Three Essays on Research Joint Ventures, Coordination Costs and Environmental R&D

Armaghan Rahimi

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Department of Economics

Faculty of Social Sciences

University of Ottawa

Abstract

This dissertation is about research and development (R&D) and formation of research joint ventures (RJV). The first chapter analyzes R&D competition and cooperation regimes with coordination costs under full information sharing and no spillovers in a Stackelberg model. The findings show that profits and R&D incentives of RJV members decrease with coordination costs. R&D cooperation of leaders results in higher profits for insiders and also higher welfare compared with R&D competition. Checking the robustness of the results shows that with R&D spillovers and no information sharing no RJV forms. With convex costs, an RJV containing all leaders forms.

The second chapter considers a duopoly Cournot model where production may result in environmental damage. Firms can either invest in process or environmental R&D. In the first case, we assume an exogenous emission tax. With high enough emission tax, welfare is always higher under public R&D than cooperation. Under endogenous emission tax, when the regulator acts before firms' decision on R&D, with high R&D spillovers, public R&D yields higher welfare than R&D cooperation. When the regulator sets the emission tax after firms' decision on R&D, welfare under R&D cooperation is higher than public R&D. Comparison of commitment and no commitment also shows that commitment increases private R&D.

Chapter three investigates the endogenous formation of coalitions under the size announcement game in a Cournot framework and analyzes the effect of coordination costs on equilibrium and optimal coalitions. When there are industry-wide R&D spillovers numerical simulations show that with high enough coordination costs no RJV forms in equilibrium, which also maximizes welfare. When there is intra coalition full information sharing and no inter-coalitions R&D spillovers with high enough coordination costs, the equilibrium coalition structure is more concentrated than when coordination costs are low and the size is higher than when RJVs could not form endogenously. Also, with high enough coordination costs, the welfare maximizing coalition is less concentrated than the equilibrium one while the opposite is true for low coordination costs.

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to my dear parents,

Forough Hezarehei and Ali Rahimi

and my lovely sister,

Azadeh Rahimi

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General introduction

Research and development (R&D) and formation of research joint ventures (RJV) are topics which are widely studied in the industrial organization area. Looking at the literature on this topic, we identify some important aspects that have been neglected by previous studies. One of the weak points of this literature is that most papers ignore the presence of coordination costs in the formation of RJVs which may affect the profitability of R&D cooperation. Also, most of the results obtained are based on simultaneous choice of R&D, while firms can choose their R&D investments in a sequential game. So, in the first chapter of the thesis, we consider the exogenous sequential formation of RJV with coordination costs. The purpose is to compare investment, output and profit of firms under R&D cooperation and competition regimes. Moreover, we find the equilibrium and optimal sizes of RJV and the impact of change in coordination costs on these sizes.

Pollution can be a by-product of production. So, when firms invest in cost reducing R&D and as a result, production increases, the side effect can be an increase in environmental damage. In the second chapter, we consider a duopoly Cournot model incorporating this effect when the emission tax is set exogenously. We compare the welfare effect of two technology policies: encouraging R&D cooperation and public R&D. Further, we perform the same comparison under an endogenous emission tax when firms invest in environmental R&D instead of production R&D. The findings are analyzed with and without commitment by the regulator.

Also, the findings obtained in most R&D papers are under the assumption that only one exogenous coalition can form. In chapter three, we extend previous studies by considering endogenous formation of RJVs based on the size announcement game in a Cournot framework. We find the equilibrium and optimal coalition structures and the effect of increases in coordination costs on these results.

Chapter 1

Research Joint Ventures with Stackelberg leadership and Coordination Costs

1.1 Introduction

Research and development (R&D) plays an important role in innovation, so it has become the focus of concern by policy makers. Since the 1980s, there have been a considerable number of studies analyzing R&D and the formation of research alliances. This concern about industrial R&D has also noticeably increased in Canadian industries. According to the Council of Canadian Academies (2013, p.111), “Canada’s most IR&D strength are most concentrated in four industries: aerospace, ICT, oil and gas extraction, and pharmaceutical and medicine manufacturing”.

A large portion of the existing literature compares cooperation and competition R&D regimes with a focus on simultaneous choice of R&D by firms. There are few studies concerning R&D and RJVs in which firms move sequentially for choosing their levels of R&D investment and output. An example of sequential move in choosing R&D investment, as mentioned by Mallozzi and Tijs (2012), is an International Environment Agreement (IEA) where signatories behave as leaders and non-signatories act as followers. Moreover, an important issue which is ignored in most of the R&D literature is coordination costs. As discussed by Falvey et al. (2010), forming and running a research joint venture, assigning rules and contracts and interacting with members to share and update their R&D information are costly and the costs increase with the number of firms contributing in innovation cooperation.

In this study, we analyze an oligopoly model where firms choose their levels of R&D investment and output sequentially rather than simultaneously. A group of firms behave as leaders and the rest as followers in all stages of choosing R&D and output levels. First, we assume that in each of these groups, firms choose their R&D and output competitively and there is no information sharing between them. Then, we assume that a group of leaders form a research joint venture and fully share information amongst them. In order to choose their R&D, the firms maximize their joint profit, but they still compete on the output market. For leaders and followers who remain outside of the coalition, there is no information sharing. All outsider firms, leaders and followers, behave competitively in both R&D and output stages. We extend previous leader-follower studies in R&D by considering research joint venture coordination costs. Then, we use numerical simulations to compare R&D competition and cooperation for different levels of coordination costs. Next, we compute the equilibrium and optimal sizes of the research joint venture and analyze the effect of increases in coordination costs on this comparison. Then, we consider two extensions. First, we analyze the case where there are R&D spillovers between leaders and also from leaders to followers with and without RJV formation. In this part, when the RJV is formed, the R&D spillover rate does not change. Second, we study a model with convex production costs and full information sharing between RJV members.

This research attempts to answer the following questions: what is the effect of the formation of a research joint venture by a group of leaders on their own and other firms' R&D investment, output and profit? What are equilibrium and optimal sizes of the RJV? How do the results change by considering coordination costs? Do the results change with changing the assumptions about R&D spillovers and the production cost function?

The main findings of this paper are that with formation of RJV, for sufficiently high coordination costs insider leaders invest less in R&D than outsider leaders. Insiders invest less in R&D than the competition case but still produce more and gain higher profits.

Outsider leaders and followers have lower incentives to invest in R&D, have lower production and gain lower profits compared with the competition case. However, welfare is always higher under R&D cooperation than R&D competition.

The remainder of the paper is organized as follows. In the next section, we review some of the existing literature on R&D and RJVs. In the third section, we present and solve the model under both R&D competition and R&D cooperation and analyze the results using numerical simulations. Subsection 3.4 is devoted to computing equilibrium and optimal sizes of the RJV. In section 4, we analyze the first extension, with spillovers and no information sharing. In section 5, we consider the second extension with convex production cost. The last section concludes.

1.2 Literature Review

One of the seminal papers in the R&D literature based on which many other studies have been developed is D'Aspermont and Jacquemin (1988). In their paper, they consider an industry with two firms that invest in R&D and generate spillovers. They compare three cases: one in which firms behave noncooperatively in both output and R&D stages, one in which firms cooperate at the R&D stage and behave non-cooperatively at the output stage, and one in which firms behave cooperatively in both stages. Comparing output and R&D investment between these three cases reveals that with high spillovers, when firms cooperate only in R&D, output is higher than in the two other cases. When firms collude in both R&D and output, R&D investment is greater than when they cooperate only in R&D and greater than under competition in both stages. However, in all cases, output and R&D are lower than the levels which maximize welfare.

Kamien et al. (1992) extend the model of D'Aspermont and Jacquemin (1988) to more than two firms with Cournot or Bertrand competition in the product market. They study four different cases: R&D competition (there is incomplete spillovers between firms, they compete in the R&D stage), R&D cartelization (there is incomplete spillovers between firms, they jointly maximize their profit at the R&D stage), RJV competition (while there is full information sharing between firms, they compete at the R&D stage) and RJV cartelization (where there is full information sharing between firms and they jointly maximize their profit at the R&D stage). In all cases, outputs and prices are chosen noncooperatively. Comparison of the four cases shows that among all these models, RJV cartelization yields the highest R&D investment, highest profit and lowest price. In contrast, RJV competition lowers R&D and raises prices. These results hold under Cournot and under most cases of Bertrand competition.

Suzumura (1992) considers an oligopoly model where firms conduct cost-reducing R&D; they can either cooperate or behave non-cooperatively in choosing their R&D investments. In his paper, he compares R&D equilibrium levels under these two R&D regimes with the socially optimal levels based on first-best and second-best welfare (where output choice is left to firms) criteria. Based on his findings, when spillovers are high, both cooperative and non-cooperative models yield socially insufficient R&D levels. Also, when there is no spillover, cooperative R&D levels will be socially insufficient and non-cooperative R&D levels will be excessive in terms of first and second-best welfare criteria.

Building on these seminal papers, some other authors have explicitly analyzed RJV membership and stability. Atallah (2003) uses a three-stage oligopoly model. In the first stage firms decide on joining the research joint venture. In the next stage, firms choose the amount of their R&D investment and RJV members decide on the level of spillovers between themselves. Finally, they choose output noncooperatively. Based on his findings, depending on the leakage of information to outsiders, insiders choose extreme levels of information sharing. In other words, if there is large leakage of information to outsiders, RJV members will choose no information sharing, and they will choose maximal information sharing when there is no spillovers to outsiders (extreme levels of information sharing are also discussed by Amir and Wooders (1999) and Poyago-Theotoky (1999)). According to this paper, RJVs with larger size are more likely to share information. Also, depending on three effects, (coordination effect, competition effect and information sharing effect), the size of the RJV may increase or decrease with information sharing.

Poyago-Theotoky (1995) analyzes an oligopoly model with a homogeneous product and assumes different levels of R&D spillovers between firms. She shows that for certain values of spillovers, the equilibrium size of the research joint venture is less than the optimal size. Therefore, she concludes that some policies should be implemented to encourage firms to follow some industry-wide cooperative agreements. Another result that she obtains is that the R&D investment of research joint venture members is always higher than non-members.

While much of the existing RJV literature shows that formation of R&D alliances has benefits, there are some empirical studies that show joint ventures' failures or unsatisfactory performance cases. According to Killing (1983), almost 30-40 percent of joint ventures break down. He studies 37 international research ventures and finds that almost 30% of them experience "in trouble" situations. Kogut (1989) conducts a case study of 92 manufacturing joint ventures in the United States and shows that a considerable number of these joint ventures terminated within their first six years of formation. Veugelers (1998) mentions costs of formation, costs of running the cooperation and problems of exchanging or controlling information between members as some of the difficulties that raise the risk of joint venture breakdown.

Falvey et al. (2010, 2013) study a two-stage oligopoly model; firms decide on R&D in the first stage and on output in the second stage. They can either compete in the R&D stage or cooperate with others by forming a RJV. They assume that for insiders, there is full information sharing, while there is no spillover among outsiders. The key novelty of their model is the incorporation of research coordination costs. They investigate the effects of change in the RJV coordination costs on equilibrium levels under R&D competition and R&D cooperation. In contrast to previous studies, they find that R&D cooperation does not necessarily increase R&D investment compared with R&D competition. As their study shows, for sufficiently high coordination costs, RJV insiders reduce their R&D investment and therefore, as a result of the reduction in their output, consumer surplus and social welfare may decline to levels lower than R&D competition. Falvey et al. (2013) check the robustness of the results by considering R&D spillovers between outsiders and also between insiders and outsiders. According to their findings, for high levels of spillovers, welfare may increase while the RJV is no longer profitable. Falvey et al. (2010) use numerical simulations and calculate equilibrium and optimal sizes of the research joint venture with and without coordination costs. They conclude that when the R&D cost also embodies coordination costs, the size of the research joint venture will be reduced.

Reviewing the existing literature on R&D and research joint ventures shows that there are very few works in which firms move sequentially. There are some studies in which sequential moves of firms in innovation race are taken into account, such as Reinganum

(1985), Doraszelski (2003) and Etro (2004), and the incentives of first and second movers in investing in innovation are investigated. Vandekerckhove and De Bondt (2008) develop a four-stage leader-follower model with possibility of symmetric and asymmetric spillovers between leaders, followers and also between leaders and followers. Leaders are first-movers in the R&D and output stages. Three different strategies of choosing R&D are considered: cooperation of leaders and competition of followers, cooperation of followers and competition of leaders, and competition of leaders and followers. Using numerical simulations, R&D investment incentives of leaders and followers, consumer surplus and welfare are compared and discussed in each circumstance. Results show that with symmetric spillovers, as in two-stage models, in most cases leaders invest more than followers. But, with asymmetric spillovers, in many cases followers invest more. For some levels of spillovers, cooperation of followers may lead to higher consumer surplus and welfare relative to leaders' cooperation.

O'Sullivan (2004) uses a Cournot duopoly framework and compares R&D competition and cooperation regimes when firms choose R&D simultaneously. Then it is assumed that one of these two firms can be a first mover in the R&D stage. Cooperation and competition of leader and follower are analyzed to examine the investment incentive of firms in both cases and also to find if the leader will attempt to deter entry. Finally, the results of simultaneous and sequential moves are compared.

In this study, we consider a sequential leader-follower model, where firms produce a homogeneous product in the output market. In all stages of R&D investment and production, leaders move first. In the R&D stage, a group of leaders can form a research joint venture to cooperate with other insiders or they can compete with each other. However, in both cases, leaders and followers choose their outputs competitively. One difference between this paper and previous R&D studies with sequential moves is that we capture R&D cooperation of firms both by assuming full information sharing between RJV partners and by jointly maximizing their profits at the R&D stage. For non-cooperating firms we assume no information sharing between them. These assumptions about cooperative and non-cooperative behaviour of firms are close to the assumptions made by Kamien et al. (1992) in the case of RJV cartelization (in a simultaneous framework). Another way in which this paper differs from several existing studies is that we explicitly incorporate coordination costs, which are convex and increase with the size of the RJV. In the first extension, like in Vandekerckhove and De Bondt (2008), we assume symmetric spillovers between leaders and some R&D spillovers from leaders to followers. The difference of our study with their research is that we analyze a model with RJV coordination costs in which a subset of leaders forms an RJV. One of the assumptions based on which we (and almost all previous papers on RJVs) solved the model is with a linear production cost function. In the second extension, we change this assumption to a convex production cost function and examine the effects on the results.

1.3 The basic Model

We consider a sequential oligopoly model in both R&D and output stages. There are *n* firms, where *k* of them are leaders and *n*-*k* firms are followers. The inverse demand function is

$$P = A - \sum_{i=1}^{k} y_i^l - \sum_{j=k+1}^{n} y_j^f \ , \tag{1}$$

where, P, A, y_i^l and y_j^f respectively represent price, choke price, output of a leader and output of a follower. We first consider the case where there is no cooperation in R&D.

1.3.1 R&D Competition

In this part, we assume that there are no involuntary R&D spillovers between firms. The unit cost of production for leader i and follower j are respectively

$$c_i^l = c - x_i^l \qquad i = 1,\dots, k \tag{2}$$

$$c_j^f = c - x_j^f \qquad j = k+1, \dots, n\,, \tag{3}$$

where c is the initial cost of production, x_i^l and x_j^f are R&D outputs of a representative leader firm and a representative follower firm. As we can see, a dollar increase in R&D output by a firm reduces its marginal cost by one dollar.

The profit functions are

$$\pi_i^l = \left(P - c_i^l\right) y_i^l - \frac{\tau\, {x_i^l}^2}{2} \tag{4}$$

$$\pi_j^f = \left(P - c_j^f\right) y_j^f - \frac{\tau\, {x_j^f}^2}{2}\ . \tag{5}$$

$\frac{\tau\, x^2}{2}$ represents a diminishing returns R&D cost function, where $\tau>0$ is a parameter of the R&D cost function.

