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MARIE-LAURE CABON-DHERSIN and SHYAMA V. RAMANI

DOES TRUST MATTER FOR R&D COOPERATION? A GAME THEORETIC EXAMINATION

ABSTRACT. The game theoretical approach to R&D cooperation does not investigate the role of trust in the initiation and success of R&D cooperation: it either assumes that firms are non-opportunists or that the R&D cooperation is supported by an incentive mechanism that eliminates opportunism. In contrast, the present paper focuses on these issues by introducing incomplete information and two types of firms: opportunist and non-opportunist. Defining trust as the belief of each firm that its potential collaborator will respect the contract, it identifies the trust conditions under which firms initiate R&D alliances and contribute to their success. The higher the spillovers, the higher the level of trust required to initiate R&D cooperation for non-opportunists, while the inverse holds for opportunists.

KEY WORDS. Non-cooperative game, R&D cooperation, Trust and opportunism.

JEL CLASSIFICATION CODE: C720 Non-cooperative games; L130 Market structure, firm strategy and performance; D320 Management of technology, innovation and R&D.

1. INTRODUCTION

Arrow (1962) first established the classic result that firms tend to under-invest in R&D, when knowledge spillovers are high, or when competitors can capture any new knowledge that is created, easily and cheaply. However, firms can internalize such spillovers through R&D cooperation and appropriate higher returns than under non-cooperation. Such R&D consortia involve cooperation in terms of cost sharing, information sharing or both. They allow firms to realize higher returns from R&D expenditure through non-duplication of research and enable learning through sharing of information. R&D cooperation is increasing in the high-tech sectors due to growing research costs and rising technological and market uncertainty. This trend has stimulated an extensive game theoretical literature concerning incentives for inter-firm R&D cooperation.

This literature may lead us to believe that R&D cooperation between firms is quite common and that collaboration once initiated between any set of firms, is unlikely to fail. However, in reality, neither of these two predictions is entirely valid. Even in high tech sectors, where R&D consortia are definitely multiplying, cooperation at the R&D level is still more the exception than the rule. Furthermore, a large number of joint ventures, including those involving R&D cooperation, break down before completion of the project (Kogut, 1989). Though some of these breakdowns can be explained by mistaken exante perceptions of the costs and benefits associated with cooperation, others are cited as having broken down due to manifestations of opportunism (Deeds and Hill, 1998).

Firms entering into a relationship via a common R&D project often do not fix the details about what the partners are expected to do during the course of the cooperation ex-ante. Given such incomplete contracts, the harmonization of firm motivations is imperfect, and the efficiency of cooperation is limited. Moreover, third party verifications of R&D efforts is usually impossible. Thus, trust becomes necessary to justify the engagement of firms in cooperation.

Let us define 'opportunism' as cheating on contracts, commitments or engagements and an 'opportunist' as an agent who cheats whenever it is in his interest to do so. In any R&D cooperation, there is a potential for opportunism stemming from the inherent incompleteness of R&D contracts, as it is not possible for a third party to monitor R&D effort and information transfer. Hence, it is difficult to prevent opportunism through legal contracts ex-ante. This in turn implies that the evaluation of potential opportunism plays a crucial role in the initiation and success of R&D cooperation. Reformulating the same argument, trust is defined simply as the *probabilistic belief of a firm that its partner in the R&D consortium will respect the contract,*[1] has a crucial impact on the initiation and the success of the R&D alliance. However, game theoretic models have little to say on the role of trust in the initiation and success of R&D cooperation, especially in a 'one shot game', because in the economics literature trust is usually endogenized through repetition of the game.

The notion of trust retained in this paper is different from the standard formulation of trust in game theory. In conventional game theory, trust between agents emerges as a result of a reputation mechanism and/or repetition of interactions. In contrast, our model consists of a one-shot sequential game, where there is no repetition, no punishment scheme and no incentive mechanism to induce trust. Trust is taken as an exogenous parameter, an initial endowment of each firm in terms of a priori belief that the other firm will honor the contract. Furthermore, the objective of this paper is not to understand the determinants of the degree of trust or the measurement of trust, which is indeed the subject of an extensive empirical literature (to be detailed later on). Our analysis focuses only on the role and impact of trust on cooperation and contract initiation.

In order to contribute to a better understanding of the relationships between trust, opportunism and success in R&D cooperation, the present paper introduces heterogeneous firms and incomplete information in the seminal R&D cooperation models of d'Aspremont and Jacquemin (1988) and Kamien et al. (1992). Conventional models consider all firms to be either opportunist or all firms to be non-opportunist. In both these cases, there is no role for trust. Thus, by introducing heterogeneity in terms of the propensity for opportunistic behaviour, we create room for trust and are able to understand the impact of trust on R&D cooperation.

A firm can be one of two types, either opportunist or nonopportunist. A non-opportunist firm never cheats on a contract even when it is in its interest to do so. The behavior of a non-opportunist firm is motivated by considerations other than opportunism such as moral values or the costs of cheating. An opportunist firm, cheats on a contract if cheating yields a higher payoff than abiding by the contract. There is no 'screening' mechanism to identify opportunists and no 'incentive' mechanism to prevent cheating. The 'trust' of each firm, is its belief that its potential collaborator will respect the contract. In this case, the risk of opportunism is real and the initiation and success of cooperation depends on the initial trust configurations of the firms.

In this context, two central questions are examined:

(i) What is the relationship between the trust configurations and the initiation of R&D cooperation?
(ii) What is the relationship between the trust configurations and the outcome of R&D cooperation?

In answering the above two questions, the present paper makes a fourfold contribution to the game theoretic based literature on R&D cooperation.

First, it shows that there can be situations where an R&D cooperation is not initiated and situations where an R&D cooperation fails after initiation. This implies that the standard result of the game theoretic models, according to which R&D cooperation is always initiated and successfully achieved, is not likely to be verified. Furthermore, since R&D contracts are not always implemented in the context of a repeated game, the above definition also permits us to avoid having recourse to reputation mechanisms, which suppose that trust can only emerge through repeated interaction.

Second, the results of the paper question the usually held opinions that opportunism is a systematic obstacle to contract initiation, while trust is a sufficient condition for the same. It doubly invalidates this stance by identifying exceptions to this apparent rule. For instance, when spillovers are high, and when the firms involved are opportunists, R&D cooperation can be initiated without trust. Moreover, when two opportunists initiate a contract, they may cheat, but the R&D alliance need not be unsatisfactory, i.e., each firm can earn more than under noncooperation.

Third, the model refines the standard results of game theoretic models of R&D cooperation. For instance, the conclusions of d'Aspremont and Jacquemin (1988) or Kamien et al.

(1992) (See DeBondt (1997) for an extensive survey) can also be inferred as a special case of our model, when non-opportunist partners in the R&D alliance have sufficient trust in one another to initiate cooperation and the level of spillovers is sufficiently high. In this case, R&D expenditure under cooperation is greater than under non-cooperation, and there is an increase in social welfare. Our results also extend those of Kesteloot and Veugelers (1995), who find that a high level of spillovers always leads to a greater instability of cooperation. We show that a high level of spillovers imply a greater instability of cooperation for a non-opportunist firm, which anticipates confronting an opportunist firm, but not so for opportunist firms.

Finally, the paper identifies the role of trust in the initiation and success of cooperation. Trust facilitates the initiation of R&D cooperation, but is neither necessary nor sufficient to ensure higher payoffs than from non-cooperation. The level of trust required for the initiation of R&D cooperation depends on the type profile of the firms and on the level of spillovers.

It can be argued that it is not surprising to observe failure and non-initiation of R&D cooperation emerging as equilibrium outcomes with a positive probability, since we have introduced incomplete information with no possibility for 'screening' or 'signaling'. While this is true, we wish to reiterate that by not allowing for the elimination of opportunism through screening or signaling, we are forced to examine how beliefs on player types influence the decision to cooperate. Furthermore, by considering heterogeneity in terms of the opportunistic nature of firms (rather than in terms of their degree of risk aversion, their competence, their profitability etc.) we are able to interpret beliefs on player types in terms of trust. This not only allows us to formulate a pertinent definition of trust, but it also permits us to study the relation between trust, opportunism, initiation and success of cooperation in R&D.

This paper is organized as follows. Section 2 briefly surveys the literature on R&D cooperation and trust in the game theoretic literature. Section 3 presents our model and Section 4 contains the results. Section 5 concludes the paper.

2. GAME THEORETIC APPROACHES TO R&D COOPERATION AND TRUST

This section briefly reviews the main papers on R&D cooperation modeled as games, but it is not meant to be an exhaustive survey. It also compares the concept of trust as developed in this paper with the existing notions.

