammerschmidt ([17]) for the non-cooperative case where she showed that the investment in innovative R&D decreases with the learning parameter. This is due to the fact that the learning parameter in her model has a multiplicative impact on both the free spillover parameter and the learning capacity, while in our model we disentangle the two phenomena.

As a direct consequence of the two preceding results, total knowledge increases with l. Therefore, for any given cost structure, it seems that the significant determinants of innovative R&D are the firms' behavior (cooperate or not in R&D) and the spillover parameter β. We discuss below the welfare implications of this result.

Claim 6.4 ***Cooperative versus non-cooperative R&D strategies.*** *For any cost configuration*

1. *when the spillover is sufficiently low, that is $\beta \ll 0.5$, firms invest more in **innovative R&D** in the non-cooperative equilibrium than in the RJV solution. It is the other way around for $\beta \gg 0.5$ (Figure 2);*[4]

2. *when the spillover is sufficiently low, that is $\beta \ll 0.5$, non-cooperative*

[4]The exact threshold where investments are the same is around 0.5, but depends on other parameter values.

investment in ***absorptive research*** *is higher than its cooperative counterpart (Figure 3);*

3. *when the spillover is sufficiently low (high), that is $\beta \ll 0.5$ ($\beta \gg 0.5$) the* ***total knowledge*** *is higher (lower) in the non-cooperative equilibrium than in the RJV solution (Figure 4).*

The first result is the same as in [1]. It appears that the statement made in the first item and in the early literature ([1], [5], [9], [13]) is robust to the inclusion of additional features in the model, namely, absorptive research and learning. When the free spillover is low, non-cooperating firms invest more in innovative research than cooperating ones. This incites them to invest more in absorptive research under non-cooperation in order to increase the R&D externality. This result is new and interesting because the studies (i.e., [15], [16], [17]) that have considered investment in absorptive research as a decision variable did not include a free spillover parameter and have not compared cooperation to non-cooperation. The level of total knowledge, which results from both types of R&D, goes generally in the same direction as innovative research.

Claim 6.5 ***Comparison of innovative and absorptive research.*** *The investment in innovative R&D is always higher than the investment in absorptive R&D (Figures 2 and 3).*

The above result is valid for both the non-cooperative and cooperative cases, and holds even when the investment cost in innovation is much higher than the one for absorption ($A = 5 > D = 1$), and when the learning parameter is very high. The intuition behind this result is that the investment in absorption takes its economic value from innovation. This result confirms the result found in [17] in the non-cooperative case and extends it to the RJV case.

In the next two claims, we summarize the results regarding the outcomes.

Claim 6.6 ***Impact of spillover and learning parameters on outcomes.***

1. *For any cost configuration, increasing β leads to:*

   (a) *higher individual profits. This holds true under both modes of play (Figure 5);*

   (b) *higher consumers' surplus when firms cooperate, and almost no impact when they behave non-cooperatively (Figure 6);*

(c) higher total welfare under cooperation (Figure 7).

2. *For any cost configuration, increasing l does not significantly affect profits, consumers' surplus or welfare.*

We observe that a higher value for the free spillover parameter is beneficial to firms in both modes of play. However, increasing β has a positive effect on consumers' surplus and social welfare in the cooperative case, and almost no impact on consumers' surplus in the non-cooperative case. In the cooperative case, a higher β leads to a higher effective research and lower production cost. Consequently, profits and consumers' surplus are higher, and so is the social welfare. On the contrary, a higher β leads to a lower effective research in the non-cooperative case, and hence to a higher unit-production cost (see Claim 2). This leads to the ambiguity of the impact of β on social welfare. The literature in this area does not assess the impact of varying the spillover parameter on outcomes.

From Claim 3, we know that increasing l, reduces the unit production cost but increases the investment cost in absorption. Consequently, varying the learning parameter has a little impact on firms profits and production, consumers' surplus, and social welfare. Therefore, even if a higher value for the learning parameter increases the efficiency of investing in absorptive research, it has no impact on profits, consumers' surplus and social welfare. This last result contradicts the one established by Grünfeld ([11]) who found a significant impact of the learning parameter on welfare. However, notice that [11] does not consider the possibility of investing in absorptive capacity, so that the the learning parameter in his model represents the efficiency of own inventive R&D in promoting absorptive capacity.