We use a four-stage game to find the equilibrium levels of R&D and output. Note that within each group of leaders and followers, firms solve a simultaneous Cournot model, while they follow a subsequent Stackelberg model between stages of R&D and output. The four stages are as follows:

Stage 1: Leaders simultaneously choose the level of R&D output. So, leader firm *i* solves the following problem

$$\max_{x_i^l} \ \pi_i^l \qquad i = 1, \dots, k. \tag{6}$$

Stage 2: Each follower decides on the level of investment in R&D to maximize its profit

$$\max_{x_j^f} \ \pi_j^f \qquad j = k+1, \dots, n\,. \tag{7}$$

Stage 3: Taking the information gained from R&D stages, leader firm *i* determines the level of output by solving

$$\max_{y_i^l} \ \pi_i^l \qquad i = 1, \dots, k. \tag{8}$$

Stage 4: Follower *j* chooses its output to maximize its profit

$$\max_{y_j^f} \ \pi_j^f \qquad j = k+1, \dots, n\,. \tag{9}$$

We use backward induction to solve this model and compute the subgame perfect equilibrium. The result of each stage is as follows:

Stage 4:

$$\sum_{j=k+1}^{n} y_j^f = \frac{(n-k)\,(A-c)+[k(n-k)+k+1]\sum_{j=k+1}^{n} x_j^f-(n+k)(n-k+1)\sum_{i=1}^{k} x_i^l}{(k+1)(n-k+1)}\ . \tag{10}$$

Stage 3:

$$\sum_{i=1}^{k} y_i^l = \frac{k(A-c)-k\sum_{j=k+1}^{n} x_j^f+(n-k+1)\sum_{i=1}^{k} x_i^l}{(k+1)} \ . \tag{11}$$

Stage 2:

$$\sum_{j=k+1}^{n} x_j^f = \frac{2(n-k)[(k+1)(n-k+1)-1][A-c-(n-k+1)\sum_{i=1}^{k} x_i^l]}{\tau(k+1)^2(n-k+1)^2-2[(k+1)(n-k+1)-1][k(n-k+1)+1]} \ . \tag{12}$$

Stage 1:

$$\sum_{i=1}^{k} x_i^l = \frac{2(A-c)(n-k+1)[(\tau-2)(-k^2+n+kn)+\tau]\Gamma}{-2(1-k+n)[2k^2-2(1+k)n+(1+k)(1-k+n)^2\tau]\Gamma+\Phi} \ . \tag{13}$$

Where $\Gamma \equiv -2[k^2-(1+k)n][k^2+n-k(2+n)]+k(1+k)(1-k+n)^2\tau$

and $\Phi \equiv \tau[-2[n+k(n-k)][1+k(n-k+1)]+(1+k)^2(1-k+n)^2\tau]^2$.

Since firms in each group of leaders and followers are identical, we impose symmetry in (10), (11), (12) and (13). Then, substituting equilibrium levels of x_j^f and x_i^l from (12) and (13) into (10) and (11), we obtain the equilibrium levels of y_j^f and y_i^l (not shown due to their length).

1.3.2 R&D Cooperation

In this section we consider the formation of one RJV by a group of leaders. So, s ($1 \leq s \leq k$) leaders form a RJV while k-s leader firms and n-k follower firms stay out of the RJV (s =1 means no RJV forms). We assume full information sharing between RJV members and no information sharing between outsider firms. Also, there are no R&D spillovers between RJV members and outsiders. RJV members cooperate in R&D by maximizing their joint profits and sharing information, but in the product market all firms compete in Cournot. So, the model we analyze is similar to the "RJV cartel" discussed by Kamien et al. (1992) with the difference that our model is in Stackelberg framework and incorporates coordination costs.

The unit cost of production of an RJV member is reduced by the total information received from all insiders

$$c_i^{lr} = c - \sum_{i=1}^{s} x_i^{lr} \qquad i = 1, \dots, s \ , \tag{14}$$

where lr indicates RJV membership.

The unit cost of each outsider is reduced just by the level of its own R&D output. So, the unit cost of an outsider leader is

$$c_{\mathrm{i}}^{lo} = c - x_i^{lo} \qquad i = s+1, \dots, k \ , \tag{15}$$

where lo indicates an outsider leader.

The unit cost of an outsider follower is

$$c_j^{fo} = c - x_j^{fo} \qquad j = k+1, \dots, n \ , \tag{16}$$

where fo indicates a follower.

The profit function of a representative insider leader can be written as

$$\pi_i^{lr} = \left(P - c_i^{lr}\right) y_i^{lr} - \frac{z(s)\, {x_i^{lr}}^2}{2} \ . \tag{17}$$

$\frac{z(s)\, x^{lr^2}}{2}$ is the R&D cost of an RJV member, $z(s) > 0$ represents coordination costs where $z'(s) > 0$ and $z(1) = \tau$. This definition of $z(s)$ is the same as Falvey et al. (2010, 2013). $z'(s) > 0$ captures the fact that with the increase in the number of RJV members, coordination costs increase.

Profit functions of an outsider leader and a follower are given by

$$\pi_i^{lo} = \left(P - c_i^{lo}\right) y_i^{lo} - \frac{\tau\, x_i^{lo^2}}{2} \tag{18}$$

$$\pi_j^{fo} = \left(P - c_j^{fo}\right) y_j^{f} - \frac{\tau\, x_j^{fo^2}}{2} \; . \tag{19}$$

At stage 1, RJV members maximize their joint profits with respect to R&D, and each outsider leader independently maximizes its own profit with respect to R&D output. They simultaneously solve the following maximization problem:

$$\max_{x_i^{ln}} \sum_{i=1}^{s} \pi_i^{lr} = \left(P - c_i^{lr}\right) y_i^{lr} - \frac{z(s)\, x_i^{lr^2}}{2} \qquad i = 1, \dots, s \tag{20}$$

$$\max_{x_i^{lo}} \pi_i^{lo} = \left(P - c_i^{lo}\right) y_i^{lo} - \frac{\tau\, x_i^{lo^2}}{2} \qquad i = s+1, \dots, k \; . \tag{21}$$

At stage 2, each follower chooses its R&D investment to maximize its profit:

$$\max_{x_j^{fo}} \pi_j^{fo} = \left(P - c_j^{fo}\right) y_j^{fo} - \frac{\tau\, x_j^{fo^2}}{2} \qquad j = k+1, \dots, n \; . \tag{22}$$

At stage 3, insider and outsider leaders competitively choose output:

$$\max_{y_i^{lr}} \pi_i^{lr} = \left(P - c_i^{lr}\right) y_i^{lr} - \frac{z(s)\, x_i^{lr^2}}{2} \qquad i = 1, \dots, s \tag{23}$$

$$\max_{y_i^{lo}} \pi_i^{lo} = \left(P - c_i^{lo}\right) y_i^{lo} - \frac{\tau\, {x_i^{lo}}^2}{2} \qquad i = s+1, \dots, k\,. \tag{24}$$

Then, at the last stage, each follower decides on its level of output to maximize its profit:

$$\max_{y_j^{fo}} \pi_j^{fo} = \left(P - c_j^{fo}\right) y_j^{fo} - \frac{\tau\, {x_j^{fo}}^2}{2} \qquad j = k+1, \dots, n\,. \tag{25}$$

Using backward induction yields the following results:

Output stage:

$$\sum_{j=k+1}^{n} y_j^{fo} = \frac{(n-k)\,(A-c) + [k(n-k)+k+1]\sum_{j=k+1}^{n} x_j^{fo} - (n+k)(n-k+1)[s\sum_{i=1}^{s} x_i^{lr} + \sum_{i=s+1}^{k} x_i^{lo}]}{(k+1)(n-k+1)}\,. \tag{26}$$

$$\sum_{i=1}^{s} y_i^{lr} = \frac{s(A-c) - s\sum_{j=k+1}^{n} x_j^{fo} + (n-k+1)[s\sum_{i=s+1}^{k} x_i^{lo} - (k-s+1)\sum_{i=1}^{s} x_i^{lr}]}{(k+1)}\,. \tag{27}$$

$$\sum_{i=s+1}^{k} y_i^{l0} = \frac{(k-s)(A-c) - (k-s)\sum_{j=k+1}^{n} x_j^{fo} + (n-k+1)[(s+1)\sum_{i=s+1}^{k} x_i^{lo} - (k-s)\sum_{i=1}^{s} x_i^{lr}]}{(k+1)}\,. \tag{28}$$

R&D stage:

$$\sum_{j=k+1}^{n} x_j^{fo} = \frac{2(n-k)[(k+1)(n-k+1)-1][A-c-(n-k+1)(s\sum_{i=1}^{s} x_i^{lr} + \sum_{i=s+1}^{k} x_i^{lo})]}{\tau(k+1)^2(n-k+1)^2 - 2[(k+1)(n-k+1)-1][k(n-k+1)+1]}\,. \tag{29}$$

Since the solutions for $\sum_{i=1}^{s} x_i^{lr}$ and $\sum_{i=s+1}^{k} x_i^{lo}$ are too long, we just show them as a function of parameters and variables, but the full equations are available upon request.

$X^{lr}\ (x_i^{lo}, A, c, n, k, s, \tau, \rho)$ where $X^{lr} \equiv \sum_{i=1}^{s} x_i^{lr}$.

$X^{lo}\ (x_i^{lr}, A, c, n, k, s, \tau, \rho)$ where $X^{lo} \equiv \sum_{i=s+1}^{k} x_i^{lo}$.

Imposing symmetry and simultaneously solving the last two functions, we find the equilibrium levels of x_i^{lr} and x_i^{lo}. By substituting these into (26), (27), (28) and (29), we find equilibrium levels of $x_j^{fo}, y_i^{lr}, y_i^{lo}, y_j^{fo}$.

1.3.3 Comparing equilibria under R&D competition and cooperation[1]

In this section, we make a comparison of competitive and cooperative R&D regimes. Due to the complexity of the solutions, we use numerical simulations to analyze the results. For this purpose, first we need to assume a particular functional form for $z(s)$, which satisfies $z(s)$>0, $z'(s)$>0 and $z(1) = \tau$. So, we use the same functional form as chosen by Falvey et al. (2010):

$$z(s) = \tau s^{\rho} \tag{30}$$

where $s \geq 1,\ \rho \geq 0.$

Also, we need to initialize some values for parameters of the model, so we set parameters values as follows: *A*=500, *c*=100, τ=800, *n*=20 (we use the same parameter values for the numerical simulations in the next sections).

The results of our simulations are shown in figures 1 through 12. To plot figures 1-3, we have assumed $k = 10$ and $s \leq 10$. According to figure (1), with no coordination cost, RJV insiders always invest more in R&D than outsider leaders. This is because they benefit from sharing information with their partners and also by jointly maximizing their profits. However, with increases in coordination costs their investment decreases and for high levels

[1] Graphs and results obtained in this section are based on numerical simulations and specific choices of values for parameters, *n*, *k* and *s*. However, the results are robust for other values and they are available from the author upon request.

of coordination costs ($\rho = 1$), x_i^{lr} falls bellow x_i^{lo}. As shown in figures (2) and (3), insiders' profit and output are higher than outsiders', but the gap decreases with coordination costs. With higher coordination costs, insiders reduce their R&D and output and as a result earn lower profits. On the other side, in response to the increase in coordination costs, outsider leaders increase their investment in R&D, produce more and earn higher profits.

Result 1. *For sufficiently high coordination costs, insider leaders invest less in R&D than outsider leaders. More specifically:*

(i) If $\rho=0$, $\forall$ s , $x^{lr}>x^{lo}$.

(ii) If $\rho=0.5$, $\exists\ \bar{s}$ such that $\forall s<\bar{s}$, $x^{lr}>x^{lo}$ and *$\forall s>\bar{s}$, $x^{lr}<x^{lo}$.*

(iii) If $\rho=1$, $\forall$ s, $x^{lr}<x^{lo}$.

(iv) $\forall\ \rho,s$, $\pi^{lr}>\pi^{lo}$, $y^{lr}>y^{lo}$.

For the remaining figures, we have assumed $s = 10$ and $k \in [10,19]$. As shown in figures 4 to 6, R&D investment of insider leaders (x_i^{lr}) with no coordination cost is strictly higher than under R&D competition (x_i^{l}). When coordination costs are very high, the investment level of coalition members is always lower than leaders' investment under R&D competition. However, production and profit of insider leaders are higher than when there is no cooperation.

Result 2. *Under R&D cooperation, with high enough coordination costs, insiders have lower incentives to invest in R&D, but still gain higher profits than under R&D competition.*

More specifically:

(i) If ρ=0 , $\forall$ *k,* $x^{lr} > x^{l}$.

(ii) If ρ=0.5 , $\exists\, \bar{k}$ *such that* $\forall k < \bar{k}$, $x^{lr} < x^{l}$ and $\forall k > \bar{k}$, $x^{lr} > x^{l}$.

(iii) If ρ=1 , $\forall$ *k,* $x^{lr} < x^{l}$.

(iv) $\forall \rho, k$ *:* $\pi^{lr} > \pi^{l}$, $y^{lr} > y^{l}$.

Figures (7) through (12) show the comparison of investment, output and profit of outsider leaders and followers under R&D cooperation (by insider leaders) versus R&D competition. R&D cooperation increases the R&D, output and profits of all insiders. Our results about the effect of formation of an RJV on R&D investment, production and profit levels of firms are the same as Falvey et al. (2010, 2013). When coordination costs increase, we see the same changes in the R&D investments and profits ranking of firms under cooperative and non-cooperative regimes. However, while we find that even with increases in coordination costs, production of the cooperative firms is always higher than their production under a competition regime, Falvey et al. (2010, 2013) provide a critical level of coordination costs after which production of insiders falls below their production under competition and also below the production of outsiders. The greater market power of Stackelberg leaders (in our model) reinforces the effect of cooperation in increasing output.

Result 3. *Under R&D cooperation, followers and outsider leaders have lower incentives to invest in R&D, have lower production and obtain lower profits than under R&D competition. More specifically:*

(i)) $\forall \rho, k$ *:* $x^{lo} < x^{l}$, $y^{lo} < y^{l}$, $\pi^{lo} < \pi^{l}$.

(ii)) $\forall \rho, k$ *:* $x^{fo} < x^{f}$, $y^{fo} < y^{f}$, $\pi^{lo} < \pi^{f}$.

While the Falvey et al. (2010, 2013) results show that with full information sharing and high coordination costs, cooperation between firms leads to lower welfare compared with the competition case, figure (13) shows that cooperation between a group of leaders always increases welfare. In table (1) numerical comparisons of welfare under R&D competition and cooperation for *n*=20, *k*=12, *s*=5, and also for *n*=20, *k*=14, *s*=10 are shown. As we can see, despite the decrease in the profits of followers and outsider leaders under R&D cooperation, because of the increase in the profits of insiders and consumer surplus, the overall effect is an increase in welfare. The results of a numerical example are presented in Table 1.

Result 4. *Welfare is always higher under R&D cooperation than R&D competition*:

$\forall \rho, k: \; W^{r} > W^{nr}$.

Table 1. Welfare under R&D cooperation and competition

n=20		R&D Cooperation					R&D Competition				Comparison
		π_j^{fo}	π_i^{lo}	π_i^{lr}	CS^r	W^r	π_j^{f}	π_i^{l}	W^{nr}	CS^{nr}	
***k*=12 *s*=5**	***ρ*=0**	3.8715	27.5121	125.515	79215.8726	80604.3	14.1042	100.229	79994.5	78506.7	$\pi_j^{fr}<\pi_j^{f}$
	***ρ*=0.5**	10.8981	23.46294	107.388499	78902.47465	80135.6					$\pi_i^{lo}<\pi_i^{l}$
	***ρ*=1**	13.3004	94.5166	102.698	78549.6512	80034.5					$\pi_i^{lr}>\pi_i^{l}$
***k*=14 *s*=10**	***ρ*=0**	7.9343	72.8596	131.13	80107.8	78878.6584	11.2681	103.473	79996.4	78664.6	$CS^r>CS^{nr}$
	***ρ*=0.5**	10.0079	91.9016	113.793	80033.5	78741.1606					$W^r>W^{nr}$
	***ρ*=1**	10.8293	99.444	107.44	80010.7	78690.7576					