2.1. *R&D cooperation between symmetric non-opportunist firms*

The first models on R&D cooperation considered the simple context of identical non-opportunist firms in order to examine the conditions under which R&D cooperation promotes private and social welfare. They showed that R&D cooperation might be motivated by cost and information sharing in the presence of spillovers. When spillovers are high, R&D cartels (involving cost and information sharing) call for high R&D expenditures. This leads to economies of scale in terms of cost reduction, since each firm also benefits from the increased R&D efforts of other firms, given the high level of spillovers. The seminal article by d'Aspremont and Jacquemin (1988) is one of the most influential papers in this group. Their basic R&D cartel model in a duopoly framework has now been extended along various lines, with the consideration of oligopolies, heterogeneous products, product innovation, vertical cooperation, participation in multiple R&D cartels, multiple participants, etc. (Kamien et al. 1992; Motta, 1992; Suzumura, 1992; Ziss, 1994; DeBondt, 1997; Hinloopen, 2000). More recent models have also confirmed the preceding results taking into account the endogenization of spillovers (Katsoulacos and Ulph, 1998; Poyago-Theotoky, 1999).

Another set of models studies the impact of spillovers in a stochastic or dynamic context. When spillovers or imitations are likely, R&D cartels are again initiated due to the internalization of market spillovers of knowledge and non-duplication of research efforts (Grossman and Shapiro, 1987; Beath et al. 1988; Katsoulacos, 1988; Choi, 1993).

A third set focuses on the incentives for R&D cooperation in the absence of spillovers. Marjit (1991) shows that when the probability of discovery is very high or low, by sharing costs, firms can reduce the risk associated with uncertain returns, and they can also undertake research that might not have been financially feasible otherwise. Combs (1993) extends this model by considering the case, where firms share the knowledge generated by R&D, but cannot share costs. In this case, the firms initiate cooperation only when the probability of success is high.

2.2. *R&D cooperation between asymmetric non-opportunist firms*

A few of the recent papers examine the incentives for R&D cooperation given asymmetric firms.[2] Poyago-Theotoky (1997) studies an *n*-firm market with specialist and non-specialist firms, where the specialist firms can improve upon some of the characteristics of the commodity through R&D. She then shows that depending on the extent of quality improvement, R&D cooperation may or may not be socially desirable.

2.3. *R&D cooperation between symmetric opportunist firms*

R&D cooperation between a set of symmetric opportunist firms has been examined by some authors in a repeated game framework (Kesteloot and Veugelers, 1995). In this type of model, opportunist firms are made to cooperate by implementing an implicit system of sanctions that results in a loss of reputation, or non-renewal of contracts, for any manifestation of opportunism. Studying the impact of spillovers on the stability of contracts in the context of such repeated games, the authors show that spillovers might have a positive or negative impact on the stability of R&D cartels, depending on the nature and degree of spillovers relative to the nature and magnitude of product market competition.

2.4. *R&D cooperation between asymmetric opportunist firms*

Finally, a last set of models has studied the design of incentive systems to eliminate opportunism. They have highlighted informational asymmetries, which are at the origin of potential opportunism arising in cooperation.

Some models resolve the problems of moral hazard and adverse selection by the formulation of revelatory mechanisms and complete optimal contracts that render cooperation attractive (Picard and Rey, 1991; Gandal and Scotchmer, 1993; Morash, 1995). Pérez-Castrillo and Sandonis (1997) study a model in which the disclosure of information lowers the expected cost of the project. An R&D cartel may fail to be formed due to the moral hazard problem arising from the difficulty of contracting out information transfer. This problem is however resolved by setting up a system of punishments for deviations from the contract. Evidently, all of the models above suppose that complete contracts can be initiated, with contingency payoffs being envisaged for every possible eventuality at the time of the signature of the contract. Thus, once cooperation is initiated, it is always a success. Others, like Bhattacharya et al. (1990, 1992) attack the moral hazard problem from a different angle, developing an incentive scheme involving R&D licenses to ensure efficient sharing of information within an R&D consortium.

2.5. *Different conceptions of trust*

The *raison d'être* of trust is most often grounded in the incompleteness of contracts that characterizes inter-firm cooperation in R&D (Arrow, 1974). In other words, trust encourages inter-firm cooperation by reducing the costs of transaction and by eliminating manifestations of opportunism (Bromiley and Cummings, 1995). Trust is a social norm, which lessens the need to use hierarchy to attenuate opportunism. This has led other researchers to undertake extensive empirical studies to identify and understand the determinants of trust (Sako and Helper, 1998; Glaeser et al. 2000).

In addition, there exists an extensive empirical literature that considers trust as a form of 'social capital' and studies the impact of inter-firm trust on sectoral or regional development. For instance, on the basis of comparative studies of national trajectories of development, the industrial success of Japan during the 1980s has been attributed to the high degree of trust that characterizes relations between Japanese managers and organizations (Casson, 1991). There are also some theoretical papers that model economic growth as an increasing function of trust (Zak and Knack, 2001).

Standard game theory predicts that trust and hence cooperation will emerge provided agents can interact repeatedly to build up reputation (Kreps, 1990). This last point has been broadly investigated within the framework of repeated games with complete or incomplete information (and with a finite or infinite horizon). Within this framework, an agent is assumed to trust another agent, whenever it is in his interest to do so. In other words, economic agents are motivated to create trust and to cooperate on the basis of calculations. Any manifestation of opportunism thus results in a penalty, such as the breakdown of trust and transactions, which in turn implies a loss of reputation or the impossibility of future interaction. Trust then emerges as an action based on the calculation of gains and losses associated with each opportunity. In our model, unlike what happens in the game theoretical models evoked above, trust cannot emerge on the basis of economic calculations, because it is a one shot game.[3] Trust is simply an exogenously given probabilistic belief of a firm (which is common knowledge) that its potential collaborator will respect its commitments. This kind of a definition (i.e., as a given belief) can now also be found in some of the papers in the trust literature (see Gueth et al. 2000; James 2002; Buskens, 2003).

Williamson (1993) presents yet another alternative view pointing out that the notion of trust put forward as a concept by economists is a direct deduction of reciprocity. According to Williamson, real trust or 'personal trust' is something that characterizes very specific relations such as those between the members of a family or lovers with no quid pro quo. Our notion of trust as a probabilistic belief of a firm that its competitor will respect the contract does not conform to the notion of 'personal trust' à la Williamson, as it can be applied to relations involving any set of economic agents.

3. MODEL OF R&D COOPERATION

We will present the game in three sub-sections. In the first, we will describe the game and introduce the notation. In the second, we will solve for the optimal strategies and the payoff functions. Lastly, using simulations, we will identify the properties of the R&D expenditure functions and the payoff functions.

3.1. *Description of the game*

There is a duopoly market with two firms i and j. Each firm i can be one of two types: an opportunist $t_{i,\mathrm{o}}$ or a non-opportunist $t_{\mathrm{i,n}}$. An opportunist firm is one that cheats on a contract, whenever it is in its interest to do so. A non-opportunist firm is one that never cheats, whether it pays to do so or not. The two firms are identical in all other respects.

There is incomplete information, i.e., each firm knows its own type but does not know the true type of the other firm. Each firm, hence, starts out with a set of beliefs about the type of the other firm. Let p be the belief of any firm that its partner is not an opportunist. Let s be the belief of any firm that an opportunist will respect a contract. The probabilistic beliefs p and s lie in the interval (0,1), i.e., they lie strictly between 0 and 1. Trust of any firm is then given by $1-(1-p)(1-s)$, i.e., the probability that a contract will be respected by a potential partner. The level of trust is common knowledge. In the above context, R&D cooperation is modeled as a two stage game. In the first stage, the firms decide on their R&D expenditures and in the second stage, they fix the quantities to be produced and sold in the market.

Let us suppose that firms can reduce their costs of production through investment in R&D. Let the R&D expenditures of firms i and j be given by x_i and x_j. Let the reduction in costs for firm i due to an R&D expenditure, x_i, be given by the function $g(x_i) = x_i^{1/2}$. The function $g(.)$ is non-negative, twice differentiable, increasing and strictly concave indicating that returns to R&D investment are subject to decreasing returns.[4]

When each firm spends on R&D, there is a spillover effect (to some non-negative extent under the given intellectual property regime), whereby the firms freely learn from the innovations or cost expenditure of other firms. Let b from (0,1) be the factor indicating the degree of spillover. Then from the spillover effect, each firm i experiences an additional reduction in costs equal to $bx_j^{1/2}$. Since R&D expenditure is assumed to reduce average costs of production, clearly the total reduction in production costs will depend on the scale of production. Let q_i stand for the quantity produced by firm i. Then the total reduction in the production costs of firm i, when firm i spends x_i on R&D, and firm j spends x_j, is given by $(x_i^{1/2} + bx_j^{1/2})q_i$. Similar is the case for firm j.