Claim 6.7 ***Ranking of outcomes.*** *For any cost configuration, we obtain that*

1. *individual profits under RJV dominate their non-cooperative counterparts. For $\beta = 0.5$, the profits are (almost) equal (Figure 5);*

2. *when the spillover is sufficiently low, that is $\beta \ll 0.5$, consumers' surplus and total welfare are higher in the non-cooperative equilibrium than in the RJV solution. It is the other way around for $\beta \gg 0.5$. For $\beta = 0.5$, consumers' surplus and total welfare are almost equal (Figures 6-7).*

We know from Claim 4 that, depending on the value of the spillover parameter β, the unit production cost (resp. the investment cost in R&D) increases (decreases) or decreases (increases) with cooperation. The consequence is that a RJV is beneficial for firms. This result is similar to the one found in Kamien et al. ([5]). Amir and Wooders ([6]) and Salant and Shaffer ([4]) found that non-cooperative asymmetric equilibriums may raise joint profit with respect to an RJV. Recall however that in our model, there is a unique non-cooperative equilibrium, which is symmetric.

When the value of the free spillover parameter is low, the unit production cost is higher and the research investment cost is lower under cooperation than competition, leading to an important reduction in production and consumers' surplus; consequently, the social welfare decreases with cooperation even though the profit of firms increases.

Conversely, when β is high, unit production cost is lower and investment in R&D is higher under a RJV, leading to an increase in production and consumers' surplus with respect to competition; since the profits of firms also increase, the social welfare is higher with cooperation and when β is high. This result is similar to the one found by Kamien et al. ([5]).

7 Conclusion

In this paper, we considered two types of R&D investment decisions, where firms may decide to invest in innovative research to reduce their production cost and/or to invest in absorptive capacity, to be able to profit from other firms' innovations. We characterized and compared cooperative and non-cooperative R&D equilibrium strategies and outcomes in a two-stage game of R&D investment followed by Cournot market competition. We also assessed the impact of varying the spillover and the learning parameters on the R&D levels and outcomes. We showed for both the non-cooperative and the cooperative case that there exist a unique symmetric subgame-perfect Nash equilibrium. As the solution, while analytical, cannot be stated in closed-form, we resorted to numerical experiments to investigate the equilibrium results. Whereas some of our results confirm what was already known for other models involving spillovers and absorptive capacity, other results extended our knowledge. By disentangling the impact of investment decisions on knowledge and on absorptive capacity, we found that some results differ from what has been found earlier under different settings.