Figure 1. R&D investment of insiders and outsider leaders

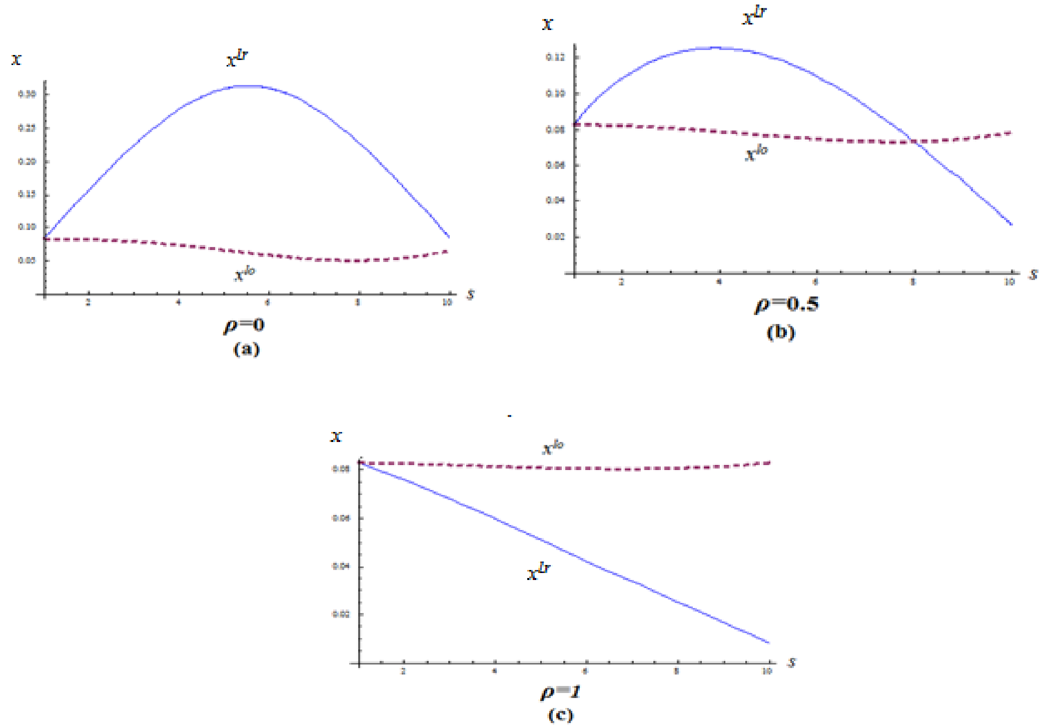


Figure 2. Profit of insiders and outsider leaders

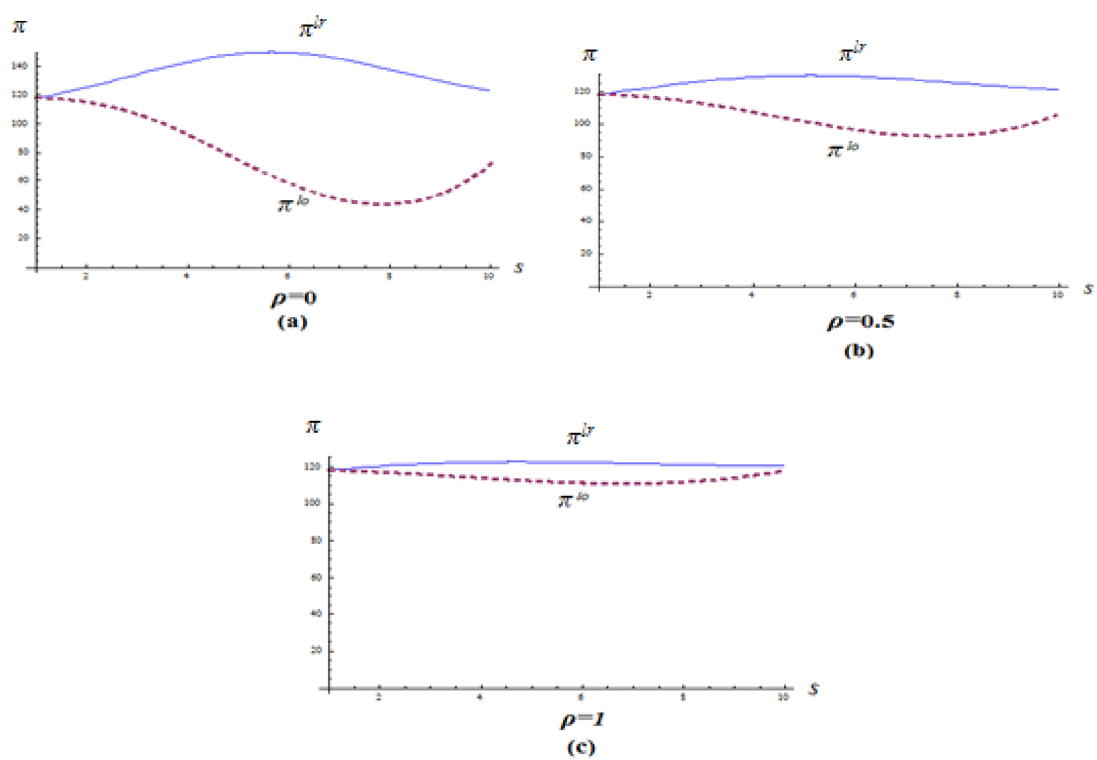


Figure 3. Output of insiders and outsider leaders

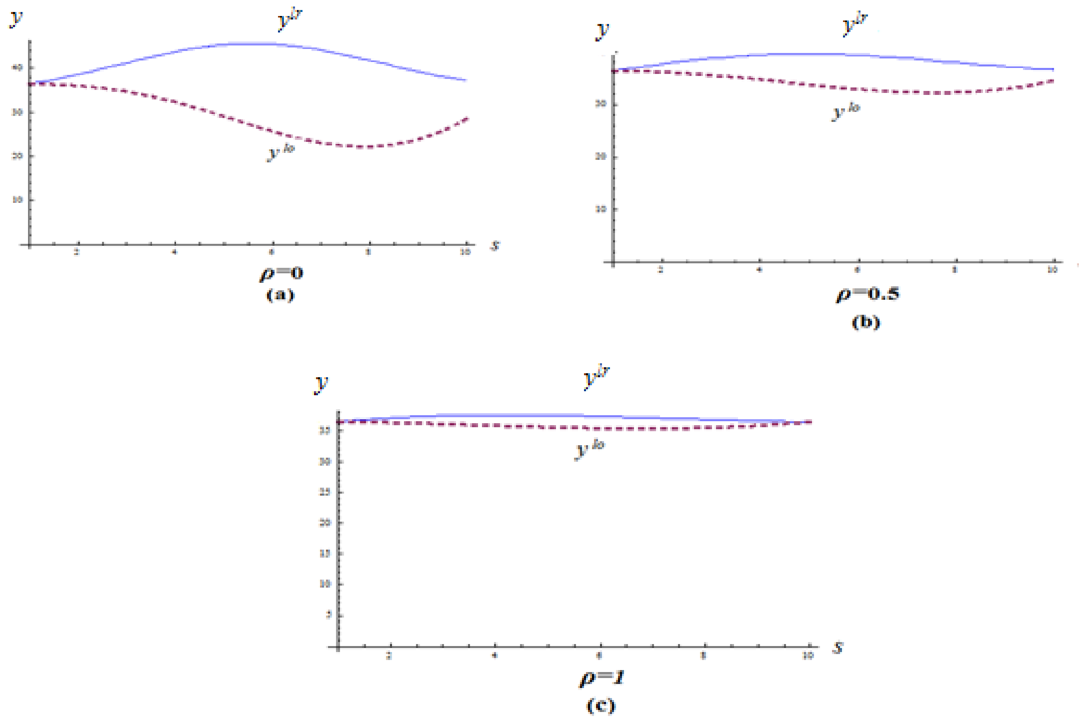


Figure 4. R&D invesment of leaders under cooperation (insiders) and competition

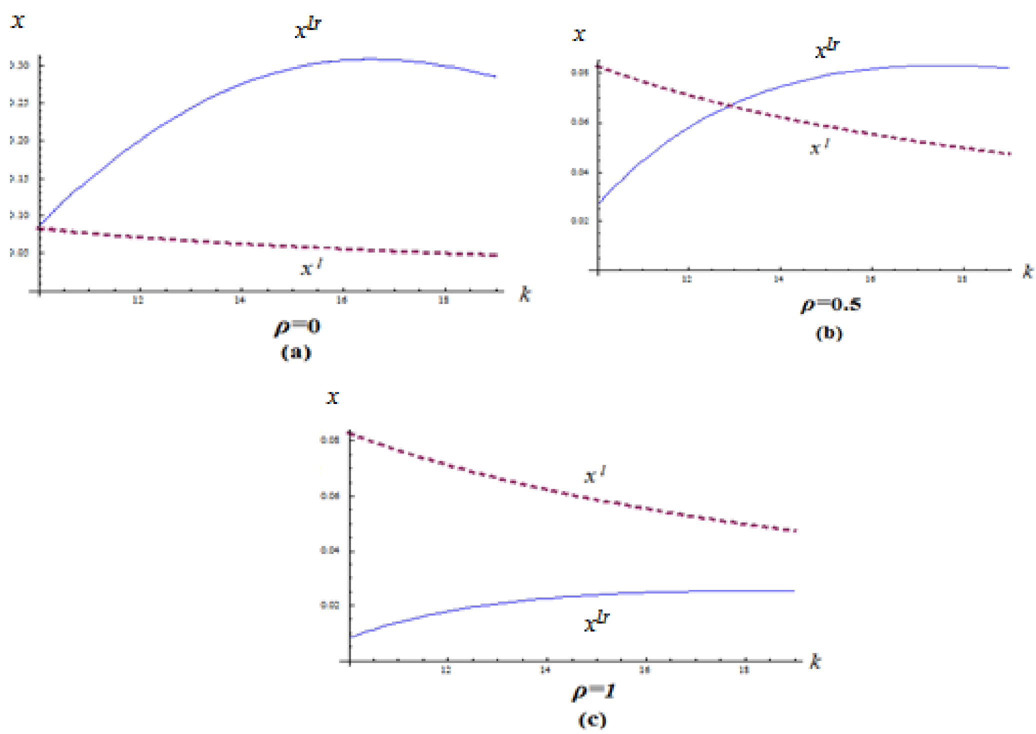


Figure 5. Output of leaders under cooperation (insiders) and competition

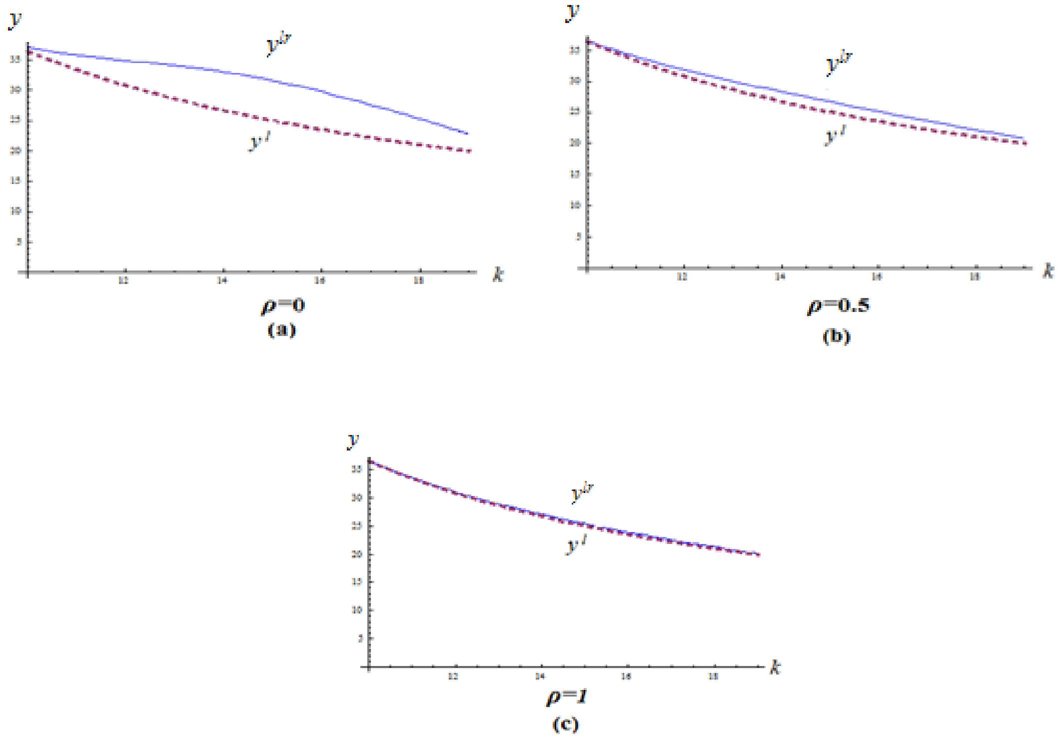


Figure 6. Profit of leaders under cooperation (insiders) and competition

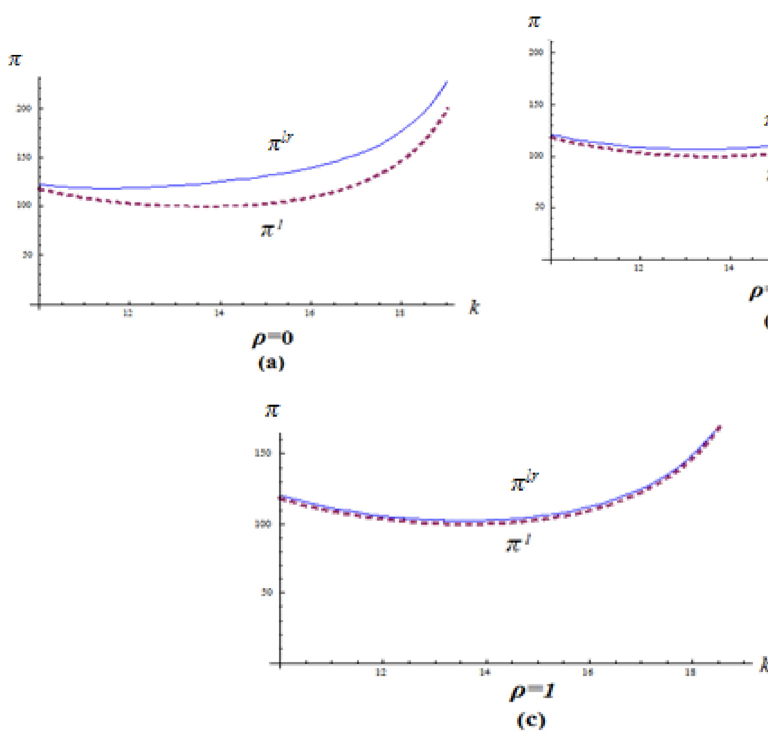


Figure 7. R&D investment of leaders under cooperation (outsiders) and competition