Each firm i faces a demand $p_i = f_i(q_i, q_j) = a - q_i - q_j$, where p_i stands for the price charged by the ith firm. The average cost of production is given by $c_i = c_j = c$, where $c > 0$ and $c < a$. Given an R&D profile of the two firms, (x_i, x_j) and the quantities to be supplied in the final market, (q_i, q_j), the profit of firm i, π_i (.), can be written as follows:

$$\pi_i = (a - q_i - q_j)q_i - (c - x_i^{1/2} - bx_j^{1/2})q_i - x_i. \qquad (1)$$

Similar is the case for firm j. The profit functions, π_i (.) and π_j (.), are strictly concave and continuous.

Now we move on to the game of R&D cooperation. It starts with nature, which chooses the type of each firm and continues with two stages.

The first stage corresponds to the undertaking of R&D investment. Each firm announces whether or not it wants to enter into a cost sharing R&D alliance. Immediately thereafter, each firm fixes its R&D expenditure, which is not observable. There is no 'screening mechanism' possible for the two firms to find out each other's types before considering the initiation of the cooperation and there is no 'incentive mechanism' that can be set up to ensure commitment. This implies that the contract initiated is necessarily incomplete and a firm that cheats thereafter cannot be punished through legal means.

An R&D cooperation is initiated only if both firms choose to enter into an alliance, otherwise not. The contract (formal or informal) of R&D cooperation stipulates that each firm spend the cooperation R&D expenditure, x^{r}, which maximizes the joint profits of the group as a whole (i.e., π_{i} (.) + π_{j} (.)). In other words, x^{r} maximizes the profit of the group, assuming that none of the firms deviate from their commitment in the rest of the game. This is in conformity with reality, where most often social norms are formulated assuming that agents will adhere to their commitments than otherwise. Therefore, firms in formulating the R&D cooperation accord, x^{r}, cannot explicitly take into account the fact that any firm can deviate from its commitment after the signing of the accord and, hence, x^{r} is independent of the trust configurations of the firms.

In the first stage, the actions available to each firm depend on its type. A non-opportunist firm can choose between non-cooperation and spending the R&D expenditure, x^{nc}, the investment that maximizes its profit function, π_{i} (.) or entering into an R&D alliance and investing x^{r}. An opportunist firm i has one more option. If an opportunist firm opts to enter into an R&D alliance, it can either respect the contract or not honor the contract. The cheating or opportunistic expenditure, x^{op}, is the R&D expenditure that maximizes its expected profit within the R&D alliance. On the other hand, a non-opportunist firm can only invest x^{r}, if it enters into an R&D cooperation, because it can not cheat on the contract by definition.[5] The decision tree of a non-opportunist firm i is illustrated in Figure 1.[6] It holds similarly for an opportunist firm. The R&D investments can be observed at the end of the first stage.

The second stage refers to the 'product market competition'. Knowing the R&D investments, the two firms produce Cournot–Nash quantities, (q_i, q_j), and compete in the final market. At the end of the second stage, for any configuration of R&D expenditures invested, (x_i, x_j), and quantities produced in the final market, (q_i, q_j), the two firms earn the Cournot–Nash profit π_{i}(.) and π_{j} (.). Then the game ends.

Given that the objective of R&D cooperation is to increase the profit earned by each of the firms as compared to

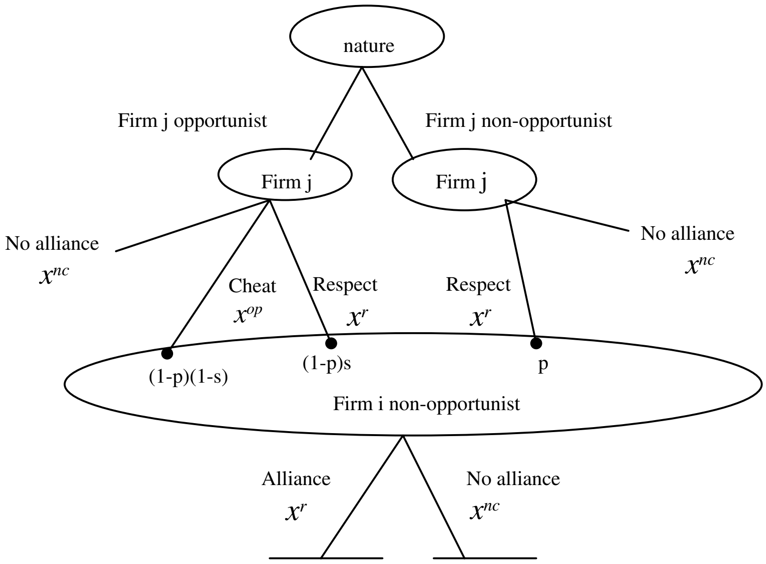

Figure 1. The decision tree of a non-opportunist firm *i*.

non-cooperation, the outcome of R&D cooperation is defined to be either *satisfactory* or *unsatisfactory* as follows:

- An R&D cooperation is *satisfactory*, if ex-post, at the end of the game, each firm earns a profit higher than that corresponding to non-cooperation;
- Otherwise, the R&D cooperation is *unsatisfactory*.

When the R&D cooperation is unsatisfactory, the R&D alliance is not internally stable in the sense that at least one of the partners regrets having entered into the alliance.

3.2. *Definition of quantities and R&D expenditures*

The Nash equilibrium quantities and the R&D expenditures corresponding to non-cooperation, cooperation and cheating, are found by backward induction. We start with quantities to be produced in the final stage. In the third stage, firms choose their output levels independently in Nash–Cournot competition, in order to maximize their own profits. For any configuration of R&D expenditures (x_i, x_j) invested by firms *i* and *j*, the equilibrium quantity of firm *i* in the third stage is given by:

$$q_i(x_i, x_j) = \underset{q_i}{\text{Argmax}} \pi_i = \underset{q_i}{\text{Argmax}}((a - q_i - q_j)q_i) \\ - (c - x_i^{1/2} - bx_j^{1/2})q_i - x_i;$$

$$q_i(x_i, x_j) = \frac{(a-c)}{3} + \frac{(x_i^{1/2}(2-b)) + (x_j^{1/2}(2b-1))}{3}. \tag{2}$$

Similar is the case for firm j.

With the Nash equilibrium quantities, we can now define the R&D expenditures under the two organizational forms of R&D 'cooperation' and 'non-cooperation'. Under non-cooperation, each firm seeks to maximize its own profit taking into account the R&D expenditure of the other firm. The Nash equilibrium non-cooperation R&D expenditure, x^{nc}, is such that no firm has any incentive to deviate from this investment, given that its competitor is also investing x^{nc}. It is defined as follows and a detailed derivation is provided in the appendix.

$$x^{\mathrm{nc}} = \underset{x_i}{\text{Argmax}}\, \pi_i(x_i, x^{\mathrm{nc}}); \\ x^{\mathrm{nc}} = \left[\frac{(2-b)(a-c)}{(7+b^2-b)}\right]^2. \tag{3}$$

The Nash equilibrium R&D cooperation contract is a vector of R&D expenditures $(x^{\mathrm{r}}, x^{\mathrm{r}})$ such that the R&D expenditure of each firm, x^{r}, maximizes the sum of the profits of the two firms within the alliance, given that the other firm is also spending x^{r}; i.e.,

$$x^{\mathrm{r}} = \underset{x_i}{\text{Argmax}}\big(\pi_i(x_i, x^{\mathrm{r}}) + \pi_j(x_i, x^{\mathrm{r}})\big); \\ x^{\mathrm{r}} = \left[\frac{(b+1)(a-c)}{(b-2)(b+4)}\right]^2. \tag{4}$$

Again, the appendix gives the details on the computation of x^{r}.

Finally, the opportunistic R&D expenditure x^{op} is defined as the R&D expenditure that maximizes the expected profit of the opportunist firm. Given the beliefs (p, s) of the opportunist firm, the expected profit function of an opportunist firm can be expressed as follows.

$$[(1-p)[s\pi_i(x_i, x^{\mathrm{r}}) + (1-s)\pi_i(x_i, x^{\mathrm{op}})] + p\pi_i(x_i, x^{\mathrm{r}})];$$

Recall that p is the belief of any firm that its partner is not an opportunist and s is the belief of any firm than an opportunist will respect a contract.