Innovative research

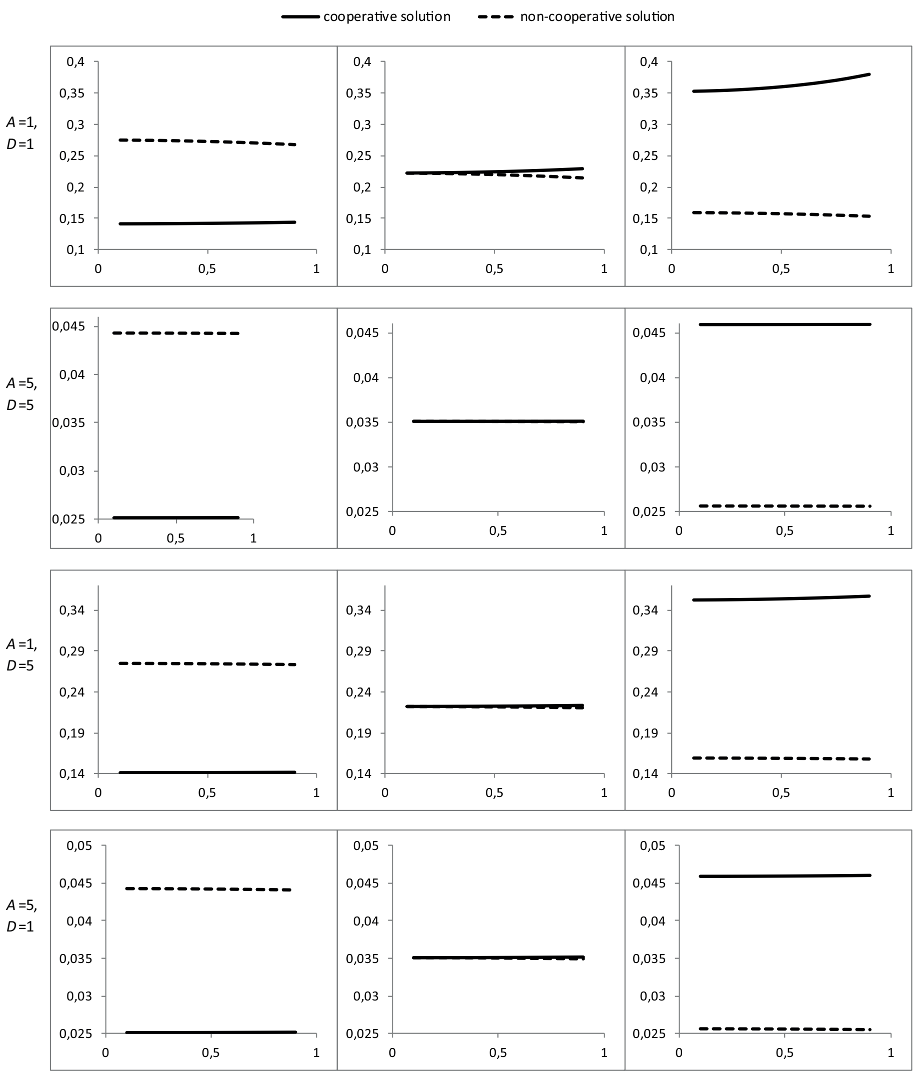

Figure 2: Impact of parameter values on innovative research. Vertical axis: level of innovative research (y^n, y^c). Horizontal axis: learning parameter (l). Left panel: $\beta = 0.1$; center panel: $\beta = 0.5$; right panel: $\beta = 0.9$. Unit cost of innovative research (A) and of absorptive research (D) in $\{1, 5\}$.