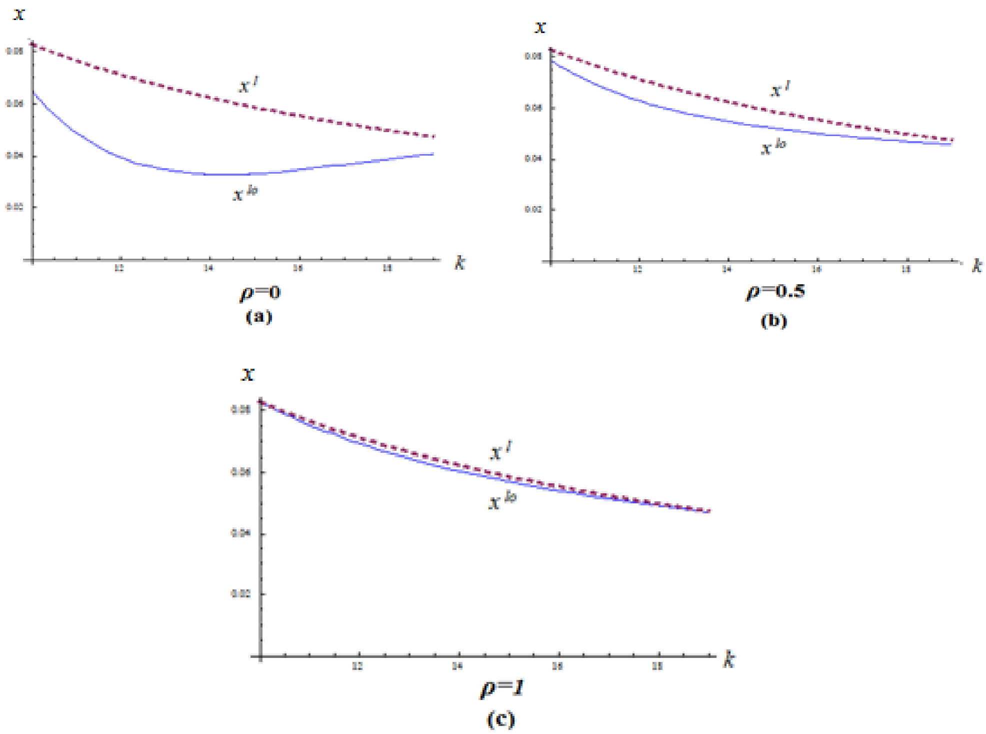


Figure 8. Profit of leaders under cooperation (outsiders) and competition

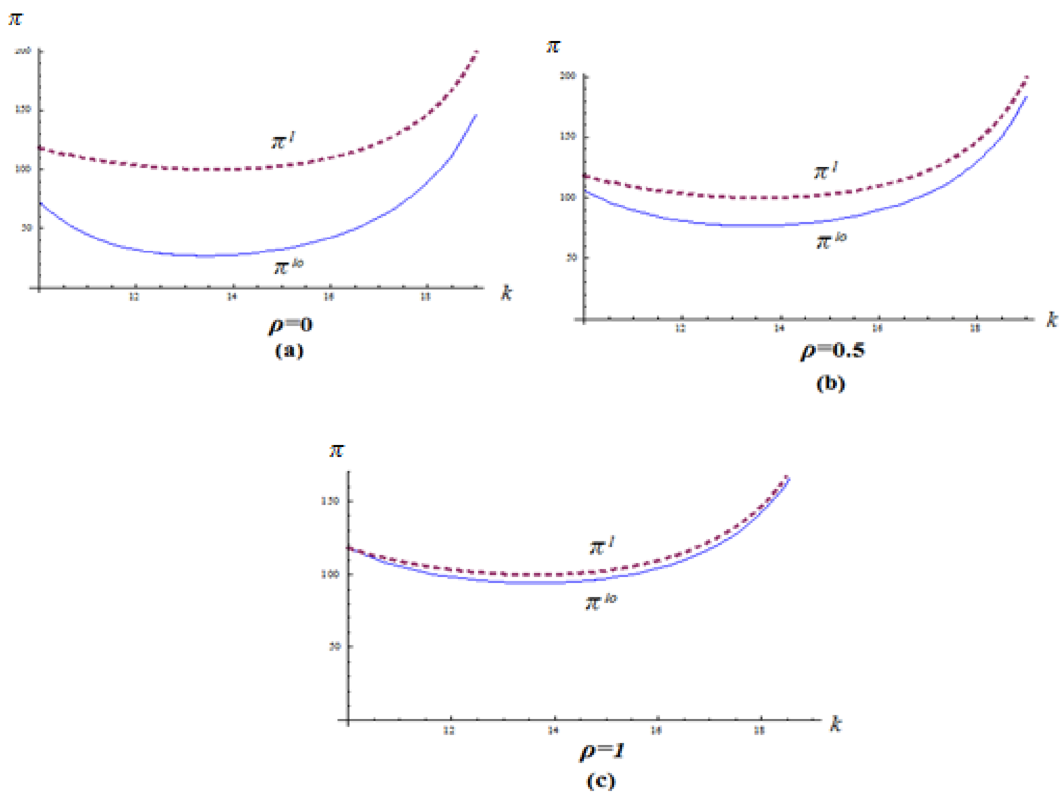


Figure 9. Output of leaders under cooperation (outsiders) and competition

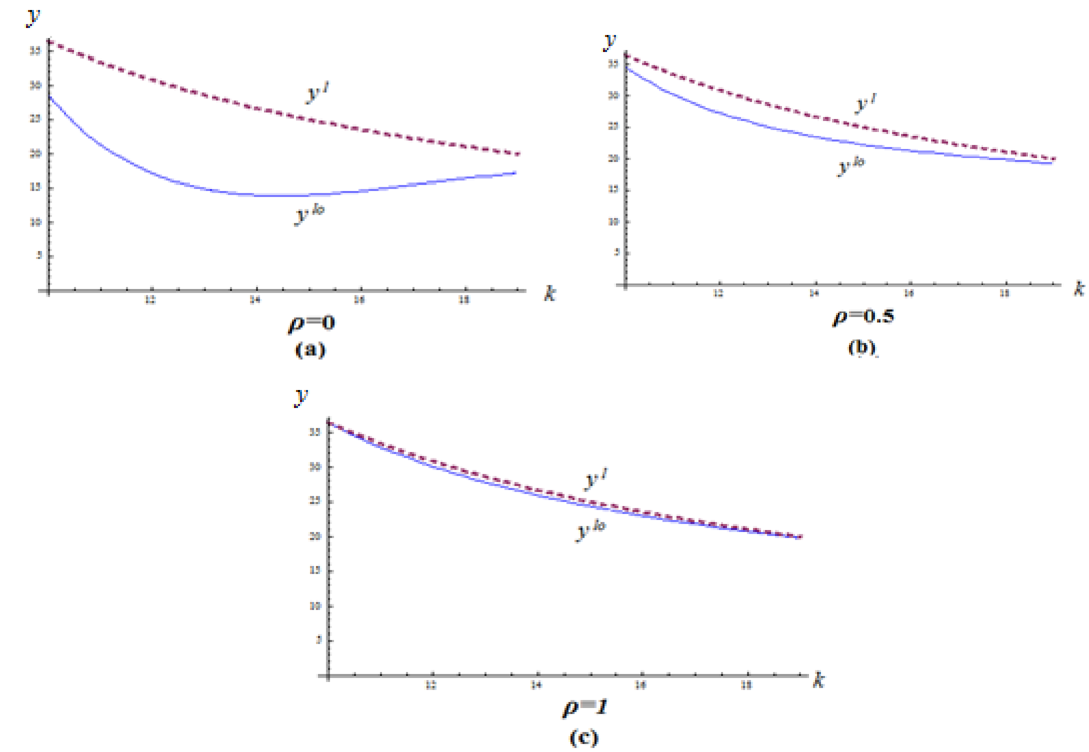


Figure 10. R&D investment of followers under cooperation and competition

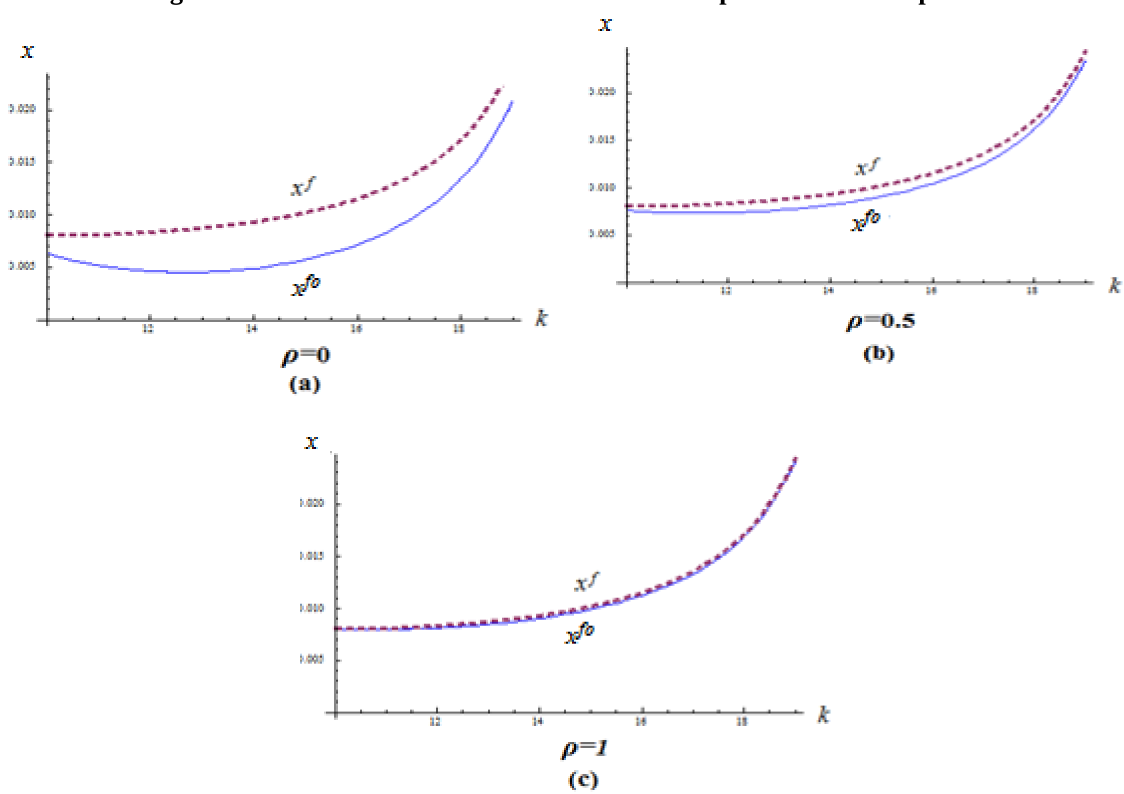


Figure 11. Output of followers under cooperation and competition

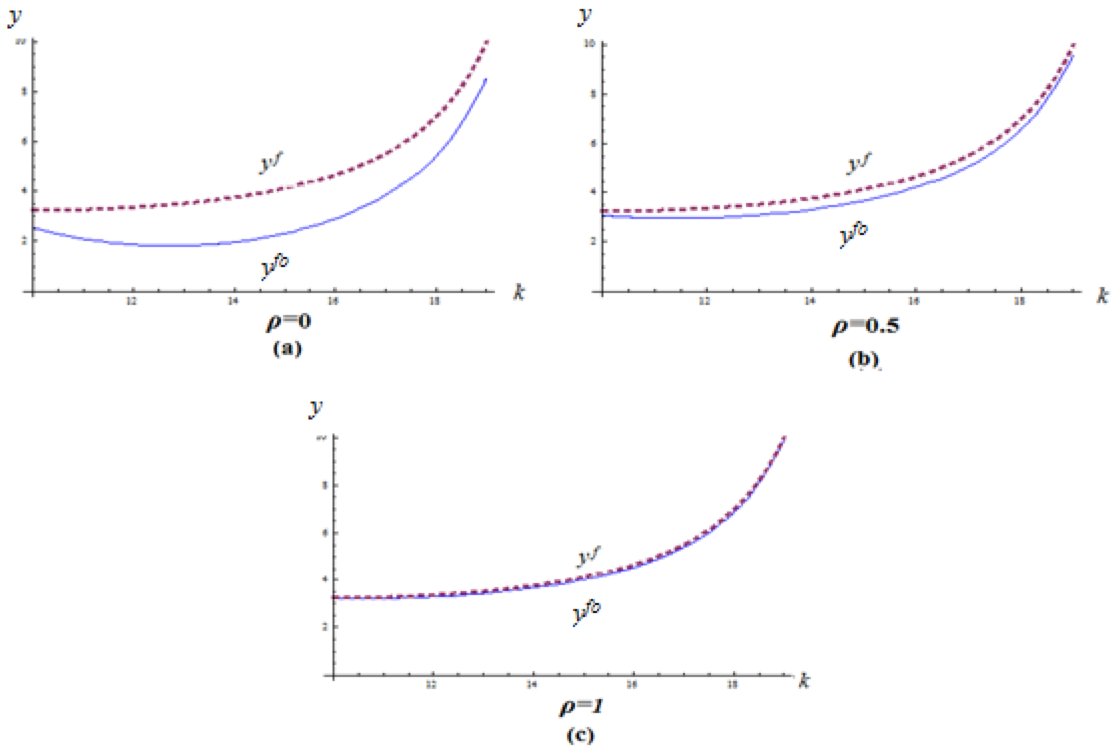


Figure 12. Profit of followers under cooperation and competition

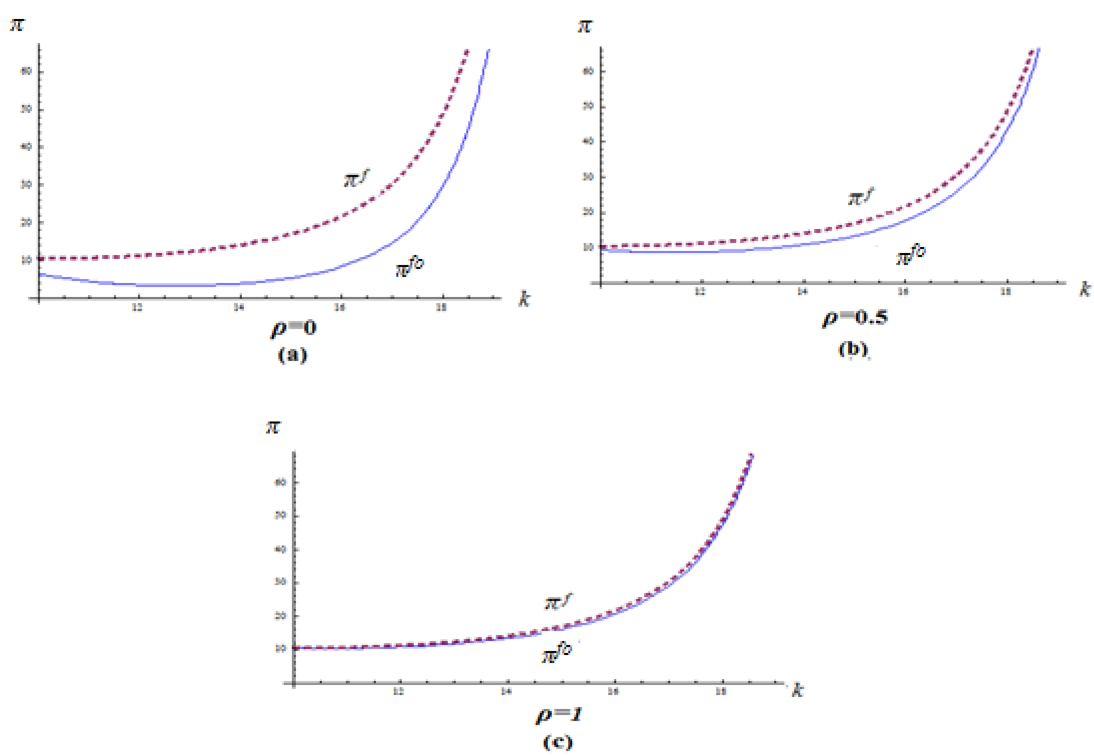
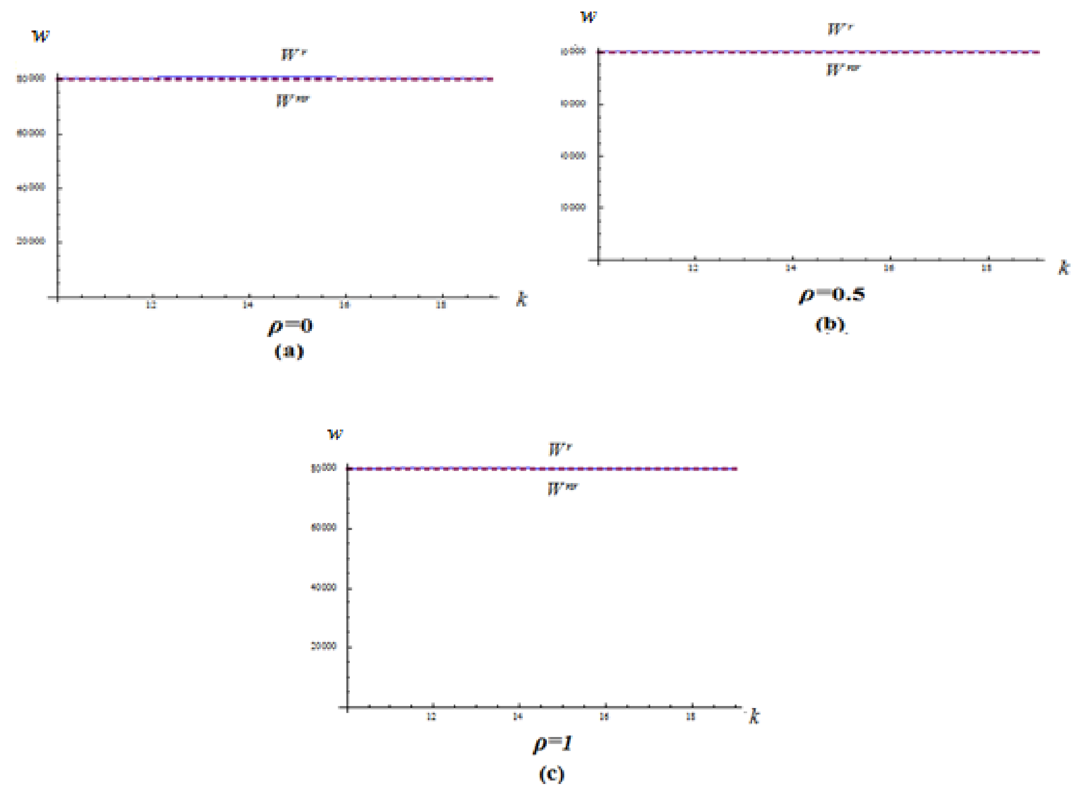


Figure 13. Welfare under cooperation and competition



1.3.4 Equilibrium and Optimal Sizes of the RJV

In this section, we determine equilibrium and optimal sizes of the RJV and explore how increases in coordination cost affect these sizes. We assume that insiders have the power to allow or prevent firms from joining the RJV, i.e. entry into the RJV is not free. Intuitively, the addition of a member to the RJV induces three effects: an information sharing effect, a competition effect and a coordination effect. As the number of RJV members increases, because of more information sharing, the unit cost of production of each insider will be reduced further and this will have a positive effect on insiders' profits. We call this benefit the information sharing effect; it encourages insiders to let new members join the RJV. However, a new member will become a stronger competitor on the output market, which leads to lower profits for insiders; this is the competition effect. Here, we consider another effect which we call the coordination cost effect: the increase in the RJV size increases R&D and therefore coordination costs. This effect reduces members' profits and reduces the incentives to admit new members into the RJV.

As discussed in the previous section, the profit of an outsider is always lower than an RJV member's profit, so an outsider will always want to join the RJV. Because of competition and coordination cost effects, insiders may elect to limit the size of the RJV.

Definition of equilibrium size of the RJV[1]: We define the equilibrium size of RJV as the level of s that maximizes the profit of an insider:

$$s^e = \underset{s \in n}{arg\ max}\ \pi_i^{*\,lr}(s)\ ,$$

(or the closest integer to s yielding the highest possible profit for insiders).