The opportunistic R&D expenditure x^{op} is then computed as the R&D expenditure the maximizes the above expression. Again the particulars of the derivation are provided in the appendix, and here we just state the definition of x^{op}.

$$x^{\mathrm{op}} = \underset{x_i}{\mathrm{Argmax}}[(1-p)[s\pi_i(x_i, x^{\mathrm{r}}) + (1-s)\pi_i(x_i, x^{\mathrm{op}})] + p\pi_i(x_i, x^{\mathrm{r}})]$$

$$\Leftrightarrow x^{\mathrm{op}} = \left[\frac{(a-c)(2-b) + \left(\sqrt{x^{\mathrm{r}}}(2b-1)(2-b)(p+(1-p)s\right)}{[(1-p)(1-s)(7-b+b^2)] + [(p+(1-p)s)(5+4b-b^2)]}\right]^2 \tag{5}$$

This finishes our presentation of the model.

3.3. *Results on the properties of R&D expenditures and the payoff function*

The properties of the R&D expenditure functions and the profit functions are given in the following three lemmas, all of which have been derived using simulations.

LEMMA 1. *Properties of the R&D expenditure function*

(L1.1) The opportunistic R&D expenditure $x^{\mathrm{op}}(b, p, s)$ *is an increasing function of p and s for all values of spillovers b. Furthermore,* $x^{\mathrm{op}}(b, p, s) > x^{\mathrm{nc}}(b)$ *always.*
(L1.2) For any given level of spillovers b, and beliefs (p,s) the R&D expenditures $x^{\mathrm{nc}}(b), x^{\mathrm{r}}(b)$ *and* $x^{\mathrm{op}}(b, p, s)$ *are such that:*

$$x^{r}(b) < x^{nc}(b) < x^{op}(b,p,s) \textit{ for } b < 0.5; \tag{6}$$

$$x^{nc}(b) < x^{op}(b,p,s) < x^{r}(b) \textit{ for } b > 0.5. \tag{7}$$

According to the definition of $x^{op}(b,p,s)$, it is a linear function of p and s. When there is no trust, i.e., $p = s = 0$, then $x^{op}(b,p,s) = x^{nc}(b)$. Furthermore, whenever p or s increases, the function $x^{op}(b,p,s)$ shifts upwards. Finally, when there is complete trust, i.e., $p = s = 1$, then:

$$x^{op}(b,1,1) = \left[\frac{\sqrt{x^{nc}} + \left(\sqrt{x^{r}}(2b-1)(2-b)\right)}{(5+4b-b^{2})}\right]^{2} > x^{nc}(b).$$

Since $x^{op}(b,p,s)$ goes from $x^{nc}(b)$ to a value greater than $x^{nc}(b)$ as p and s increase from 0 to 1, the linearity and continuity of the function $x^{op}(b,p,s)$ in p and s implies that it is increasing in p and s and is always equal to or greater than $x^{nc}(b)$.

The second part of the lemma, L1.2, is illustrated in Figure 2. For any value of the spillover b, the ranking of the R&D functions under the different scenarios are the same for any market size a and cost of production c, with $a > c$. Thus, opportunistic R&D effort, $x^{op}(b,p,s)$, is always the inverse of the cooperative effort, $x^{r}(b)$, in the sense that when the latter is high, the former is low and vice versa. This supports the intuition that opportunism is the opposite of cooperation.

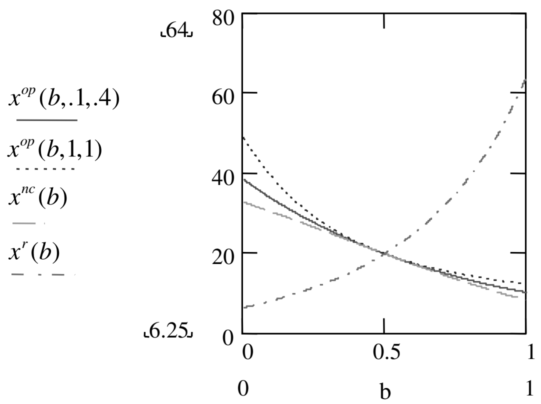

Figure 2. R&D expenditures as a function of spillovers.

It is a well-established result that the cooperative effort $x^{r}(b)$ is always less than the non-cooperative effort $x^{nc}(b)$ for low levels of spillovers and the opposite for high levels of spillovers. Therefore, we will not prove it here. The intuition behind this result is that the returns to individual R&D investment are very high, when the spillovers are low. This leads to a higher investment by individual firms than by a R&D consortium (Katz, 1986; d'Aspremont and Jacquemin, 1988; Kamien et al., 1992).

LEMMA 2. *Properties of the payoff function of the opportunist firm for all possible beliefs (p,s)*

(L2.1) For any opportunist firm i, cheating always yields a higher payoff than respecting the contract:

$$\pi_i\left(x^{op}, x^{r}, t_{i,o}\right) \geq \pi_i\left(x^{r}, x^{r}, t_{i,o}\right); \tag{8}$$

$$\pi_i\left(x^{op}, x^{op}, t_{i,o}\right) \geq \pi_i\left(x^{r}, x^{op}, t_{i,o}\right). \tag{9}$$

(L2.2) For any opportunist firm i, cheating always yields a higher payoff when firm j respects the contract rather than when firm j also cheats on the contract:

$$\pi_i(x^{op}, x^{r}, t_{i,o}) \geq \pi_i(x^{op}, x^{op}, t_{i,o}). \tag{10}$$

(L2.3) For any opportunist firm i, rent from cheating is higher (lower) when firm j respects the contract rather than when firm j also cheats on the contract given a sufficiently low (high) level of spillovers :

$$\begin{aligned}&[\pi_i(x^{op}, x^{r}, t_{i,o}) - \pi_i(x^{r}, x^{r}, t_{i,o})]\\&\quad > [\pi_i(x^{op}, x^{op}, t_{i,o}) - \pi_i(x^{r}, x^{op}, t_{i,o})] \quad \textit{for } b < 0.5\end{aligned} \tag{11}$$

$$\begin{aligned}&[\pi_i(x^{op}, x^{r}, t_{i,o}) - \pi_i(x^{r}, x^{r}, t_{i,o})]\\&\quad < [\pi_i(x^{op}, x^{op}, t_{i,o}) - \pi_i(x^{r}, x^{op}, t_{i,o})] \quad \textit{for } b > 0.5\end{aligned} \tag{12}$$

All the results given in Lemma 2, can be read off directly from Figure 3. For any value of the spillover b, the ranking of the profit functions under the different scenarios are the same

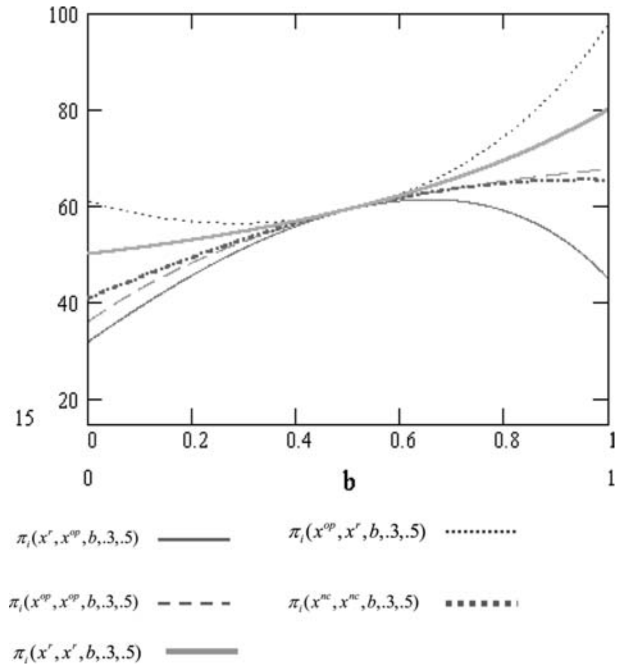

Figure 3. Profit functions under various R&D profiles ($p = .3$ and $s = .5$).

for any market size a and cost of production c, with $a > c$ and for all possible beliefs (p, s).