Absorptive research

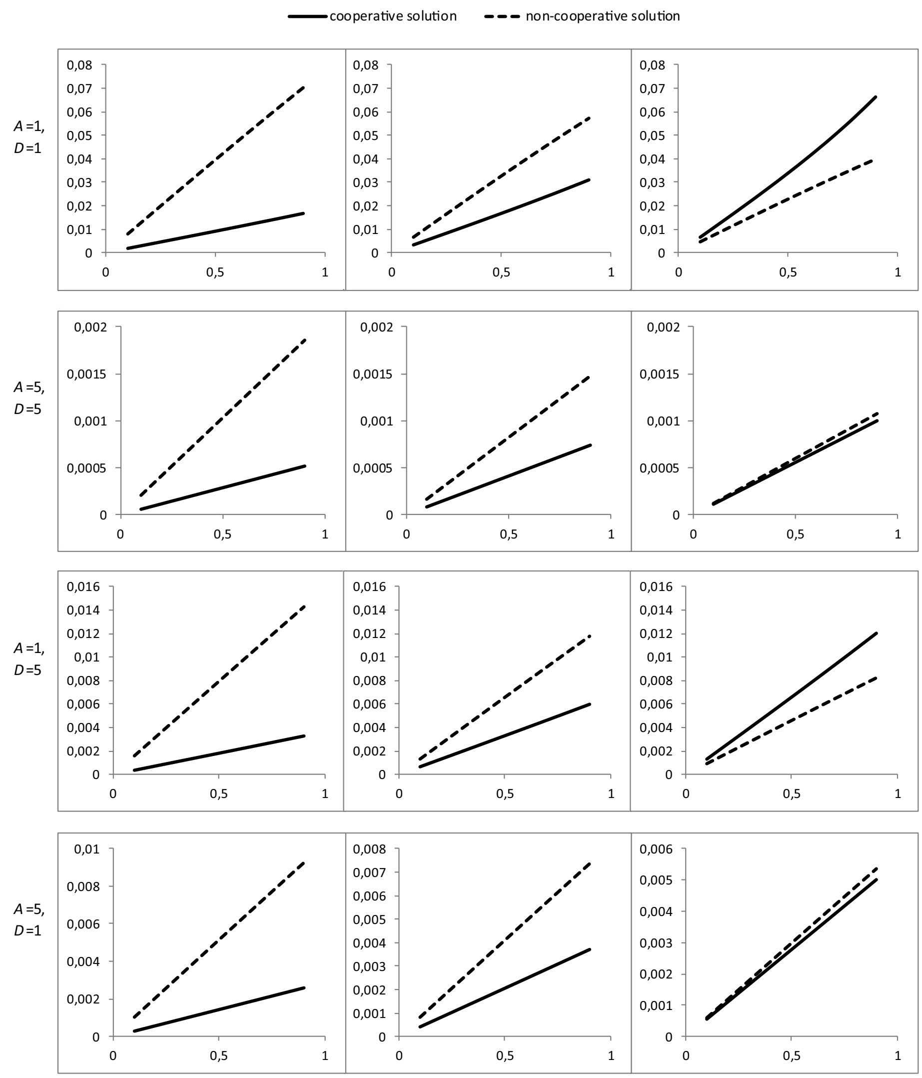

Figure 3: Impact of parameter values on absorptive research. Vertical axis: level of absorptive research (a^n, a^c), where $a = \frac{x-\beta}{l}$. Horizontal axis: learning parameter (l). Left panel: $\beta = 0.1$; center panel: $\beta = 0.5$; right panel: $\beta = 0.9$. Unit cost of innovative research (A) and of absorptive research (D) in $\{1, 5\}$.