The equilibrium size of the RJV, s^e, must satisfy the following stability conditions:

i) $\pi_i^{*\,lr}(s^e) > \pi_i^{*\,lr}(s^e - 1)$,

ii) $\pi_i^{*\,lr}(s^e) > \pi_i^{*\,lr}(s^e + 1)$,

iii) $\pi_i^{*\,lr}(s^e) > \pi_i^{*\,lo}(s^e - 1)$.

Condition (i) indicates that insiders have no incentive to eject any member from the RJV. Condition (ii) stipulates that insiders will not accept entrance of an additional firm to RJV. The last condition states that no insider has an incentive to leave the RJV.

[1] The definitions of the equilibrium and optimal sizes of the RJV are the same as in Payago-Theotoky (1995) and Falvey et al. (2010). Also, stability conditions used here are close to what is usually adopted in the literature (e.g. Poyago-Theotorky, 1995; Atallah, 2003; Falvey et al., 2010).

Definition of optimal size of the RJV: The optimal size of the RJV is the size that maximizes total surplus, which is defined as follows:

$$W^* = s\,\pi_i^{*\,lr} + (k-s)\pi_i^{*\,lo} + (n-k)\pi_j^{*\,fo} + CS^*\,, \tag{31}$$

where $CS^* = \frac{\left(\sum_{i=1}^{s} y^{*lr}_{i} + \sum_{i=s+1}^{k} y^{*lo}_{i} + \sum_{j=k+1}^{n-k} y^{*fo}_{j}\right)^2}{2}$.

To find the optimal size of RJV, we need to solve:

$$s^{opt} = \arg\max_{s\in n} W^*(s)$$

(or the closest integer to s yielding the highest possible welfare).

To obtain tractable results, we use numerical simulations. Numerical simulation is applied for n=5, 10, 15 and 20, $0 \le \rho \le 1$ and different values of k. Results of numerical simulations for equilibrium and optimal sizes of the RJV are presented in tables 2 through 5.

Table 2. Equilibrium and optimal sizes of the RJV, *n*=5

		ρ =0	ρ =0.25	ρ =0.5	ρ =0.75	ρ =1
K=3	s^e s^{opt}	2 2	2 2	2 2	2 2	2 2
K=4	s^e s^{opt}	3 3	3 3	3 3	3 3	3 3
K=5	s^e s^{opt}	3 4	3 4	3 4	3 4	3 4

Table 3. Equilibrium and optimal sizes of the RJV, *n*=10

		ρ =0	ρ =0.25	ρ =0.5	ρ =0.75	ρ =1
K=3	s^e s^{opt}	2 2	2 2	2 2	2 2	2 2
K=4	s^e s^{opt}	3 3	3 3	3 3	3 3	3 3
K=5	s^e s^{opt}	3 4	3 4	3 4	3 4	3 4
K=6	s^e s^{opt}	4 5	4 5	4 5	3 5	3 5
K=7	s^e s^{opt}	4 6	4 6	4 6	4 6	4 6
K=8	s^e s^{opt}	5 7	5 7	4 7	4 7	4 7
K=9	s^e s^{opt}	5 8	5 8	5 8	5 8	4 7

Table 4. Equilibrium and optimal sizes of the RJV, *n*=15

		ρ =0	ρ =0.25	ρ =0.5	ρ =0.75	ρ =1
K=3	s^e	2	2	2	2	2
	s^{opt}	2	2	2	2	2
K=4	s^e	3	3	3	3	3
	s^{opt}	3	3	3	3	3
K=5	s^e	3	3	3	3	3
	s^{opt}	4	4	4	4	4
K=6	s^e	4	4	4	3	3
	s^{opt}	5	5	5	5	5
K=7	s^e	4	4	4	4	4
	s^{opt}	6	6	6	6	6
K=8	s^e	5	5	4	4	4
	s^{opt}	7	7	7	7	7
K=9	s^e	5	5	5	5	4
	s^{opt}	8	8	8	8	7
k=10	s^e	6	5	5	5	5
	s^{opt}	8	8	8	8	8
k=11	s^e	6	6	6	5	5
	s^{opt}	9	9	9	9	9
k=12	s^e	7	6	6	6	5
	s^{opt}	10	10	10	10	10
k=13	s^e	7	7	6	6	6
	s^{opt}	11	11	11	11	10
k=14	s^e	8	7	7	6	6
	s^{opt}	12	12	12	11	11

Table 5. Equilibrium and optimal sizes of the RJV, *n*=20

		ρ =0	ρ =0.25	ρ =0.5	ρ =0.75	ρ =1
K=3	s^e s^{opt}	2 2	2 2	2 2	2 2	2 2
K=4	s^e s^{opt}	3 3	3 3	3 3	3 3	3 3
K=5	s^e s^{opt}	3 4	3 4	3 4	3 4	3 4
K=6	s^e s^{opt}	4 5	4 5	4 5	3 5	3 5
K=7	s^e s^{opt}	4 6	4 6	4 6	4 6	4 6
K=8	s^e s^{opt}	5 7	4 7	4 7	4 7	4 7
K=9	s^e s^{opt}	5 8	5 8	5 8	5 7	4 7
k=10	s^e s^{opt}	6 8	5 8	5 8	5 8	5 8
k=11	s^e s^{opt}	6 9	6 9	6 9	5 9	5 9
k=12	s^e s^{opt}	7 10	6 10	6 10	6 10	5 10
k=13	s^e s^{opt}	7 10	7 11	6 11	6 11	6 10
k=14	s^e s^{opt}	8 11	7 11	7 11	6 11	6 11
K=15	s^e s^{opt}	8 12	8 12	7 12	7 12	6 11
k=16	s^e s^{opt}	9 13	8 13	8 13	7 13	7 13
k=17	s^e s^{opt}	9 13	9 14	8 14	8 14	7 13
k=18	s^e s^{opt}	10 14	9 15	8 15	8 14	7 14
k=19	s^e s^{opt}	10 15	10 15	9 15	8 15	8 15

As we can see from the tables, for $k \geq 6$, the equilibrium size of the RJV decreases with coordination costs (Falvey et al., 2010 get the same result in a Cournot setting). This is because with high coordination costs, the negative effect of an additional member on the profit of each insider is higher and therefore insiders' profits are maximized for a lower value of s. In most cases, the optimal size of the RJV is independent from coordination costs. However, for some higher levels of k, for ρ close to 1, the optimal size of the RJV decreases with coordination costs.

Comparing all four tables, we can see that when concentration decreases, the equilibrium and optimal sizes of the RJV remain the same for a given number of leaders. In other words, an increase in the number of followers does not affect the equilibrium and optimal sizes of the RJV. Followers are not sufficiently independent from a strategic point of view to affect s^e and s^{opt}.

Another point is that for the cases with a large number of leaders, the equilibrium size of the RJV is always less than the optimal size. Insiders do not internalize the benefit to consumers from a larger RJV and lower prices. This leads to an RJV that is too small. At the same time, insiders do not account for the reduction of profits of outsiders. This leads to an RJV which can be too large. As the gain to consumers is quantitatively more important than the loss to outsiders, $s^e \leq s^{opt}$.

Result 5. *The equilibrium size of the RJV decreases with the increase in coordination costs, but the optimal size mostly does not react to this increase. Moreover, the equilibrium size is less than the optimal size in most cases.*

1.4 R&D spillovers and no information sharing

In this section, to test the robustness of the results to the type of R&D cooperation, we assume that there are R&D spillovers between leaders and also from leaders to followers. Since leaders choose their R&D investment before followers, we assume that there are no spillovers from followers to leaders. Furthermore, there is no information sharing between RJV members. With $0 \leq \beta < 1$ as the spillovers rate, the unit costs of production of leaders and followers are:

$$c_i^l = c - (1-\beta)x_i^l - \beta \sum_1^k x_i^l \qquad i = 1, \dots, k \tag{32}$$

$$c_j^f = c - (1-\beta)x_j^f - \beta\left(\sum_{k+1}^n x_j^f + \sum_1^k x_i^l\right) \quad j = k+1, \dots, n. \tag{33}$$

When firms choose the level of R&D investment competitively, the equilibrium is:

$$\sum_{j=k+1}^n x_j^f = \frac{2(n-k)\big((k+1-\beta)(n-k+1)-1\big)\Big(A-c-\big((\beta-1)(n-k)+2\beta-1\big)\sum_{i=1}^k x_i^l\Big)}{\Theta}, \tag{34}$$

where

$$\Theta \equiv \gamma(k+1)^2(n-k+1)^2 - 2((n-k+1)(k+1-\beta)+2\beta-1)((n-k+1)(\beta k(n-k)+(1-\beta)(k+1))+(2\beta-1)(n-k))$$

$$\sum_{i=1}^k y_i^l = \frac{k(A-c)-k(1+\beta(n-k-1)\sum_{j=k+1}^n x_j^f + ((n-k+1)(1-\beta)+\beta k)\sum_{i=1}^k x_i^l}{(k+1)} \tag{35}$$

$$\sum_{j=k+1}^n y_j^f = \frac{(n-k)\,(A-c)+(k(n-k+1)+1)(1+\beta(n-k-1))\sum_{j=k+1}^n x_j^f}{(k+1)(n-k+1)}$$

$$-\frac{(n+k)((1-\beta)(n-k+1)-\beta)\sum_{i=1}^k x_i^l}{(k+1)(n-k+1)} \tag{36}$$

$$\sum_{i=1}^k x_i^l = \frac{2Mk(\tau(k+1)^2(n-k+1)^2-2(k+1)(n-k+1)\big(1+\beta(n-k-1)\big)\big((n-k+1)(k+1-\beta)+2\beta-1\big))(A-c)}{\tau(n-k+1)(k+1)^2-\Psi}, \tag{37}$$

where

$\Theta \equiv \tau(k+1)^2(n-k+1)^2 - 2((n-k+1)(k+1-\beta) + 2\beta - 1)((n-k+1)(\beta k(n-k) + (1-\beta)(k+1)) + (2\beta-1)(n-k))$

$M \equiv \big((1-\beta)(n-k)+1\big)\Theta - 2(n-k)\big(1+\beta(n-k-1)\big)\big((n-k+1)(k+1-\beta)+2\beta-1\big)((\beta-1)(n-k)+2\beta-1)$

$\Psi \equiv 2M(((1-\beta)(n-k+1)+k\beta)\Theta - 2k(n-k)\big(1+\beta(n-k-1)\big)\big((n-k+1)(k+1-\beta)+2\beta-1\big)\big((\beta-1)(n-k)+2\beta-1)$

By assuming symmetry of firms for leaders and followers, we find x_i^l, x_j^f, y_i^l, y_j^f.

Now, we examine the case in which a group of leaders cooperate in R&D and form an RJV. When the RJV is formed, spillover remains the same as under R&D competition. The equilibrium is:

$$\sum_{j=k+1}^{n} y_j^{fo} = \frac{(n-k)\,(A-c)+(k(n-k+1)+1)(1+\beta(n-k-1))\sum_{j=k+1}^{n} x_j^{fo}}{(k+1)(n-k+1)} - \frac{(n-k)((1-\beta)(n-k+1)-\beta)(\sum_{i=1}^{s} x_i^{lr}+\sum_{i=s+1}^{k} x_i^{lo})}{(k+1)(n-k+1)} \tag{38}$$

$$\sum_{i=1}^{s} y_i^{lr} = \frac{s(A-c)-s(1+\beta(n-k-1))\sum_{j=k+1}^{n} x_j^{fo}+(n-k+1)((1-\beta)\big((k-s+1)\sum_{i=1}^{s} x_i^{lr} - s\sum_{i=s+1}^{k} x_i^{lo}\big)}{(k+1)} + \frac{\beta s(\sum_{i=1}^{s} x_i^{lr}+\sum_{i=s+1}^{k} x_i^{lo})}{(k+1)} \tag{39}$$

$$\sum_{i=s+1}^{k} y_i^{lo} = \frac{(k-s)(A-c)-(k-s)(1+\beta(n-k-1))\sum_{j=k+1}^{n} x_j^{fo}+(n-k+1)(1-\beta)\big((s+1)\sum_{i=s+1}^{k} x_i^{lo}\big)}{(k+1)} - \frac{(k-s)((n-k+1)(1-\beta)\sum_{i=1}^{s} x_i^{lr}-\beta(\sum_{i=1}^{s} x_i^{lr}+\sum_{i=s+1}^{k} x_i^{lo}))}{(k+1)}\,. \tag{40}$$

To analyze the model, we use numerical simulations. Numerical simulations indicate that in this framework, for any degree of information spillover, even with zero coordination costs, profits of the cooperative leaders are less than the outsider leaders' profits[1]. Therefore, the only equilibrium is that no RJV forms. Hence, information sharing is crucial for the formation of RJVs.

Result 6. *With R&D spillovers and no information sharing, leaders have no incentive to join the RJV and therefore no RJV forms.*

1.5 Convex production costs

In this section, to test the robustness of the results to the assumptions regarding the cost function, we assume that the marginal cost of production is increasing in output. Increasing marginal costs reduces the incentives of RJV members to expand their output and therefore to invest in R&D. We want to see how the equilibrium and optimal sizes of the RJV will change. Total production costs of leaders and followers under R&D competition are

$$TC_i^l = \frac{c}{2} {y_i^l}^2 - x_i^l y_i^l \qquad i = 1, \ldots, k \tag{41}$$

$$TC_j^f = \frac{c}{2} {y_j^f}^2 - x_j^f y_j^f \qquad j = k+1, \ldots, n. \tag{42}$$

Marginal costs are

$$c_i^l = c y_i^l - x_i^l \qquad i = 1, \ldots, k \tag{43}$$

$$c_j^f = c y_j^f - x_j^f \qquad j = k+1, \ldots, n. \tag{44}$$

The profit functions of leaders and followers are as follows

[1] Numerical results are available upon request.

$$\max_{x_i^l} \; \pi_i^l = \left(Py_i^l - TC_i^l\right) - \frac{\tau\, {x_i^l}^2}{2} \qquad i = 1, \dots, k \tag{45}$$

$$\max_{x_j^f} \; \pi_j^f = \left(Py_j^f - TC_j^f\right) - \frac{\tau\, {x_j^f}^2}{2} \qquad j = k+1, \dots, n\,. \tag{46}$$

The stages of the game are the same as before. Using backward induction, we obtain the following results for each stage:

Stage 4:

$$\sum_{j=k+1}^{n} y_j^f = \frac{(n-k)\,[(c(n-k+c+1)+c+1)A-(n-k+c+1)\sum_{i=1}^{k} x_i^l]}{(n-k+c+1)(c(n-k+c+1)+(c+1)(k+1))}$$
$$+\frac{(k+c)(n-k+c+1)+c+1)\sum_{j=k+1}^{n} x_j^f}{(n-k+c+1)\big(c(n-k+c+1)+(c+1)(k+1)\big)}\,. \tag{47}$$

Stage 3:

$$\sum_{i=1}^{k} y_i^l = \frac{k[(c+1)A-\sum_{j=k+1}^{n} x_j^f]+(n-k+c+1)\sum_{i=1}^{k} x_i^l}{c(n-k+c+1)+(c+1)(k+1)}\,. \tag{48}$$

Stage 2:

$$\sum_{j=k+1}^{n} x_j^f = \frac{H(n-k)(c+1)[(c(n-k+c+1)+c+1)A-(n-k+c+1)\sum_{i=1}^{k} x_i^l]}{\gamma(c+1)^2(n-k+c+1)^2[c(n-k+c+1)+(k+1)(c+1)]^2-H(c+1)[(n-k+c+1)(c+k)+c+1]}\,, \tag{49}$$

where

$H \equiv (c+2)[(n-k+c+1)(c(n-k+c+1)+k(c+1)+1)-(c+1)]$

Stage 1:

$$\sum_{i=1}^{k} x_i^l = \frac{Mk(c+1)[c(n-k+c+1)+c+1][c(n-k+c+1)+2(c+1)][\Theta-H(n-k)(c(n-k+c+1)+c+1)]A}{\tau(n-k+2c+1)[2c(n-k+2c+1)+2c+1]^2[c(n-k+c+1)+(c+1)(k+1)]^2\Theta^2-\Psi}\,, \tag{50}$$

where:

$$\Theta \equiv \tau(n-k+c+1)^2(c+1)^2[c(n-k+c+1)+(c+1)(k+1)]^2 - H(c+1)[(c+k)(n-k+c+1)+c+1]$$

$$M \equiv \Theta(n-k+c+1)[c(n-k+c+1)+k(c+1)] + H(n-k)(c+1)(n-k+c+1)[c(n-k+c+1)+c+1]$$

$$\Psi \equiv M(n-k+c+1)\big(c(n-k+c+1)+2(c+1)\big)\big(c(n-k+c+1)+c+1\big)[\,H\,k\,(2c+1)(n-k)+\Theta]\,.$$

Imposing symmetry in (48) through (51), we find the equilibrium levels of x_i^l , x_j^f, y_i^l and y_j^f (due to their length, they are not shown).