Lemma (L2.1) reveals that cheating is a dominant strategy for an opportunist firm in this R&D cooperation game. According to Lemma 1, $x^{\mathrm{op}} > x^{\mathrm{r}}$ for low levels of spillovers. By investing more, the cheating firm brings down the costs of production more and because of the low level of spillovers, the contract respecting partner cannot benefit from such efforts. This permits the opportunist firm to supply a greater quantity in the final market and earn a higher revenue than when it respects the contract. Thus, for low levels of spillovers, the benefit of opportunism comes from being more R&D intensive than the contract respecting partner, and earning a higher revenue in the final market. When the spillovers are high, $x^{\mathrm{op}} < x^{\mathrm{r}}$, i.e., an opportunist firm spends less on R&D but still the opportunist firm manages to reduce its cost of production more than proportionately, because the high level of spillovers permits it to free-ride on the R&D efforts of the contract respecting partner. Here, the benefits of opportunism stem from being less R&D intensive and economizing on the R&D investment but still bringing down costs through free riding.[7]

Lemma (L2.2) confirms that though it pays for an opportunist firm to cheat, it also incurs a cost when it is cheated upon in turn. Furthermore, lemma (L2.3) entails that the opportunist firm i has more to lose by not cheating, when firm j cheats, for high levels of spillovers, or when knowledge generated by firm j can be captured to a greater extent.

Given these properties of the profit function of an opportunist firm, it is clear that a game between two opportunists corresponds to a prisoner's dilemma paradigm. Moreover, it implies that at equilibrium $s = 0$, i.e., an opportunist will always cheat. Consequently, at equilibrium, trust is equivalent to the probability of encountering a non-opportunist, i.e., p.

LEMMA 3. *Comparison of payoffs under different R&D investment profiles for all possible beliefs (p, s)*

(L3.1) An R&D cooperation without manifestation of opportunism always yields a higher profit than non-cooperation.

$$\pi_i(x^{\mathrm{r}}, x^{\mathrm{r}}, t_i) = \pi^{\mathrm{r}} \geq \pi_i(x^{\mathrm{nc}}, x^{\mathrm{nc}}, t_i) = \pi^{\mathrm{nc}}. \tag{13}$$

(L3.2) An R&D cooperation without manifestation of opportunism always yields a higher profit than when both players cheat.

$$\pi^{\mathrm{r}} \geq \pi_i(x^{\mathrm{op}}, x^{\mathrm{op}}, t_o) = \pi^{\mathrm{op}}. \tag{14}$$

(L3.3) An R&D cooperation in which one firm cheats, yields a higher profit to the cheating firm than non-cooperation. An R&D cooperation in which one firm cheats yields a lower profit to the firm that is being cheated upon than non-cooperation.

$$\pi_i(x^{\mathrm{r}}, x^{\mathrm{op}}, t_i) \leq \pi^{\mathrm{nc}} \leq \pi_i(x^{\mathrm{op}}, x^{\mathrm{r}}, t_i). \tag{15}$$

(L3.4) An R&D cooperation in which all firms cheat may or may not lead to a lower profit as compared to non-cooperation depending on the level of the spillovers.

$$\pi^{\text{op}} > \pi^{\text{nc}} \quad \textit{for } b > 0.5. \tag{16}$$

$$\pi^{\text{op}} < \pi^{\text{nc}} \quad \textit{for } b < 0.5. \tag{17}$$

All the results given in Lemma 3 can also be inferred directly from Figure 3, in which the profit obtained under the different cooperation scenarios is compared with the profit obtained under non-cooperation for different values of the spillover b. We now give the intuition behind such results.

Lemma (L3.1) confirms the standard game theoretic result on R&D cooperation that R&D cooperation without any manifestation of opportunism always leads to a higher payoff than non-cooperation. Then, Lemma (L3.2) indicates that initiation of contract is a viable option only if commitment to the contract is of economic interest to both parties, i.e., if the profit to any firm from an R&D cooperation without cheating is always higher than the profit to any firm from an R&D cooperation in which no firm respects the contract. Lemma (L3.3) points out that it will be in the interest of an opportunist firm to initiate a contract if it perceives the other firm to be a non-opportunist, while the opposite holds for a non-opportunist firm. Finally, lemma (L3.4) holds because, when two opportunist firms initiate an R&D cooperation, their R&D investment is higher (recall Lemma 1), their quantities supplied in the final market are higher, and therefore, their final market prices are lower, than under non-cooperation. However, when the spillovers are high, each of two cheating firms enjoys a greater return on R&D investment. This enables the two cheating firms to sufficiently lower their costs of production so as to enjoy a higher profit than under non-cooperation. Thus, opportunist firms enjoy full benefits from the spillovers externality and this reasoning holds for all possible beliefs on the type of their partner.

4. RESULTS ON OPPORTUNISM, TRUST AND R&D COOPERATION

It can be noted that the definition of the R&D cooperation and non-cooperation, (and cheating) expenditures are independent of the levels of trust. In the remainder of the article, we will identify the type profiles and the belief or trust configurations under which an R&D cooperation will be initiated and will evolve with or without the manifestation of opportunism.

Given the payoff structure corresponding to the different strategy profiles as specified in the above results (Eqs (8)–(17)), it is clear that for any set of beliefs, any Bayesian Nash equilibrium involving R&D cooperation will be a separating equilibrium. Since cheating is a dominant strategy for any opportunist firm, in all Nash equilibria where an R&D cooperation is initiated, an opportunist firm will cheat in the second stage, spending x^{op}, whereas a non-opportunist firm by definition will respect the contract, investing x^{r}. By the same logic, all Nash equilibria where R&D cooperation is not initiated will be pooling equilibria, with both firms spending the non-cooperation R&D effort, x^{nc}.

It is a well-established fact that in most situations, R&D cooperation without opportunism leads to a higher profit and higher consumer surplus as compared to non-cooperation (d'Aspremont and Jacquemin, 1988, Kamien and al, 1992, Suzumura, 1992). Can the same hold true even with opportunism? To answer this question, we will examine the conditions under which a separating equilibrium (with manifestation of opportunism) is either *satisfactory* or *unsatisfactory*. Under the former, each firm earns a higher profit under R&D cooperation than under non-cooperation, while the latter implies the inverse. Furthermore, for simplicity, we term R&D cooperation to be *socially satisfactory* if the welfare (i.e., sum of firm profits and consumer surplus) is greater under R&D cooperation than under non-cooperation. In the following proposition we will show that while R&D cooperation without opportunism is always satisfactory both from the societal view and the firm's view, sometimes even cooperation with opportunism is better than non-cooperation.

PROPOSITION 1. *Role of opportunism.*

1.1 An R&D cooperation can be satisfactory even if there is manifestation of opportunism.
1.2 An R&D cooperation can be socially satisfactory even if there is manifestation of opportunism.
1.3 An R&D cooperation is unsatisfactory only if there is manifestation of opportunism.

(1.1) Two opportunists can initiate an R&D cooperation satisfactorily if the spillover is high enough. According to Lemma 2, cheating is a dominant strategy for opportunist firms and therefore two opportunist firms will both cheat in the second stage of the game. Furthermore, the R&D cooperation is satisfactory because each firm obtains a payoff greater than under non-cooperation: $\pi^{\text{op}} > \pi^{\text{nc}}$ for $b > 0.5$ (Eq. (16)). When the spillovers are high and two opportunists cheat, their R&D efforts are reduced, but there is still substantial cost reduction, because they capture the knowledge generated by each other's R&D through high spillovers.

(1.2) Consider the case where two opportunist firm enter into an R&D alliance. From Lemma 3, we know that $\pi^{\text{op}} > \pi^{\text{nc}}$ *for* $b > 0.5$ and therefore, from each firm's point of view, the R&D cooperation would be satisfactory, even with the manifestation of opportunism. Whenever spillovers are high, it is preferable for all firms, including opportunist ones, to undertake R&D investment under a cooperative framework rather than alone.

Now, let us examine the consumer surplus. From Lemma 1, we know that for all beliefs *(p,s)* and a value of spillovers $b > 0.5$, we have $x^{\text{op}}(b,p,s) > x^{\text{nc}}$. Then, from Equation (2), we can deduce that for all beliefs (p,s) and a value of spillovers $b > 0.5$, the quantities produced and sold at equilibrium are such that:

$$Q^{\text{op}} = 2q_i(x^{\text{op}}(b,p,s), x^{\text{op}}(b,p,s)) > Q^{\text{nc}} = 2q_i^{\text{nc}}.$$

Consider the utility of a representative consumer to be given by $U(Q,Z) = u(Q) + Z$ where $u(Q) = aQ - 1/2bQ^2 \quad (a,b > 0)$

and Z is a competitive numeraire good. In this case, even with the two firms in the R&D alliance cheating, the consumer surplus is higher than under non-cooperation. Of course, the manifestation of opportunism is detrimental to consumer welfare, as it would be even higher without opportunism. However, this interesting case highlights the fact that opportunism need not pose a hurdle to the initiation of cooperation either for the firms or for the consumers. Society also benefits from a higher investment in the creation of innovations.