Effective R&D

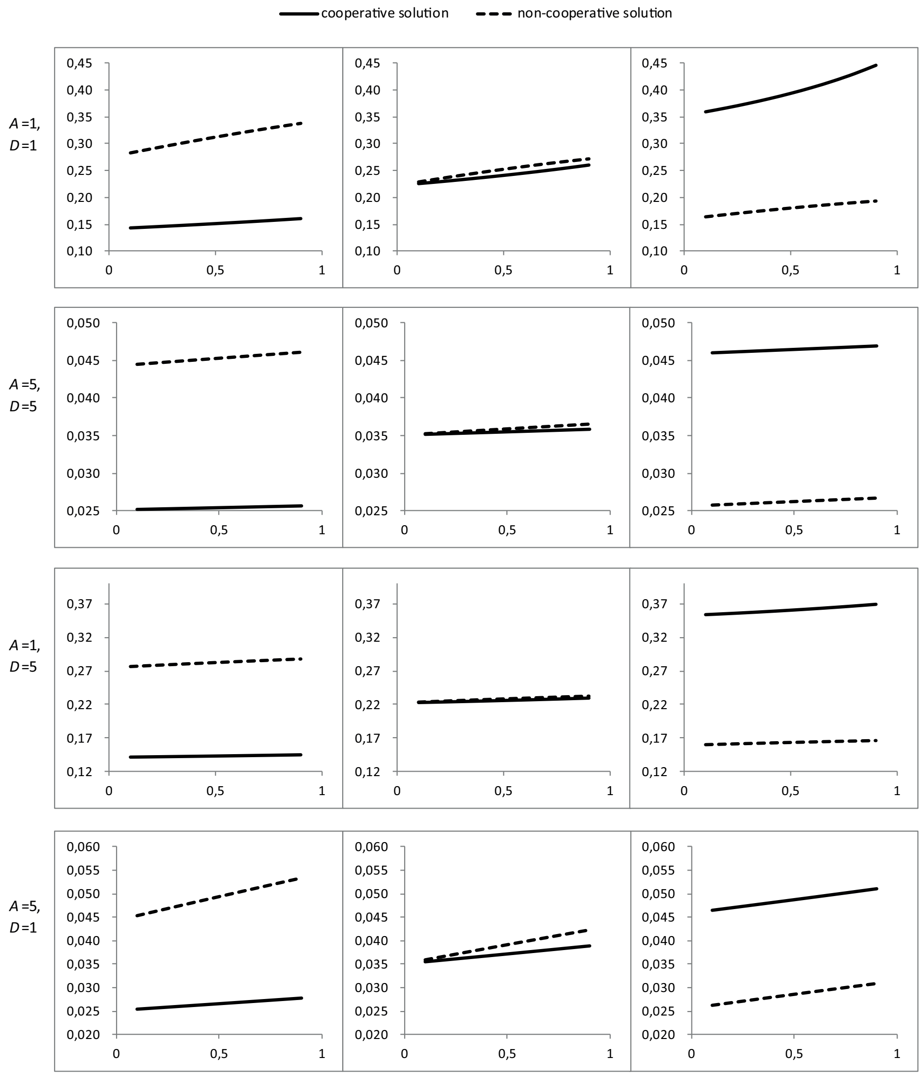

Figure 4: Impact of parameter values on effective R&D. Vertical axis: total level of R&D $(y^n + a^n, y^c + a^c)$, where $a = \frac{x-\beta}{l}$. Horizontal axis: learning parameter (l). Left panel: $\beta = 0.1$; center panel: $\beta = 0.5$; right panel: $\beta = 0.9$. Unit cost of innovative research (A) and of absorptive research (D) in $\{1, 5\}$.

Firm profits

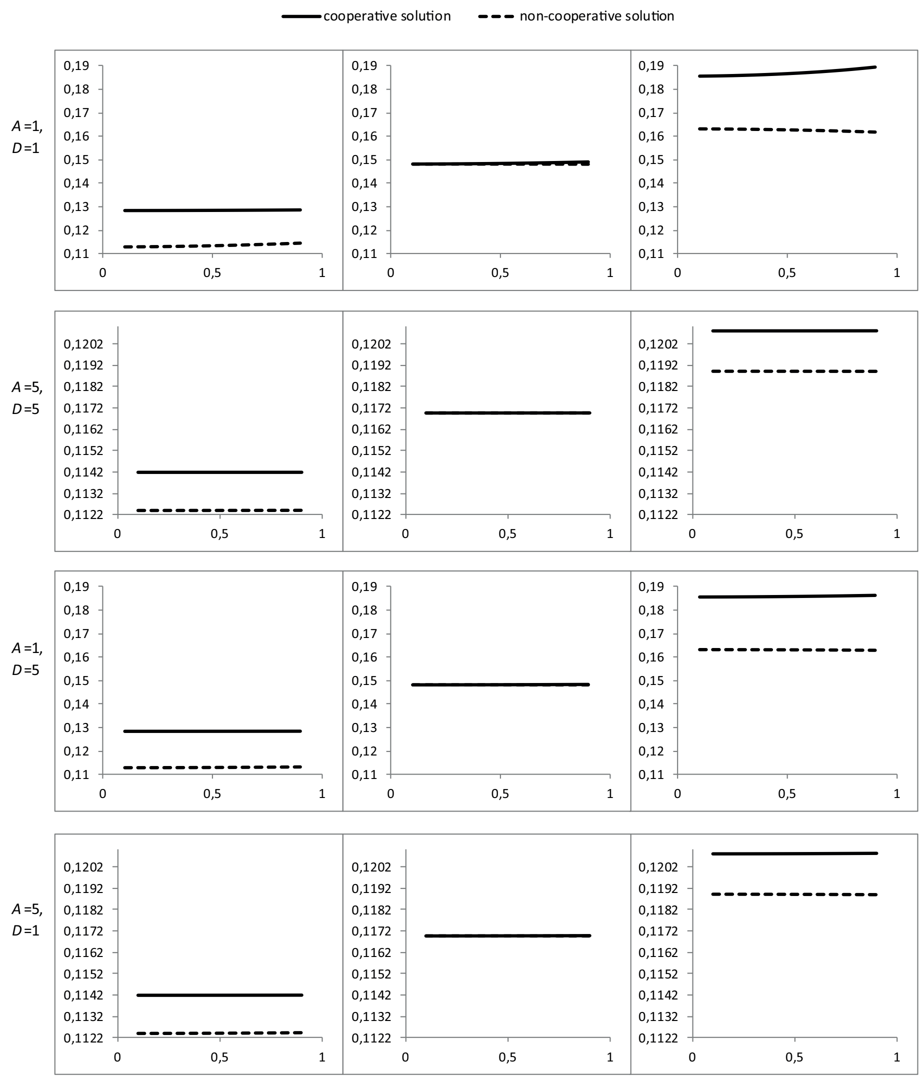

Figure 5: Impact of parameter values on firms profits. Vertical axis: equilibrium profits (Π^n, Π^c). Horizontal axis: learning parameter (l). Left panel: $\beta = 0.1$; center panel: $\beta = 0.5$; right panel: $\beta = 0.9$. Unit cost of innovative research (A) and of absorptive research (D) in $\{1, 5\}$.