Now, we assume that s ($1 \le s \le k$) leaders form an RJV. There is full information sharing between insiders and no information sharing between outsiders. Moreover, there are no involuntary spillovers. Total production costs of insiders, outsider leaders and followers under R&D cooperation are

$$TC_i^{ln} = \frac{C}{2} {y_i^{lr}}^2 - \sum_{i=1}^{s} x_i^{lr}\ y_i^{lr} \quad i = 1, \dots, s\,, \tag{51}$$

$$TC_i^{lo} = \frac{C}{2} {y_i^{lo}}^2 - x_i^{lo} y_i^{lo} \qquad i = s+1, \dots, k, \tag{52}$$

$$TC_j^{fo} = \frac{C}{2} {y_j^{fo}}^2 - x_j^{fo} y_j^{fo} \qquad j = k+1, \dots, n\,. \tag{53}$$

Therefore, the unit costs are

$$c_i^{lr} = c y_i^{lr} - \sum_{i=1}^{s} x_i^{lr} \qquad i = 1, \dots, s, \tag{54}$$

$$c_{\mathrm{i}}^{lo} = c y_i^{lo} - x_i^{lo} \qquad i = s+1, \dots, k, \tag{55}$$

$$c_j^{fo} = c y_j^{fo} - x_j^{fo} \qquad j = k+1, \dots, n. \tag{56}$$

The profit functions are

$$\pi_i^{lr} = \left(P y_i^{lr} - TC_i^{lr}\right) - \frac{z(s)\, {x_i^{lr}}^2}{2} \tag{57}$$

$$\pi_i^{lo} = \left(Py_i^{lo} - TC_i^{lo}\right) - \frac{\tau\, x_i^{lo^2}}{2} \tag{58}$$

$$\pi_j^{fo} = \left(Py_j^{fo} - TC_j^{fo}\right) - \frac{\tau\, x_i^{fo^2}}{2}. \tag{59}$$

Using backward induction we find:

$$\sum_{j=k+1}^{n} y_j^{fo} = \frac{(n-k)\,[(c(n-k+c+1)+c+1)A-(n-k+c+1)(s\sum_{i=1}^{s} x_i^{lr} + \sum_{i=s+1}^{k} x_i^{lo}\,)\,]}{(n-k+c+1)(c(n-k+c+1)+(c+1)(k+1))}$$
$$+\frac{[(k+c)(n-k+c+1)+c+1]\sum_{j=k+1}^{n} x_j^{fo}}{(n-k+c+1)(c(n-k+c+1)+(c+1)(k+1))}\ . \tag{60}$$

$$\sum_{i=1}^{s} y_i^{lr} = \frac{s[c(n-k+c+1)+c+1]\,[(c+1)A-\sum_{j=k+1}^{n} x_j^{fo}]}{[c(n-k+c+1)+(s+1)(c+1)][c(n-k+c+1)+(k-s+1)(c+1)]-s(k-s)(c+1)^2}$$
$$+\frac{s(n-k+c+1)[(c(n-k+c+1)+(k-s+1)(c+1))\sum_{i=1}^{s} x_i^{lr}-(c+1)\sum_{i=s+1}^{k} x_i^{lo})}{[c(n-k+c+1)+(s+1)(c+1)][c(n-k+c+1)+(k-s+1)(c+1)]-s(k-s)(c+1)^2}\ . \tag{61}$$

$$\sum_{i=s+1}^{k} y_i^{l0} = \frac{(k-s)[c(n-k+c+1)+c+1][(c+1)A-\sum_{j=k+1}^{n} x_j^{fo}]}{[c(n-k+c+1)+(s+1)(c+1)][c(n-k+c+1)+(k-s+1)(c+1)]-s(k-s)(c+1)^2}$$
$$+\frac{(n-k+1)[(c(n-k+c+1)+(s+1)(c+1))\sum_{i=s+1}^{k} x_i^{lo}-s(k-s)(c+1)\sum_{i=1}^{s} x_i^{lr}\ ]}{[c(n-k+c+1)+(s+1)(c+1)][c(n-k+c+1)+(k-s+1)(c+1)]-s(k-s)(c+1)^2}\ . \tag{62}$$

Since the results for $\sum_{i=1}^{s} x_i^{lr}$ and $\sum_{i=s+1}^{k} x_i^{lo}$ are long, we only show them as functions of parameters and variables.[1]

$X^{lr}\,(x_i^{lo}, A, c, n, k, s, \tau, \rho)$ where $X^{lr} \equiv \sum_{i=1}^{s} x_i^{lr}$.

$X^{lo}\,(x_i^{ln}, A, c, n, k, s, \tau, \rho)$ where $X^{lo} \equiv \sum_{i=s+1}^{k} x_i^{lo}$.

By imposing symmetry, we find the equilibrium values of x_i^{lr}, x_i^{lo}, x_j^{fo}, y_i^{lo}, y_i^{lr} and y_j^{fo}.

[1] All the equations are available upon request.

We use numerical simulations with the same number of firms and parameter values as used in the previous sections to find the equilibrium and optimal sizes of the RJV. The results show that when the unit cost of production is increasing in output, the profits of outsiders are always lower than insiders' and their profits increase when they join the RJV. Also, insiders' profits increase when a new member joins the RJV. As a result, outsiders always have an incentive to join the RJV and insiders always accept new members. The process of joining the RJV continues until all the outsider leaders join the RJV and no leader remains outside of the RJV. This result holds even with high coordination costs.

Result 7. *With convex production costs, insiders' profits are always higher than outsiders'. Therefore, all the leaders join the RJV and the only equilibrium is that an RJV containing all leaders forms.*

In table (6) we can see the numerical results for the two cases of linear and convex production costs for n=20, k=11, s=7. As we can see, with convex production cost, insider and outsider leaders have lower output and therefore lower investment in R&D.

Table 6. R&D investment, production and profit under linear and convex production costs

		x^{fo}	y^{fo}	π^{fo}	x^{lo}	y^{lo}	π^{lo}	x^{lr}	y^{lr}	π^{lr}
Linear	ρ=0	0.00512496	2.06721	4.26286	0.0483654	21.1045	43.6044	0.307283	42.1307	139.73
production	ρ=0.5	0.00721963	2.91212	2.91212	0.0681332	29.7303	86.5325	0.0992276	35.9949	119.143
Costs	ρ=1	0.00786075	3.17072	10.0288	0.0741836	32.3705	102.583	0.0355478	34.117	112.859
Convex	ρ=0	0.00517283	4.13162	870.574	0.00517259	4.13392	870.583	0.0478989	4.13861	871.654
production	ρ=0.5	0.0053942	4.13192	870.7	0.00517298	4.13527	870.714	0.0130043	4.13612	870.904
Costs	ρ=1	0.00517297	4.13195	870.714	0.00517302	4.1353	870.727	0.0049145	4.13559	870.792

1.6 Conclusion

In this study, an oligopoly model with sequential moves of firms in the R&D and production markets was analyzed. Coordination costs of RJVs, which were ignored in most studies of RJVs, were considered. For this purpose, we applied the same functional form and assumptions for R&D cost function as Falvey et al. (2010). Then, using numerical simulations, the effects of RJV formation on R&D investments, production and profits of firms under different levels of coordination costs were analyzed. The results showed that with linear production costs, full spillovers between RJV participants and no spillover between non-participants, insiders gain higher profits compared with R&D competition. Also, welfare is always higher in the cooperative regime than in the non-cooperative case. The R&D investment incentives and also profits of RJV members decrease with coordination costs. Optimal and equilibrium sizes of the RJV were analyzed under different levels of coordination costs. For a large enough number of leaders, the equilibrium size of the RJV is less than the optimal size. As numerical results showed, except for the case with a large number of leaders and a high level of coordination costs, in most cases the optimal size of the RJV is independent from coordination costs, but the equilibrium size of the RJV always decreases with them. These results remain the same when more followers are added to the model.

One assumption of the model was the absence of spillovers and full information sharing between cooperative firms. This assumption was changed in an extension, where it was assumed that with and without an RJV, R&D spillovers exist between leaders and from leaders to followers. The numerical simulations results established that in this case, the RJV members earn lower profits than non-participant leaders, and therefore, they have no incentive to join the RJV and no RJV is formed. In another extension, another assumption of the basic model was changed: it was investigated how the previous results change if production costs are convex. In this case, profits of insiders are always greater than outsiders' and their profits increase with accepting new members in the RJV. This means that outsiders always have an incentive and also are allowed by insiders to join the RJV. Therefore, an RJV containing all leaders forms.

Since according to the results, the equilibrium size of RJVs is usually smaller than the optimal size, policy makers should adopt some technology policies that encourage the formation of RJVs of greater size.

The results obtained in this study may change with changes in some of the assumptions of the model. For instance, firms can produce differentiated products in the product market. Also, it is possible that more than one alliance forms. These changes can be analyzed in future research.

References

Amir, R. and Wooders, J., 1999, "Effects of one-way spillovers on market shares industry prices welfare, and R&D cooperation", *Journal of Economics and Management Strategy*, Vol. 8, No. 2, pp. 223-249.

Atallah, G., 2003, "Information sharing and the stability of cooperation in research joint ventures", *Economics of Innovation and New Technology*, Vol. 12, No. 6, pp. 531-554.

Council of Canadian Academies, 2013, "The State of Industrial R&D in Canada; the Expert Panel on the State of Industrial R&D in Canada".

D'Aspremont, C. and Jacquemin, A., 1988, "Cooperative and non-cooperative R&D in duopoly with spillovers", *American Economic Review*, Vol. 78, No. 5, pp. 1133-1137.

Doraszelski, U., 2003, "An R&D race with knowledge accumulation", *RAND Journal of Economics*, Vol. 34, No.1, pp. 20-42.

Etro, F., 2004, "Innovation by Leaders", *Economic Journal*, Vol. 114, No. 495, pp. 281-303.

Falvey, R., Poyago-Theotoky, J., Teerasuwannajak, K.T., 2010, *Costly research joint ventures : the role of coordination costs.*

Falvey, R., Poyago-Theotoky, J., Teerasuwannajak, K.T., 2013, "Coordination costs and research joint ventures", *Economic Modelling*, Vol. 33, July, pp. 965-976.

Kamien, M.I., Muller, B. and Zang, I., 1992, "Research joint ventures and R&D Cartels", *American Economic Review*, Vol. 82, No. 5, pp. 1293-1306.

Kogut, B., 1989, "The stability of joint ventures: reciprocity and competitive rivalry", *Journal of Industrial Economics*, Vol. 38, No.2, pp. 183-198.

Mollazi, L., Tijs, S., "Stackelberg assumptions vs. Nash assumption in partially cooperative games", *Czech Economic Review*, Vol. 6, No. 1, pp. 5-13.

O'Sullivan, P., 2004, *The effect of R&D leadership on Research Joint Venture formation*.

Poyago-Theotoky, J., 1995, "Equilibrium and optimal size of a research joint venture in an oligopoly with spillovers", *Journal of Industrial Economics*, Vol. 43, No. 2, pp. 209-225.

Poyago-Theotoky, J.,1999, "A note on endogenous spillovers in a non-tournament R&D duopoly", *Review of Industrial Organization*, Vol. 15, No. 3, pp. 253-262.

Reinganum, J., 1985, "A two-stage model of research and development with endogenous second-mover advantages", *International Journal of Industrial Organization*, Vol. 3, No. 3, pp. 275-292.

Suzumura, K., 1992, "Cooperative and noncooperative R&D in an oligopoly with spillovers", *American Economic Review*, Vol. 82, No. 5, pp. 1307-1320.

Vandekerckhove, J., De Bondt, R., 2008, "Asymmetric spillovers and investments in research and development of leaders and followers", *Economics of Innovation and New Technology*, Vol. 17, No. 5, pp. 417-433.

Veugelers, R., 1998, "Collaboration in R&D: an assessment of theoretical and empirical findings", *De Economist*, Vol. 146, No. 3, pp. 419-443.

Chapter 2

R&D Cooperation and Public R&D in the Presence of Environmental Damage and Emissions Taxation

2.1 Introduction

Several papers in the industrial organization literature have studied research and development (R&D) investment and investigated the effect of different R&D regimes on the levels of investment, profit and social welfare. In studying social welfare, few of these studies consider the possible environmental damage and pollution that production may cause. As Petrakis and Poyago-Theotoky (2002) explain, encouraging process R&D reduces production costs and increases output, but on the other hand, pollution increases as a by-product of production. Two main technology policies that have been discussed in previous papers are encouraging R&D cooperation and R&D subsidization. The current paper focuses on the effects of R&D cooperation and public research investments. While in an oligopolistic market, private firms maximize their profits, the goal of public research institutes is usually to create knowledge to maximize social welfare. Examples of public research institutions are university laboratories and research institutes, which are usually funded by governments.

In the case of environmental damage as a result of production, the role of the regulator in choosing the level of emission tax is also vital and can influence the final results. In the first part of this paper, first we assume that the emission tax is set by the regulator exogenously. In the rest of the paper, we study the model under the assumption that the regulator plays an active role in choosing the environmental policy, so he can set the emission reducing tax endogenously. Under this assumption, two possibilities are considered. First, we consider the government as a player which decides about the emission tax before firms choose their R&D investments (commitment). Second, firms decide on R&D investment before the regulator, so they can influence the decision of the regulator on the level of emission reducing tax (no commitment). According to Hepburn (2006) and Puller (2006) this is called a *ratchet effect*. In this study, we analyze both scenarios.

Welfare comparison of public R&D with R&D cooperation under firms' process R&D indicates that while with low exogenous emission tax R&D cooperation leads to higher welfare, with high emission tax, public R&D results into higher welfare. For firms' environmental R&D case, when the regulator sets the emission tax in the first stage (commitment), with low R&D spillovers welfare is higher under R&D cooperation, while the reverse is true for high R&D spillovers. In the scenario where the regulator sets the emission tax after firms' decision on R&D (no commitment), welfare is always greater under R&D cooperation. Another finding of this paper is that under commitment, public R&D is higher than in the no commitment case. Comparison of commitment and no commitment indicates that commitment increases private R&D.

The paper is organized as follows. In the next section, we review the existing literature on production and environmental R&D in the presence of pollution and the literature on public research institutes and their interaction with private firms. Section 3 presents the model under an exogenous emission tax, process R&D cooperation and public research investment and compares the welfare effect of these technology policies. Section 4.1 assumes a three stage game, where the government chooses emission tax and public research in the first stage, firms choose (environmental) R&D investment in the second stage and they determine the output level in the final stage; then, we compare R&D cooperation and public R&D investment. Section 4.2 explores the case where the regulator decides about the emission tax and public R&D after observing firms' R&D commitment. Section 5 investigates the effect of the regulator’s commitment on public R&D. The final section concludes.

2.2 Literature review

Petrakis and Poyago-Theotoky (2002) examine a duopoly model with R&D spillovers where production of firms causes environmental pollution. They consider two technology policies: R&D subsidisation and R&D cooperation encouragement, and the effects of each policy on welfare are investigated in detail. Their results show that under exogenous emission tax, the subsidy policy, which was optimal when ignoring the possible negative impact of the increase in R&D investment on the environment, may not be optimal for some critical values of the emission tax and environmental damage. Instead, a negative R&D subsidy may be called for *R&D taxation*. Another finding of their paper indicates that unlike many R&D studies, R&D cooperation may not be the optimal policy and under some conditions it is inferior to R&D subsidisation.

Among the studies on R&D which discuss the effect of production on the environment, some papers analyze the models in which instead of process R&D, firms invest in environmental R&D to reduce emissions. Also, the government chooses the emissions tax. Poyago-Theotoky (2003) studies Cournot and Bertrand duopolies where firms produce differentiated products. Firms contribute to the environmental emission reducing R&D investment. The government chooses the level of tax on emissions and also the subsidy to R&D investment. The results for the Cournot model show that for any degree of product differentiation, the optimal emission tax is lower than the marginal damage. Although the result is the same for the Bertrand model with differentiated products, for homogeneous products the emission tax is equal to the marginal damage. Comparing the optimal emission tax indicates lower tax under quantity competition than under price competition. Under the subsidy policy there exists a critical value of product differentiation, depending on initial emissions, above which the optimal subsidy is greater under Bertrand competition than under Cournot competition.