(1.3) An R&D cooperation will be unsatisfactory under two conditions:

- Whenever an opportunist firm initiates cooperation with a non-opportunist firm.
- Whenever two opportunist firms initiate cooperation and the spillover b is less than 0.5.

Let us examine the first case. Suppose firm i is an opportunist firm and firm j is a non-opportunist firm. From Lemma 2, we know that an opportunist firm will always cheat in the second stage, because cheating is its dominant strategy (Eqs (8) and (9)). But in this case, according to Lemma 3, the profit of the non-opportunist firm j will be less than under non-cooperation (Eq. (15)). The non-opportunist firm supplies a higher R&D effort, and in return, not only obtains a lower payoff as compared to the opportunist, but also lower than under non-cooperation. Thus, asymmetry in the nature of the firms systematically leads to unsatisfactory R&D cooperation.

Let us now examine the second case. According to Lemma 3, when two opportunists initiate a contract, it will be unsatisfactory for spillover values $b < 0.5$, (Eq. (17)). Here, the opportunist firms spend more on R&D than under non-cooperation. As explained in Lemma 3, while this leads to the lowering of production costs, because the free-riding effect is low, both opportunist firms earn less by cheating than they would have under non-cooperation.

This then brings us to our second proposition on the role of trust in the initiation of cooperation. Let p^{r} be the minimum level of trust required for a non-opportunist firm to initiate a cooperation. Let p^{op} be the minimum level of trust required for an opportunist firm to initiate a cooperation.

PROPOSITION 2. *Trust requirements of opportunist and non-opportunist firms*

2.1 For a non-opportunist firm, the minimum level of trust required, p^{r}*, is an increasing function of spillovers.*

$$\frac{\partial p^{\mathrm{r}}}{\partial b} > 0 \textit{ for all values of } b.$$

2.2 For an opportunist firm, the minimum level of trust required, p^{op}*, is a decreasing function of spillovers.*

$$\frac{\partial p^{\mathrm{op}}}{\partial b} < 0 \quad \textit{for } b < 0.5.\ p^{\mathrm{op}} = 0 \quad \textit{for } b \geq 0.5.$$

2.3 For all parameter configurations $p^{\mathrm{op}} < p^{\mathrm{r}}$.

Proof. (2.1) Now suppose firm i is a non-opportunist. Then its expected profit from an R&D cooperation is given as below:

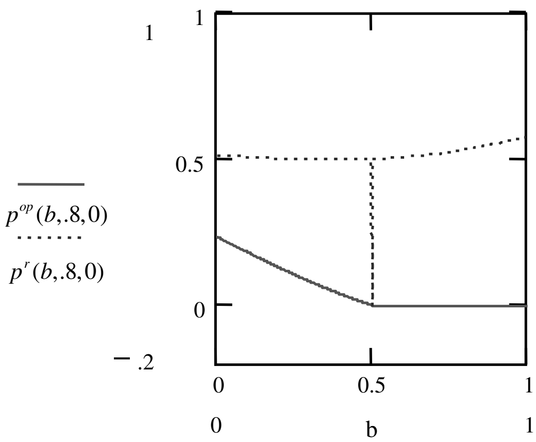

Figure 4. Trust requirements of opportunist and non-opportunist firms as a function of spillovers.

$$E\left[\pi_i\left(t_{i,\mathrm{n}}\right)|p\right] = p\pi^{\mathrm{r}} + (1-p)\pi_i\left(x^{\mathrm{r}}, x^{\mathrm{op}}, t_{i,\mathrm{n}}\right).$$

The firm initiates the contract if and only if : $E\left[\pi(t_{i,n})|p\right] \geq \pi^{\mathrm{nc}}$.

This gives the minimum level of trust for a non-opportunist firm to initiate an R&D cooperation as p^{r} below:

$$p^{\mathrm{r}} = \frac{\pi^{\mathrm{nc}} - \pi_i\left(x^{\mathrm{r}}, x^{\mathrm{op}}, t_{i,\mathrm{n}}\right)}{\pi^{\mathrm{r}} - \pi_i\left(x^{\mathrm{r}}, x^{\mathrm{op}}, t_{i,\mathrm{n}}\right)}. \tag{18}$$

The numerator is positive given Equation (15). Again, by Equations (15) and (13), the denominator is positive. Therefore, p^{r} is always greater than zero. Then simulations reveal trust to be an increasing function of the level of spillovers (see Figure 4).

(2.2) Suppose firm i is an opportunist, then it will cheat in the second stage since cheating is a dominant strategy for any opportunist. In this case, its expected profit from an R&D cooperation is equal to:

$$E\left[\pi_i\left(t_{i,\mathrm{o}}\right)|p\right] = p\pi_i\left(x^{\mathrm{op}}, x^{\mathrm{r}}, t_{i,\mathrm{o}}\right) + (1-p)\pi^{\mathrm{op}}.$$

Firm i will initiate an R&D cooperation if and only if $E\left[\pi(t_{i,\mathrm{o}})|p\right] \geq \pi^{\mathrm{nc}}$. This means that the minimum level of trust required for an opportunist to initiate a contract p^{op} is:

$$p^{\mathrm{op}} = \mathrm{Max}\left\{0, \frac{\pi^{\mathrm{nc}} - \pi^{\mathrm{op}}}{\pi_i(x^{\mathrm{op}}, x^{\mathrm{r}}, t_{i,\mathrm{o}}) - \pi^{\mathrm{op}}}\right\} \tag{19}$$

By Equation (10), the denominator of the second term within the bracket on the right hand side, is always positive. However, by Equations (16) and (17), the numerator is positive for $b < 0.5$ and negative for $b > 0.5$. Therefore, p^{op} is zero for any $b > 0.5$ which means that an opportunist will always initiate an R&D cooperation under this condition. Then, Figure 4, which shows trust requirement, p^{op}, as a function of the spillovers, confirms that it is a downward sloping function of the spillover b.

(2.3) From (2.1) and (2.2) it is clear that for $b > 0.5, p^{\mathrm{op}} < p^{\mathrm{r}}$, because $p^{\mathrm{op}} = 0$ while $p^{\mathrm{r}} > 0$. Let us then consider the case when $b < 0.5$. From Equation (9), we have that:

$$\pi^{nc} - \pi^{op} \leq \pi^{nc} - \pi_i(x^r, x^{op}, t_i). \quad (20)$$

Again, from Lemma 2 and Equation (11), we have that for $b < 0.5$:

$$[\pi_i(x^{op}, x^r, t_{i,o}) - \pi^{op}] > [\pi^r - \pi_i(x^r, x^{op}, t_{i,o})]. \quad (21)$$

Combining Equations (20) and (21), it is clear that $p^{op} < p^r$ for $b < 0.5$ also. □

Proposition 2 gives some insight on the outcome of R&D cooperation. For any level of spillovers, a non-opportunist has higher trust requirements, and hence, initiates R&D cooperation less easily. This stems from the fact that the cost of opportunism is high for very high levels of spillovers, while the benefit from cooperation is low for very low levels of spillovers. In contrast, an opportunist firm always tries to initiate an R&D cooperation, whenever the spillovers are high. Furthermore, a high level of spillovers need not lead to unsatisfactory or unstable cooperation (Proposition 1.1).

PROPOSITION 3. *Role of trust in the initiation and outcome of cooperation*

3.1. Trust is favorable but not necessary for the initiation of cooperation. The mere existence of trust is not sufficient for the initiation of cooperation.
3.2. Similarly, trust is neither necessary nor sufficient to assure satisfactory R&D cooperation.

(3.1) Trust is favorable to the initiation of R&D cooperation because the expected profit is an increasing function of trust. However, trust is not necessary for the initiation of cooperation. For instance, if the spillover value b is greater than 0.5, two-opportunist firms can initiate a contract with no trust, according to proposition 2.2. Neither is the mere existence of trust (i.e., $p > 0$) sufficient to initiate an R&D cooperation. According to Proposition 2, there are minimum trust requirements for each type profile and, unless these are satisfied, there is no initiation of cooperation. Thus, if two partners face each other and their trust configurations do not satisfy the minimum trust configurations (Eqs. (18) and (19)), an R&D cooperation will not be initiated.