Consumer's surplus

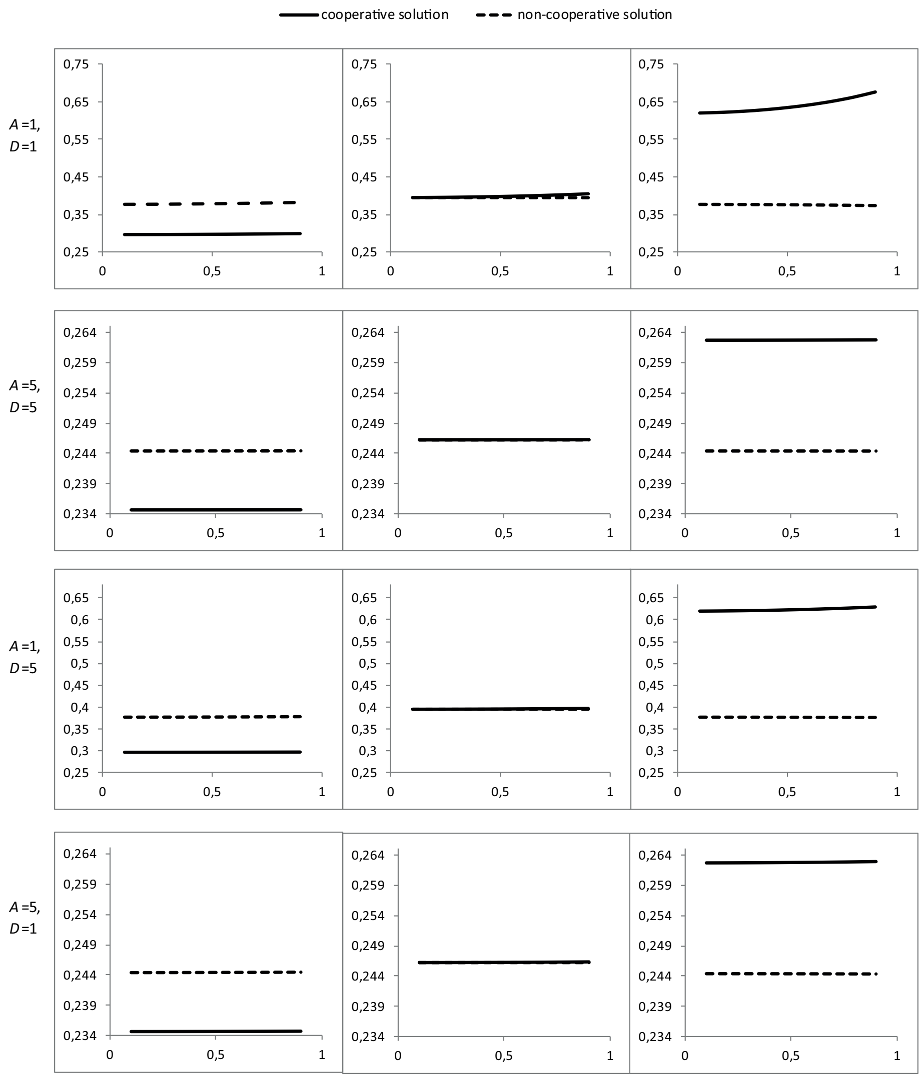

Figure 6: Impact of parameter values on consumer's surplus. Vertical axis: equilibrium consumer's surplus (CS^n, CS^c). Horizontal axis: learning parameter (l). Left panel: $\beta = 0.1$; center panel: $\beta = 0.5$; right panel: $\beta = 0.9$. Unit cost of innovative research (A) and of absorptive research (D) in $\{1, 5\}$.