Poyago Theotoky (2007) and Ouchida and Goto (2014) investigate environmental R&D in the framework introduced by Kamien et al. (1992). Poyago Theotoky (2007) assumes a duopoly model where firms sell homogeneous products in the output market. They participate in the environmental R&D investment to reduce emissions. The paper studies two scenarios: first, firms choose the level of environmental R&D non-cooperatively. Second, firms decide cooperatively on the emission reducing R&D by forming an environmental R&D cartel. In both cases, the emission tax is set by the regulator after firms make decisions on R&D. The results indicate that when the R&D cost is small, for small and large amounts of environmental damage, R&D effort and welfare are higher under R&D cartelization compared with non-cooperative R&D. In a Cournot duopoly framework Ouchida and Goto (2014) compare four scenarios of environmental R&D competition and cartelization, environmental RJV competition and cartelization, where the government chooses the social welfare maximizing emission tax.[1] They conclude that environmental RJV cartelization leads to highest profit for the firms. The socially efficient scenario depends on the damage level and also on R&D costs. Under high levels of damage and R&D costs RJV cartelization is

[1] Based on Kamien et al. (1992), R&D cartelization is the case where firms cooperate in R&D by maximizing their joint profits but the level of R&D spillover is not changed as a result of cartelization.

optimal. In contrast to the previous R&D studies, R&D competition under high damage and low R&D cost maximizes social welfare.

In the current paper, both process and environmental R&D will be studied in a duopoly framework. In one section, we assume that the emission tax is set exogenously. In the two other sections, we endogenize the emission tax. The difference of this study with previous studies is that we analyze and compare the effects of encouraging R&D cooperation and public R&D investment as two possible technology policies.

In an empirical study Robina and Schubert (2013) explore the effect of collaboration of public institutes and private firms on the innovation level of private firms in France and Germany. According to their results, while cooperation between public institutes and private firms has a positive effect on product innovation of private firms in both countries, there is no effect on process innovation in either of countries. Therefore, cooperation of public and private firms in innovation is not always recommended for all kinds of innovation.

2.3 Public R&D and R&D cooperation under exogenous emission tax

We consider a duopoly model with homogeneous products. The demand function is

$$P = a - q_i - q_j\,, \quad i,j = 1,2, \;\; i \neq j\,, \tag{1}$$

where, P, a and q respectively represent price, choke price and output. We assume that firms invest in R&D (x_i) with the cost of $\frac{\gamma {x_i}^2}{2}$ to reduce production costs, where production (q_i) generates pollution. Firms undertake an emission reducing activity (ω_i) which costs $\frac{{\omega_i}^2}{2}$ and pay a tax (t) on pollution $(q_i - \omega_i)$.

2.3.1 Public research and development investment

In this section, we assume R&D competition and R&D spillovers with the spillover rate $0 \leq \beta \leq 1$. Also, firms fully receive R&D from a public research lab. So, the marginal production cost of firm i is

$$c_i = c - x_i - x_r - \beta\, x_j\,, \quad i, j = 1{,}2,\ i \neq j. \tag{2}$$

x_i is the R&D output of firm i, x_j the R&D output of the rival and x_r is the R&D output of the public research lab.

This model is a four stage game. The stages are as follows:

Stage 1. The government invests in (cost reducing) public R&D investment to maximize total welfare.

$$max_{\,x_r}\ TW\,.$$

Stage 2. Firms choose the abatement level to maximize profit.

$$max_{\omega_i}\, \pi_i\,, \qquad i = 1{,}2\,.$$

Stage 3. Each firm invests in cost reducing R&D.

$$max_{x_i}\, \pi_i, \qquad i = 1{,}2\,.$$

Stage 4. Firms compete in Cournot.

$$max_{\,q_i}\, \pi_i\,, \qquad i = 1{,}2\,.$$

We use backward induction to solve the model and find the subgame perfect equilibrium for q_i , x_i, ω_i and x_r .

Stage 4.

$$max_{q_i}\,\pi_i = (P(q_i, q_j) - c_i)q_i - \frac{\gamma x_i{}^2}{2} - \frac{\omega_i{}^2}{2} - t(q_i - \omega_i)\,. \tag{3}$$

$$= \left(a - q_i - q_j\right)q_i - c_i q_i - \frac{\gamma x_i{}^2}{2} - \frac{\omega_i{}^2}{2} - t(q_i - \omega_i)\,. \tag{4}$$

t is the exogenous emission tax which is set by the regulator, ω_i is the abatement level, $\frac{\omega_i{}^2}{2}$ is the abatement cost and $\frac{\gamma x_i{}^2}{2}$ is the R&D investment cost.

Therefore, the equilibrium output is

$$q_i = \frac{a-2c_i+c_j-t}{3}\;. \tag{5}$$

Substituting from (2) in (5) yields

$$q_i = \frac{a-c+(2-\beta)x_i+(2\beta-1)x_j+x_r-t}{3}\;. \tag{6}$$

Substituting (6) into (4) yields profit as a function of R&D.

$$\pi_i = (\frac{a-c+(2-\beta)x_i+(2\beta-1)x_j+x_r-t}{3})^2 - \frac{\gamma x_i{}^2}{2} - \frac{\omega_i{}^2}{2} + t\omega_i\;. \tag{7}$$

Stage 3.

$$max_{x_i}\,\pi_i = (\frac{a-c+(2-\beta)x_i+(2\beta-1)x_j+x_r-t}{3})^2 - \frac{\gamma x_i{}^2}{2} - \frac{\omega_i{}^2}{2} + t\omega_i\;. \tag{8}$$

Taking the FOC we get

$$\frac{\partial \pi_i}{\partial x_i} = \frac{2}{9}(2-\beta)\left[a-c+(2-\beta)x_i+(2\beta-1)x_j+x_r-t\right]- \gamma x_i = 0 \ . \tag{9}$$

In a symmetric equilibrium $x_i = x_j = x.$ Solving (9) for x yields:

$$x = \frac{2(2-\beta)(A+x_r-t)}{9\gamma-2(2-\beta)(1+\beta)} \ , \tag{10}$$

where *A*=*a*-*c,* $A + x_r > t$ and $9\gamma - 2(2-\beta)(1+\beta) > 0$, which implies that $\gamma > \frac{16}{9}$. Based on equation (10), $\frac{\partial x}{\partial x_r} > 0$, which means that with increases in public R&D output and the value of cost reduction increase and as a result of that, firm's R&D investment increase.

The stability condition requires that $\left|\frac{2(2-\beta)(2\beta-1)}{9\gamma-2(2-\beta)^2}\right| < 1$.

Substituting (10) into (6) yields output as a function of public R&D and emission tax:

$$q = \frac{3\gamma(A+x_r-t)}{9\gamma-2(2-\beta)(1+\beta)} \ . \tag{11}$$

Substituting (10) into (7) yields

$$\pi = \frac{\gamma(A+x_r-t)^2[9\gamma-2(2-\beta)^2]}{[9\gamma-2(2-\beta)(1+\beta)]^2} - \frac{{\omega_i}^2}{2} + t\omega_i \ . \tag{12}$$

Based on the second order condition, $\frac{\partial^2 \pi_i}{\partial x_i^2} < 0$, $9\gamma - 2(2-\beta)^2 > 0$.

Stage 2.

$$max_{\omega_i}\, \pi_i = \frac{\gamma(A+x_r-t)^2[9\gamma-2(2-\beta)^2]}{[9\gamma-2(2-\beta)(1+\beta)]^2} - \frac{{\omega_i}^2}{2} + t\omega_i \ . \tag{13}$$

Taking the FOC yields in a symmetric equilibrium

$$\omega_1 = \omega_2 = t \tag{14}$$

Each firm equates the marginal abatement cost (ω_i) wih the marginal gain of reducing pollution (t). As this relation shows and as Petrakis and Poyago-Theotoky (2002) also noted in their paper, when there is no tax on the emission level, firms will not undertake any emission reduction activity.

Stage 1. Total welfare is given by:

$$TW = \sum_{i=1}^{2} \pi_i + (\frac{\sum_{i=1}^{2} q_i}{2})^2 - \frac{\gamma\, x_r^2}{2} - \frac{d[\sum_{i=1}^{2}(q_i - \omega_i)]^2}{2} + t\sum_{i=1}^{2}(q_i - \omega_i) \ . \quad (15)$$

Substituting from (12) into (15) and imposing symmetry yields:

$$TW = 2aq_i - 2c_i q_i - 2\, q_i^2 - \gamma x_i^2 - \omega_i^2 - \frac{\gamma x_r^2}{2} - 2d(q_i - \omega_i)^2 \ . \quad (16)$$

We substitute (2) into (16)

$$TW = 2(a-c)q_i - 2{q_i}^2 + 2[(1+\beta)x_i + x_r]q_i - \gamma x_i^2 - \omega_i^2 - \frac{\gamma x_r^2}{2} - 2d(q_i - \omega_i)^2 \ . \quad (17)$$

We substitute for x_i and q_i from (10) and (11) into (17) and solve the following maximization problem

$$max_{x_r}\ TW$$

Solving this problem we get

$$x_r = \frac{-8A(-2+\beta)^2 + 4t(-2+\beta)(-1+5\beta+6d(1+\beta)) - 36A(-2+d)\gamma + 18(-1+8d)t\gamma}{4(-2+\beta)^2(3+\beta(2+\beta)) + 36(-4+d+(-1+\beta)\beta)\gamma + 81\gamma^2} \ . \quad (18)$$

$$x^* = -\frac{2(-2+\beta)(2t(5+6d+\beta-\beta^2) - 9t\gamma + A(-4+2(-1+\beta)\beta+9\gamma))}{4(-2+\beta)^2(3+\beta(2+\beta)) + 36(-4+d+(-1+\beta)\beta)\gamma + 81\gamma^2} \ . \quad (19)$$

$$q^* = \frac{3\gamma(2t(5+6d+\beta-\beta^2) - 9t\gamma + A(-4+2(-1+\beta)\beta+9\gamma))}{4(-2+\beta)^2(3+\beta(2+\beta)) + 36(-4+d+(-1+\beta)\beta)\gamma + 81\gamma^2} \ . \quad (20)$$

$$\pi^* = \frac{\gamma(-2(-2+\beta)^2+9\gamma)(2t(5+6d+\beta-\beta^2)-9t\gamma+A(-4+2(-1+\beta)\beta+9\gamma))^2}{(4(-2+\beta)^2(3+\beta(2+\beta))+36(-4+d+(-1+\beta)\beta)\gamma+81\gamma^2)^2} + \frac{t^2}{2} \quad (21)$$

$$TW = \frac{2A^2\gamma(-2(-2+\beta)^2-9(-2+d)\gamma)+2At\gamma(2(-2+\beta)(-1+5\beta+6d(1+\beta))+9(-1+8d)\gamma)}{4(-2+\beta)^2(3+\beta(2+\beta))+36(-4+d+(-1+\beta)\beta)\gamma+81\gamma^2}$$

$$+\frac{t^2(-4(1+2d)(-2+\beta)^2(3+\beta(2+\beta))+2(85+32\beta-26\beta^2+6d(31-8(-1+\beta)\beta))\gamma-9(11+32d)\gamma^2)}{4(-2+\beta)^2(3+\beta(2+\beta))+36(-4+d+(-1+\beta)\beta)\gamma+81\gamma^2} \quad (22)$$

Now, we investigate the optimal level of the public research investment under different levels of environmental damage and the emission tax. $0<d<3/2$ and $0<t<5/2$ ensures positive cost-reducing R&D and output.

When $d=t=0$, which means no environmental damage and therefore no emission tax, public R&D is

$$x_r = \frac{3600-80(-2+\beta)^2}{2025+180(-4+(-1+\beta)\beta)+4(-2+\beta)^2(3+\beta(2+\beta))}, \quad (23)$$

which is positive and concave with respect to β. The intuition behind this is that with higher spillovers, there will be more underinvestment by firms and therefore x_r increases to compensate for the low x_i and, in addition, encourage firms to spend more on R&D. Figure 1 is drawn for $A=10$, $\gamma=5$ and $\beta=0.5$.[1]

[1]The results are also robust for the different parameter values.

Figure 1. Public R&D investment

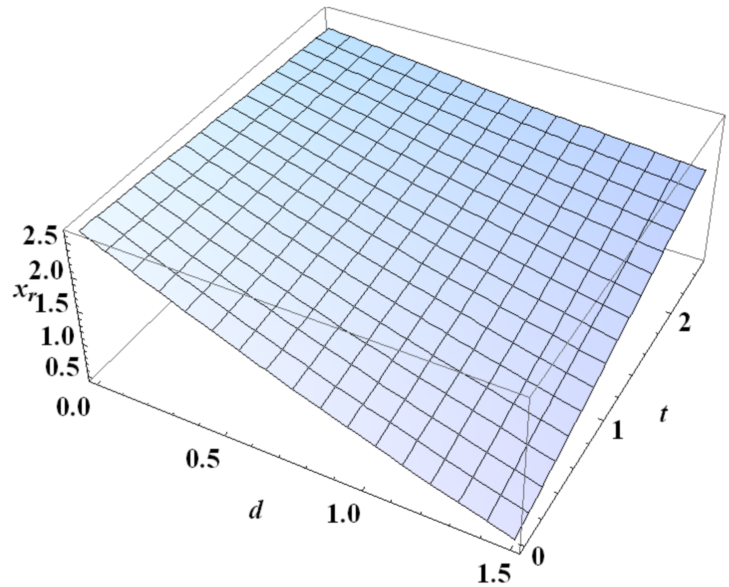


Figure 1 shows a negative relation between public R&D and environmental damage. With increases in *d*, the social value of output declines and therefore public R&D decreases to reduce firm's R&D investment. For most parameter values, as *t* increases, output and R&D investment by firms decrease, so public R&D should increase to compensate x_i. one puzzling result is that for very low environmental damage $\frac{\partial x_r}{\partial t} < 0$.

2.3.2 R&D cooperation

In this section, our assumption about the technology policy is that firms are allowed and encouraged to cooperate in R&D. So, they fully share information among themselves and choose their R&D investments to maximize joint profits. However, they still behave competitively on the output market.

Here, the marginal cost is

$$c_i = c - x_i - x_j\,, \quad i,j = 1,2, \;\; i \neq j. \tag{24}$$

As above, we start by solving the last stage of the game.

Stage 3. In this case, the output level is also chosen by solving (3) and the optimal output is (25):

$$q_i = \frac{A-c+x_i+x_j-t}{3} \quad , \quad i,j = 1,2, \;\; i \neq j.. \tag{25}$$

Stage 2. Firms solve the following problem

$$max_{x_i} \sum_{i=1}^{2} \pi_i = (\frac{A-c+x_i+x_j-t}{3})^2 - \frac{\gamma {x_i}^2}{2} - \frac{{\omega_i}^2}{2} + t\omega_i \tag{26}$$

The equilibrium R&D investment under R&D cooperation is

$$\hat{x}_= \frac{4(A-t)}{9\gamma-8} \ . \tag{27}$$

Substituting (27) into (25) we get the equilibrium output

$$\hat{q} = \frac{3\gamma\ (A-t)}{9\gamma-8} \, . \tag{28}$$

From (28) we can find the profit function

$$\pi_i = \frac{\gamma(A-t)^2}{(9\gamma-8)} - \frac{{\omega_i}^2}{2} + t\omega_i, \; i = 1,2 \quad . \tag{29}$$

Stage 1. The optimum abatement level for R&D cooperation is the same as in the case of public research (section 3.1, equation 13), so

$$\hat{\omega} = \omega_1 = \omega_2 = t. \tag{30}$$

So the equilibrium profit function is

$$\hat{\pi} = \frac{\gamma(A-t)^2}{(9\gamma-8)} + \frac{t^2}{2} \ . \tag{31}$$

Total welfare is

$$\widehat{TW} = \sum_{i=1}^{2} \hat{\pi}_i + \left(\frac{\sum_{i=1}^{2} \hat{q}_i}{2}\right)^2 - \frac{d\left[\sum_{i=1}^{2}(\hat{q}_i - \hat{\omega}_i)\right]^2}{2} + t\sum_{i=1}^{2}(\hat{q}_i - \hat{\omega}_i) \ . \tag{32}$$

Substituting from (29) into (32) yields

$$\widehat{TW} = 2(A-c)\hat{q}_i + 4\hat{x}_i\hat{q}_i - 2\,\hat{q}_i^2 - \gamma\hat{x}_i^2 - \hat{\omega}_i^2 - 2d(\hat{q}_i - \hat{\omega}_i)^2 \,. \tag{33}$$

Substituting from (27), (28) and (30) into (33) yields total welfare as a function of the tax and environmental damage:

$$\widehat{TW} = \frac{4A^2\gamma(9\gamma-4) - 2At\gamma(9\gamma+8) + t^2(11\gamma(16-9\gamma)-64) - 2d((12\gamma-8)t - 3\gamma A)^2}{(9\gamma-8)^2} \ . \tag{34}$$

2.3.3 R&D cooperation and public research investment comparison

In this section, we compare total welfare, R&D and profits under R&D cooperation and public research investment. For this purpose, we use numerical simulation with A=10 and γ=5[1], allowing for different levels of β and d and some fixed values of t. The results for total welfare are presented in figure 2.