(3.2) Satisfactory R&D cooperation can be ensured even in the absence of trust. Let us again consider the case of two opportunist firms in the context of a high level of spillovers. An opportunist firm will always earn more than under non-cooperation, if its partner is a non-opportunist firm (Eq. (15)). Furthermore, even if its partner is an opportunist firm, given a high level of spillovers, it will earn more than under non-cooperation (Eq. (16)). Thus, R&D cooperation will be initiated and it will be a success.

From Proposition 2, we know that whenever minimum trust requirements are satisfied (Eq. (18) and (19)), an R&D cooperation will be initiated. If it involves asymmetric firms, i.e., an opportunist and a non-opportunist firm, then it will always be unsuccessful because the non-opportunist will earn less than under non-cooperation. Therefore, just the existence of trust is not sufficient to ensure the success of an R&D cooperation.

This last proposition permits us to highlight the fact that trust and contract initiation are not always correlated. *This goes against what is often held up as an intrinsic truth that opportunism is systematically an obstacle to the initiation and success of R&D cooperation, while the existence of trust is sufficient to ensure successful R&D cooperation.*

5. CONCLUSION

Most game theoretic models of R&D cooperation do not deal with trust because they consider either all firms to be non-opportunists or all firms to be opportunists. Trust, whenever it appears, is the result of a repeated interaction between agents. However, not all R&D contracts are implemented in the context of a repeated game. How then are we to explain the emergence of R&D cooperation in a static context, when the partners are confronted with the problem of opportunism and they cannot formulate a complete contract that protects them against such a risk? Our approach offers some elements for an answer.

The paper shows that when opportunism can not be eliminated through some screening or incentive mechanism, the success or failure of R&D cooperation depends on the nature of firms, the configurations of trust and the level of spillovers. When two firms consider whether or not to initiate an R&D cooperation, one of the following equilibrium outcomes is possible:

- *No initiation of R&D cooperation:* For low levels of trust, under any level of given spillovers, when at least one of the partners is a non-opportunist.
- *Initiation of R&D cooperation without manifestation of opportunism:* When two non-opportunists initiate a cooperation for sufficiently high levels of trust under any given level of spillovers.
- *Satisfactory R&D cooperation with manifestation of opportunism:* When two opportunists initiate a cooperation and the spillovers are high.
- *Unsatisfactory R&D cooperation with manifestation of opportunism:* Whenever an opportunist initiates a cooperation with a non-opportunist. This also occurs when two opportunists initiate a cooperation and spillovers are low.

Thus, the paper demonstrates that the initiation of R&D cooperation depends not only on the level of spillovers, but also on the type of firms involved and their trust in one another. Furthermore, the trust requirements of each type of firm depends on the degree of spillovers.

The present article also has implications for some of the ongoing debates on trust and cooperation at a sectoral or regional level. For instance, recently, there have been a number of studies comparing interfirm cooperation in the USA, Europe and Japan. They indicate that American firms are more hesitant to initiate cooperation than their Japanese counterparts (Casson, 1991; Dunning, 1995). The reason most often evoked is that Japanese firms exhibit a higher level of trust (Sako and Helper, 1998). However, a study by Yamagashi and Yamagashi (1994) retaining the same definition of trust as used in this paper, finds that the level of trust among Japanese is lower than among Americans. Furthermore, Hagan and Choe (1998) put forward the notion that trust in Japan is simply a social norm that emerges given the system of sanctions and punishments associated with cheating on commitments.

With respect to the above literature, whatever the reasons for the existing levels of trust (whether or not they are due to a social system of sanctions), the present article points out that it is the nature of firms, their levels of trust and the levels of knowledge spillovers that determines whether or not they will cooperate. If the payoffs to cooperation are as in the game considered in the article, then populations with a higher proportion of opportunist firms will be more predisposed to initiate cooperation because they need less trust than non-opportunist firms to initiate cooperation. This is of course at loggerheads with the notion that 'trusting firms' are more prone to initiate cooperation. Therefore, if cooperation is more prevalent in a region, it could be either because the levels of trust are high or because the proportion of trusting firms or non-opportunist firms is low. More than trust, it could be the potential exploitation of opportunism that stimulates cooperation in R&D. Finally, the article also shows that under certain conditions the potential manifestation of opportunism need not pose a threat to the realization of satisfactory cooperation. This of course, calls for a further examination of not only why R&D cooperation is initiated, but also why it breaks down with or without the manifestation of opportunism.

This paper has its own limitations too. It does not discuss the welfare implications of the model's results in depth. The structure of the game, including the payoff structure, is such that an opportunist always cheats at equilibrium. This does not need to be true of all games. Extensions can explore the

R&D cooperation contexts under which an opportunist does not have the incentive to cheat systematically at equilibrium.[8] Finally, the game can be extended from a static Bayesian game, where beliefs are taken as given, to a dynamic one, where beliefs are formed endogenously. Then the conditions under which a particular belief structure can be sustained can be identified.

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APPENDIX

1. *Derivation of the non-cooperative R&D expenditure x^{nc}*

Recall that the profit function of a firm, say i, is given by :

$$\pi_i = (a - q_i - q_j)q_i - (c - x_i^{1/2} - bx_j^{1/2})q_i - x_i. \tag{1'}$$

Firm i chooses its R&D expenditure x_i so as to maximize its profit function.

$$\begin{aligned}\frac{\partial \pi_i}{\partial x_i} &= (a - 2q_i - q_j - c + \sqrt{x_i} + b\sqrt{x_j})\frac{\partial q_i}{\partial x_i} \\ &\quad + q_i\left(-\frac{\partial q_j}{\partial x_i} + \frac{1}{2\sqrt{x_i}}\right) - 1.\end{aligned} \tag{2'}$$

Now, since firm i will be maximizing its profit in the final market, we know that at equilibrium $\partial q_i/\partial x_i = 0$. Therefore, the first order necessary condition becomes:

$$\frac{\partial \pi_i}{\partial x_i} = 0 \Leftrightarrow q_i\left(-\frac{\partial q_j}{\partial x_i} + \frac{1}{2\sqrt{x_i}}\right) = 1.$$

Recall from Equation (2) that at equilibrium :

$$q_i(x_i, x_j) = \frac{(a-c)}{3} + \frac{\left(x_i^{1/2}(2-b)\right) + \left(x_j^{1/2}(2b-1)\right)}{3}.$$

Then, $\dfrac{\partial q_j}{\partial x_i} = \dfrac{(2b-1)}{6\sqrt{x_i}}$.

$$\frac{\partial \pi_i}{\partial x_i} = 0 \Leftrightarrow q_i\left(-\frac{(2b-1)}{6\sqrt{x_i}} + \frac{1}{2\sqrt{x_i}}\right) = 1. \tag{3'}$$

Furthermore, at equilibrium at the R&D stage, given symmetric firms, we know that $x_i = x_j = x^{\text{nc}}$ and therefore $q_i = q_j = q^{\text{nc}}$. Thus, we have:

$$\frac{\partial \pi_i}{\partial x_i} = 0 \Leftrightarrow q^{\text{nc}} \frac{1}{\sqrt{x^{\text{nc}}}}\left(\frac{2-b}{3}\right) = 1.$$

Then substituting the value of

$$q_i = q^{\text{nc}} = \frac{(a-c)}{3} + \frac{\sqrt{x^{\text{nc}}}(b+1)}{3}$$

in the above equation, we get that:

$$\Leftrightarrow x^{\text{nc}} = \frac{(2-b)^2(a-c)^2}{(7+b^2-b)^2}.$$

2. *Derivation of the cooperative R&D expenditure* x^{r}

The cooperative R&D expenditure x^{r} is decided so as to maximize the sum of the profit of the two firms, $\pi_i + \pi_j$. Consider firm 1.

$$\frac{\partial(\pi_i + \pi_j)}{\partial x_i} = \frac{\partial \pi_i}{\partial x_i} + \frac{\partial \pi_j}{\partial x_i}.$$

From Equation (3′), we know

$$\frac{\partial \pi_i}{\partial x_i} = q_i \frac{1}{\sqrt{x_i}}\left(\frac{2-b}{3}\right) - 1.$$

Recall that the profit function of firm j is given by :

$$\pi_j = \big(a - q_j - q_i\big)q_j - (c - x_j^{1/2} - bx_i^{1/2})q_j - x_j.$$

$$\Leftrightarrow \frac{\partial \pi_j}{\partial x_i} = \big(a - 2q_j - q_i - c + \sqrt{x_j} + b\sqrt{x_i}\big)\frac{\partial q_j}{\partial x_i} + q_j\left(-\frac{\partial q_i}{\partial x_i} + \frac{b}{2\sqrt{x_i}}\right). \tag{4'}$$