Social welfare

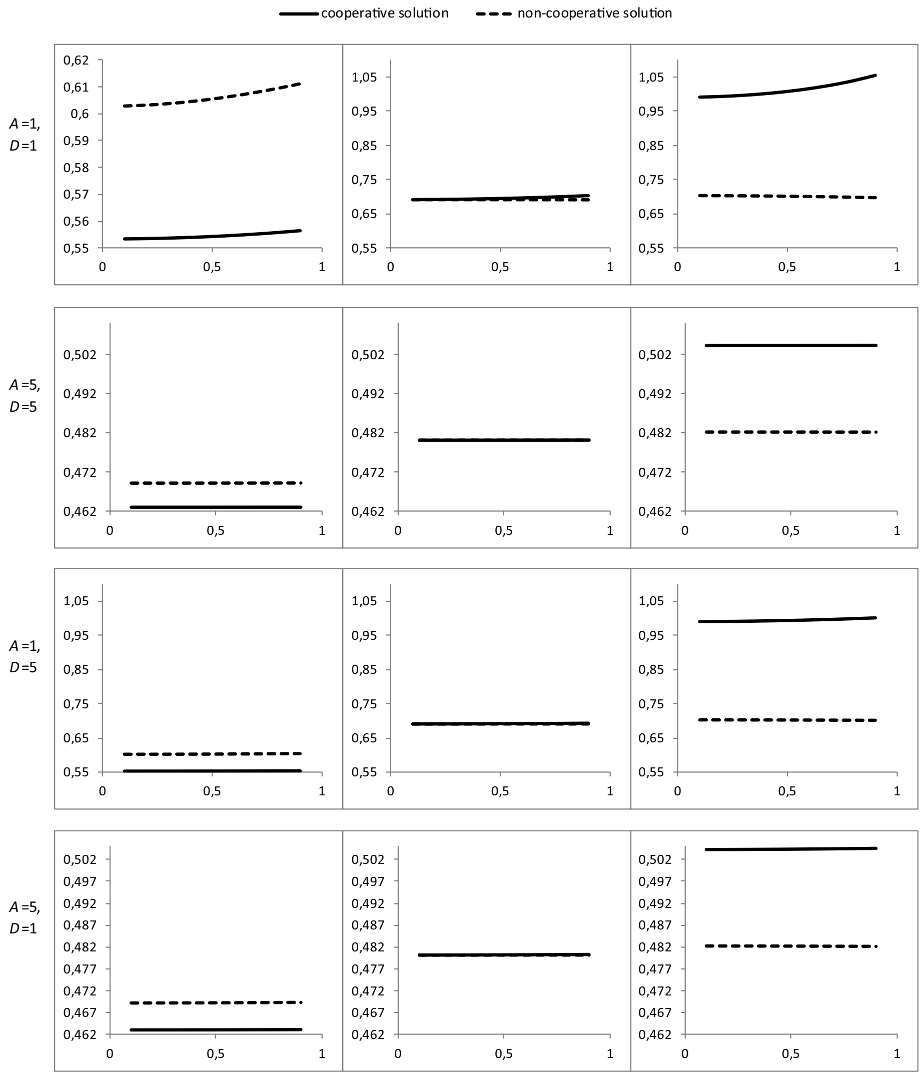

Figure 7: Impact of parameter values on total welfare. Vertical axis: equilibrium social welfare (S^n, S^c). Horizontal axis: learning parameter (l). Left panel: $\beta = 0.1$; center panel: $\beta = 0.5$; right panel: $\beta = 0.9$. Unit cost of innovative research (A) and of absorptive research (D) in $\{1, 5\}$.

We obtained that varying the learning parameter has almost no impact on innovative R&D, firms' profits, consumers' surplus and social welfare. Therefore, even if a higher absorptive parameter increases the efficiency of investing in absorptive research, it has almost no impact on social welfare.

When the free spillover is low, the investment in absorptive R&D, consumers' surplus and social welfare are higher under non-cooperation than under a RJV. However, cooperation is welfare improving when the free spillover is high.

The investment in innovative R&D is always higher than in absorptive R&D for both the cooperative and non-cooperative cases. This remains true even when the investment cost in innovation is much higher than that of absorption.This is due to the fact that the investment in absorption takes its economic value from innovation.

Increasing the free spillover, leads to higher profits under the two regimes, and to higher social welfare and investments in absorptive research in a RJV. However, increasing the free spillover reduces the investment in absorptive research under non-cooperation.

Our model is static, and considers firms that are symmetric in all parameters and results in symmetric non-cooperative and cooperative solutions. Interesting extensions would be to consider asymmetrical firms and a dynamic setting where the stock of knowledge and absorptive capacity evolves over time.

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