Given profit maximization in the final market, at equilibrium $\partial q_j/\partial x_i = 0$. Furthermore, from Equation (3′) we know that

$$\frac{\partial \pi_i}{\partial x_i} = q_i\frac{1}{\sqrt{x_i}}\left(\frac{2-b}{3}\right) - 1.$$

Thus, we have:

$$\frac{\partial(\pi_i + \pi_j)}{\partial x_i} = q_i\frac{1}{\sqrt{x_i}}\left(\frac{2-b}{3}\right) - 1 + q_j\left(-\frac{\partial q_i}{\partial x_i} + \frac{b}{2\sqrt{x_i}}\right).$$

Since

$$\frac{\partial q_i}{\partial x_i} = \frac{(2-b)}{6\sqrt{x_i}},$$

the above equation can be rewritten as :

$$\frac{\partial(\pi_i + \pi_j)}{\partial x_i} = q_i\frac{1}{\sqrt{x_i}}\left(\frac{2-b}{3}\right) - 1 + q_j\left(-\frac{2-b}{6\sqrt{x_i}} + \frac{b}{2\sqrt{x_i}}\right). \tag{5'}$$

Furthermore, at equilibrium at the R&D stage, given symmetric firms, we know that $x_i = x_j = x^{\mathrm{r}}$ and therefore $q_i = q_j = q^{\mathrm{r}}$. Then substituting the value of

$$q^{\mathrm{r}} = \frac{(a-c)}{3} + \frac{\sqrt{x^{\mathrm{r}}}(b+1)}{3}$$

in Equation (5’) we get that :

$$\frac{\partial\big(\pi_i + \pi_j\big)}{\partial x_i} = 0 \Leftrightarrow q^{\mathrm{r}} = \frac{3\sqrt{x^{\mathrm{r}}}}{b+1}.$$

$$\Leftrightarrow x^{\mathrm{r}} = \left(\frac{(a-c)(b+1)}{(b^2+2b-8)}\right)^2.$$

3. *Derivation of the opportunistic R&D expenditure* x^{op}

Let p be the probability of encountering an opportunist. Let s be the probability that an opportunist does not cheat. Then the opportunistic R&D expenditure, x^{op} of any opportunist firm i is one that maximizes its expected returns indicated below:

$$(1-p)[s\pi_i(x_i, x^{\mathrm{r}}) + (1-s)\pi_i(x_i, x^{\mathrm{op}})] + p\pi_i(x_i, x^{\mathrm{r}}).$$

or:

$$((1-p)(1-s)\pi_i(x_i, x^{\mathrm{op}})) + (p+(1-p)s)\pi_i(x_i, x^{\mathrm{r}}). \qquad (6')$$

Thus, x^{op} is the R&D expenditure that satisfies the following condition:

$$\left((1-p)(1-s)\frac{\partial\pi_i(x_i, x^{\mathrm{op}})}{\partial x_i}\right) + (p+(1-p)s)\frac{\partial\pi_i(x_i, x^{\mathrm{r}})}{\partial x_i} = 0. \qquad (7')$$

Now we will derive the value of

$$\frac{\partial\pi_i(x_i, x^{\mathrm{r}})}{\partial x_i}.$$

Recall that :

$$\pi_i(x_i, x^{\mathrm{r}}) = (a - q_i - q_j)q_i - \left(c - x_i^{1/2} - b(x^{\mathrm{r}})^{1/2}\right)q_i - x_i.$$

$$\frac{\partial\pi_i(x_i, x^{\mathrm{r}})}{\partial x_i} = \left(a - 2q_i - q_j - c + \sqrt{x_i} + b\sqrt{x^c}\right)\frac{\partial q_i}{\partial x_i} + q_i\left(\frac{1}{2\sqrt{x_i}} - \frac{\partial q_j}{\partial x_i}\right) - 1.$$

Now, since firm i will be maximizing its profit in the final market, we know that at equilibrium $\partial q_i/\partial x_i = 0$. Therefore, the above first order necessary condition becomes:

$$\frac{\partial\pi_i(x_i,x^{\mathrm{r}})}{\partial x_i}=q_i\left(\frac{1}{2\sqrt{x_i}}-\frac{\partial q_j}{\partial x_i}\right)-1. \tag{8'}$$

Recall from Equation (2) that at equilibrium :

$$q_i(x_i,x^{\mathrm{r}})=\frac{(a-c)}{3}+\frac{\left(x_i^{1/2}(2-b)\right)+\left((x^{\mathrm{r}})^{1/2}(2b-1)\right)}{3}.$$

Then,

$$\frac{\partial q_j}{\partial x_i}=\frac{(2b-1)}{6\sqrt{x_i}}.$$

Substituting this in Equation (8′) we have :

$$\frac{\partial\pi_i(x_i,x^{\mathrm{r}})}{\partial x_i}=q_i(x_i,x^{\mathrm{r}})\left(\frac{2-b}{3\sqrt{x_i}}\right)-1.$$

Then, substituting for the value of $q_i(x_i,x^{\mathrm{r}})$, we can write the above as:

$$\frac{\partial\pi_i(x_i,x^{\mathrm{r}})}{\partial x_i}=\frac{(a-c)(2-b)+\sqrt{x^{\mathrm{r}}}(2b-1)(2-b)}{9\sqrt{x_i}}-\frac{(5+4b-b^2)}{9} \tag{9'}$$

From equation (3′) we know that

$$\frac{\partial\pi_i}{\partial x_i}=q_i\frac{1}{\sqrt{x_i}}\left(\frac{2-b}{3}\right)-1.$$

Substituting for the value of q_i, we can write :

$$\frac{\partial\pi_i(x_i,x^{\mathrm{op}})}{\partial x_i}=\frac{(a-c)(2-b)}{9\sqrt{x_i}}-\frac{(7-b+b^2)}{9} \tag{10'}$$

Now substituting the value of

$$\frac{\partial\pi_i(x_i,x^{\mathrm{r}})}{\partial x_i}\quad\text{and}\quad\frac{\partial\pi_i(x_i,x^{\mathrm{op}})}{\partial x_i}$$

from Equations (9′) and (10′) into the first order condition given by Equation (7′) we can derive the opportunistic R&D expenditure x^{op} as given below :

$$x^{\mathrm{op}} = \left[\frac{(a-c)(2-b)+\left(\sqrt{x^{\mathrm{r}}}(2b-1)(2-b)(p+(1-p)s\right)}{[(1-p)(1-s)(7-b+b^2)]+[(p+(1-p)s)(5+4b-b^2)]}\right]^2.$$

NOTES

1. In this paper, the term ‘contract’ is used in a large sense, including all explicit and implicit agreements.
2. There is also literature that examines how heterogeneity can emerge given ex-ante homogeneous firms in the context of R&D investment. (see references in Amir and Wooders, 1999).
3. Such an idea is also supported by experimental evidence that confirms the existence of trust and cooperation even in one-shot interactions (Berg, Dickhaut and McCabe, 1995).
4. The R&D cost reduction function is the standard quadratic cost function introduced by Kamien et al. (1992) to capture the phenomenon of decreasing returns to R&D expenditure.
5. This is equivalent to assuming that cheating is a dominated strategy for non-opportunists or that the utility obtained from respecting a contract is greater than that from not respecting it. Please note that this assumption can be justified in many ways (see ‘The Introduction’ section).
6. The given game can also be considered as a three stage, whereby in the first stage the firms decide whether or not to enter into an R&D contract, in the second stage they decide whether or not to respect the contract, and in the third stage they decide on their quantities, with no revision of beliefs between any of the stages.
7. The observations on costs, quantities and revenues can be directly inferred from the calculations on equilibrium values. These calculations have not been included in the text to preserve conciseness.
8. A general game theoretic model to study the role of opportunism and trust in any general context has been developed by Cabon-Dhersin and Ramani (2003).

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Address for correspondence: Marie-Laure Cabon-Dhersin, Ecole Nationale Supérieure des Arts et Métiers, Paris, Groupe de Recherche sur le Risque, l'Information et la Décision (GRID), Maison de la recherche de l'ESTP, 30 Avenue du Président Wilson, 94230 Cachan, France and Ecole Normale Supérieure de Cachan.
E-mail: cabon@grid.ensam.estp.fr

Shyama V. Ramani, Institut National de la Recherche Agronomique (INRA), Université Pierre Mendès France, BP 47, 38070 Grenoble cedex9, France.
E-mail: shyamar@grenoble.inra.fr