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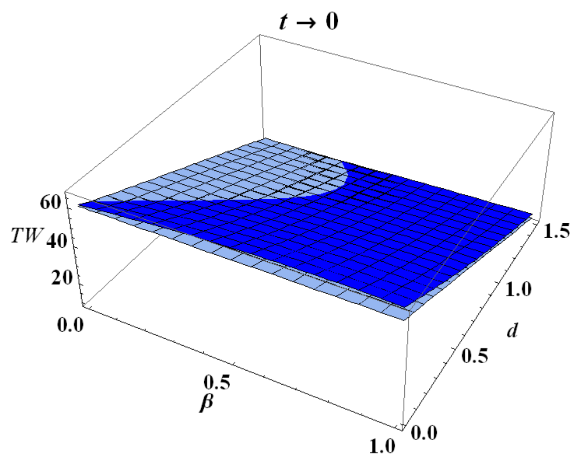
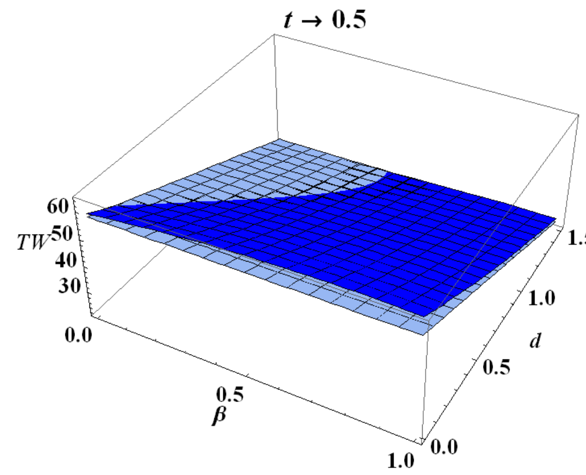
[1] The results are also robust for the different parameter values.

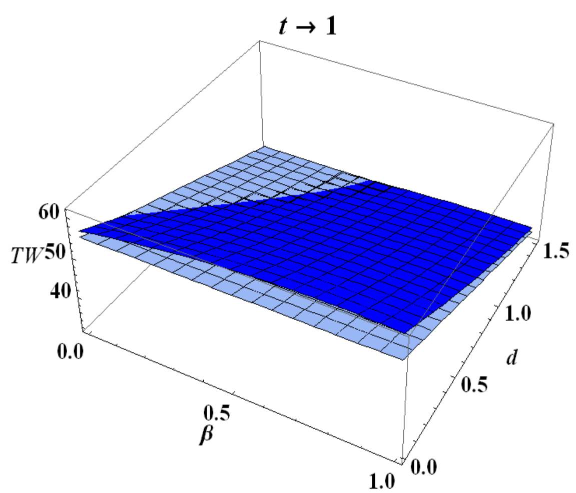
Figure 2. Total welfare comparison under R&D cooperation and public R&D investment[1]



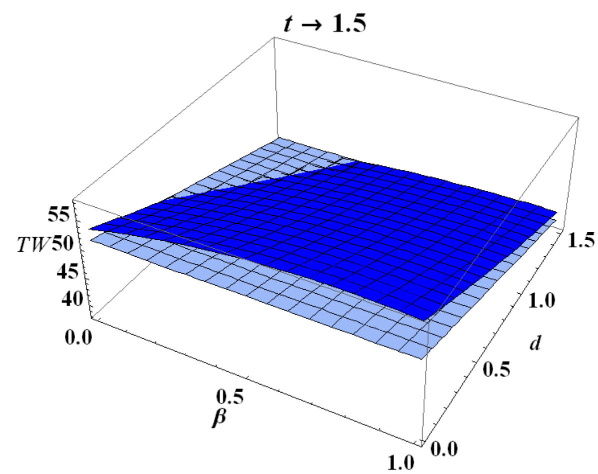
(a)



(b)

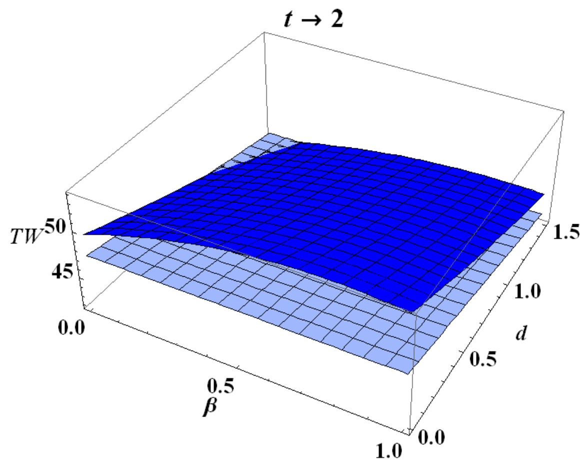


(c)

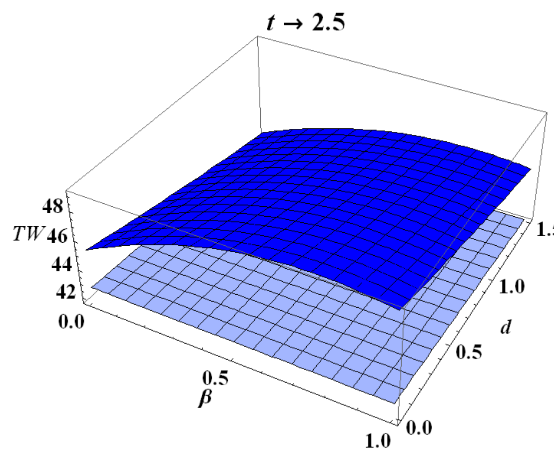


(d)

[1] The dark surface shows total welfare under public research and the light surface shows total welfare under R&D cooperation.



(e)



(f)

Figures 2-a to 2-f show that when t is not too high, *TW* is higher under R&D cooperation than under public R&D when β is low enough and d is high enough. When d is low x_r is high which pushes up private R&D. So, in this case public R&D will be a better policy. When d is high, the reverse is true, therefore with lower x_i the cost of production will be higher and public R&D is worse. As the emission tax increases, the area dominated by R&D cooperation shrinks and for high enough emission tax, welfare is always higher under public R&D investment. With cooperation, when t is very high, there is no additional source of R&D to push up x_i , while with public R&D and high t, x_r increases to raise x_i.

Figure 2 illustrates that with higher emission tax, welfare decreases under both regimes but the decrease is greater under R&D cooperation and therefore, the gap between welfare with public investment and R&D cooperation increases.

2.3.4 Comparing public R&D with R&D subsidization policy

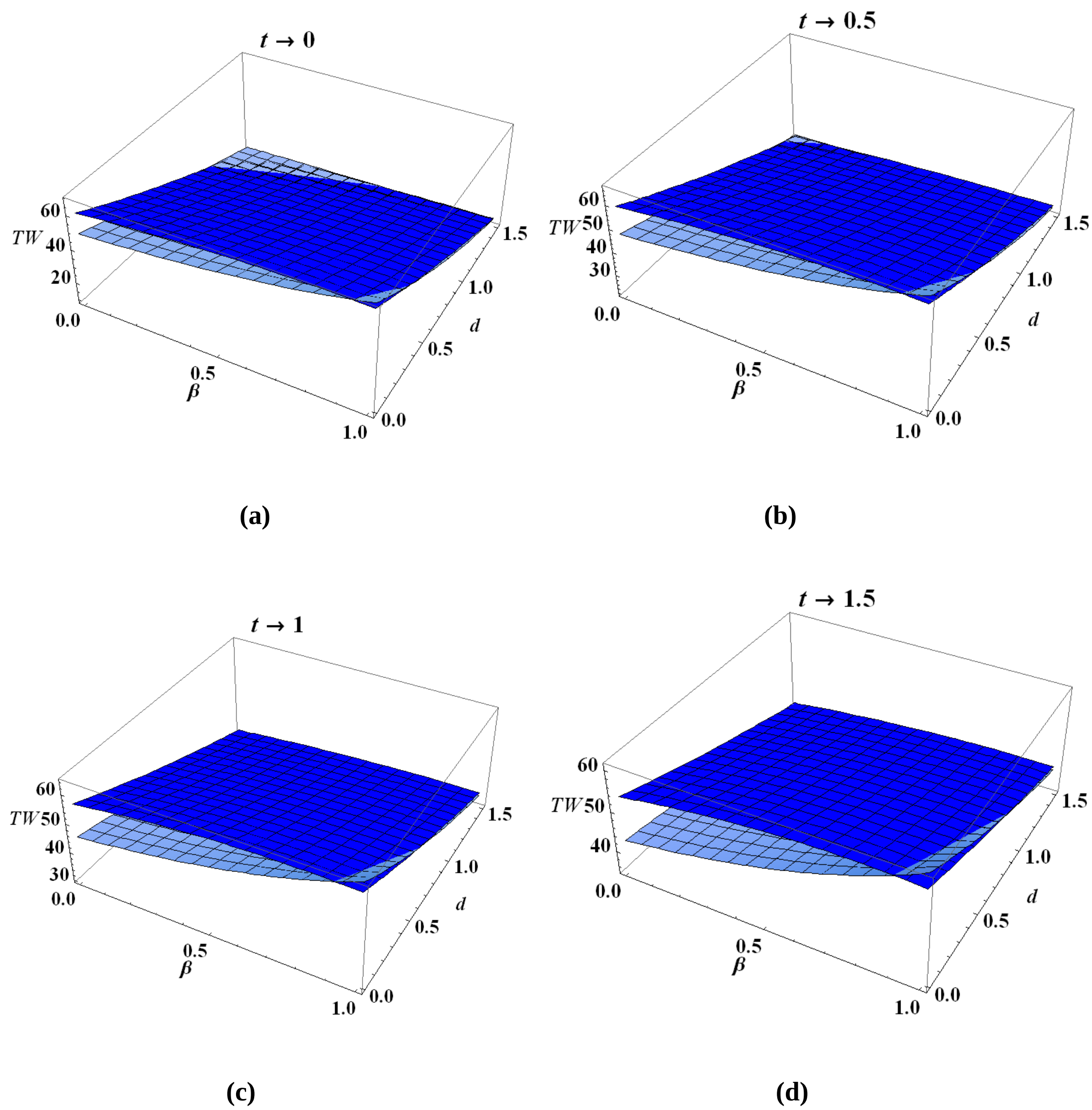
Petrakis and Poyago-Theotoky (2002) also analyze a duopoly model where production causes environmental pollution. Two technology policies considered in their paper are R&D cooperation and R&D subsidisation. They obtain the following expression for total welfare under R&D subsidization.

$$TW_s = \frac{2A\gamma(2A-t)-t^2(11\gamma-5(1+\beta)^2)+2d(A\gamma(8t-A)-t^2(16\gamma-5(1+\beta)^2))}{9\gamma-2(1+\beta)^2(2-d)} \quad (35)$$

In equation (35), the definition of parameters is the same as in this paper. Welfare comparison under the current paper results for public R&D (equation 22) with R&D subsidization policy (equation 35), for the same parameter values as in the previous section, is depicted in figure 3. In general we can say that the dollar cost of a subsidy and x_r is the same to the government, given there is no shadow cost of public funds. Moreover, a priori, the government is indifferent whether it spends one dollar on R&D or whether firms do it (through R&D cooperation, for example), since both reduce welfare by one dollar.

Figure 3 shows that for most parameter values, welfare under public investment exceeds welfare under R&D subsidization. However, when t is very high, for high levels of β, R&D subsidisation is better than public R&D. Under this condition, x_i and therefore, marginal cost of R&D is low and R&D subsidization is cheaper to the government. Considering the effect of a marginal increase in x_i on R&D cost under subsidization and public R&D for a low β, we see that with R&D subsidisation the increase in marginal R&D cost is lower and therefore this policy is preferred to public R&D.

Figure 3. Total welfare comparison under R&D subsidazation and public R&D investment[1]



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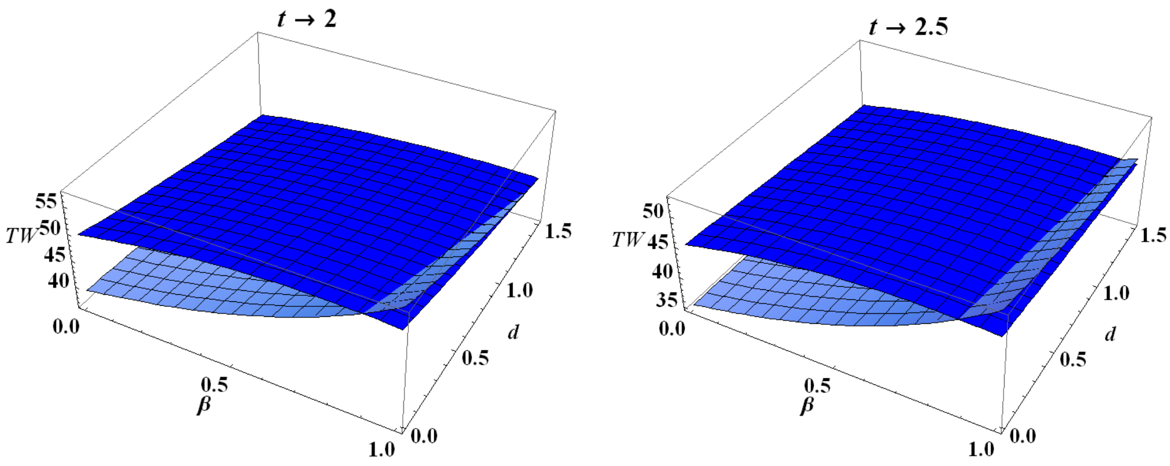
[1] The dark surface shows total welfare under public research and the light surface shows total welfare under R&D subsidisation.



(e) **(f)**

2.4 Public R&D investment and R&D cooperation under endogenous emission tax

In this section we use the same framework to incorporate environmental R&D into the model. Namely, we assume that the R&D investment by firms and the public research lab is emission-reducing instead of reducing production costs. Also, the regulator can set the emission tax endogenously. Here, we consider two scenarios and under each of them we compare R&D competition and R&D cooperation. While in the first scenario, the regulator sets the emission tax and public R&D in the first stage, in the second scenario, the decision about these levels is made after firms' decision on the R&D investment. The goal is to study the effect of the capacity of the government to commit (or not) to an environmental policy.[1]

2.4.1 Regulator acts prior to firms' R&D decision

This model is a three-stage game. In the first stage, the government chooses the levels of emission tax and public R&D investment, simultaneously. In the second stage, firms

[1] See Puller (2006).

choose their emission reducing R&D. Finally, firms competitively set their output. We follow backward induction to solve this game.

The demand function is as before,

$$P = a - q_i - q_j, \quad i,j = 1,2, \; i \neq j. \tag{36}$$

The profit function for firm *i* is

$$\pi_i = (a - q_i - q_j)q_i - cq_i - t(q_i - \omega_i) - \frac{\gamma x_i^2}{2}, \; i,j = 1,2, \; i \neq j. \tag{37}$$

Where *c* is the marginal cost of production, ω_i is abatement level and $\frac{\gamma x_i^2}{2}$ is the R&D cost.

2.4.1.1 R&D competition and public research

Here, $\omega_i = x_i + \beta x_j + x_r$ where x_i is the emission reduction R&D investment by firm i, x_j is environmental R&D by the rival and x_r is the public R&D output.

Stage 3. Each firm solves the following problem:

$$max_{q_i} \; \pi_i = (a - q_i - q_j)q_i - cq_i - t(q_i - x_i - \beta x_j - x_r) - \frac{\gamma x_i^2}{2}, \tag{38}$$

which yields

$$q_i = \frac{A-t}{3} \;, i = 1,2 \tag{39}$$

where *A*=*a*-*c*.

Stage 2. After substituting (39) into their profit function, each firm chooses its R&D to maximize its profit which yields

$$\frac{\partial \pi_i}{\partial x_i} = t - \gamma\, x_i = 0\,, \tag{40}$$

$$x_i = \frac{t}{\gamma}\,,\;\; i = 1,2. \tag{41}$$

Stage 1. The government solves the total welfare maximization problem to find the optimum level of emission tax and public R&D investment

$$TW = \sum_{i=1}^{2} \pi_i + \left(\frac{\sum_{i=1}^{2} q_i}{2}\right)^2 - \frac{\gamma\, x_r^2}{2} - \frac{d[\sum_{i=1}^{2}(q_i - \omega_i)]^2}{2} + t \sum_{i=1}^{2}(q_i - \omega_i)\;\; . \tag{42}$$

$$= 2\, Aq_i - 2{q_i}^2 - \frac{d}{2}\left[2q_i - (1+\beta)\left(x_i + x_j\right) - 2x_r\right]^2 - \frac{\gamma x_i^2}{2} - \frac{\gamma x_j^2}{2} - \frac{\gamma x_r^2}{2}\;\; .$$

$$= \frac{2A(A-t)}{3} - 2\left(\frac{A-t}{3}\right)^2 - \frac{t^2}{\gamma} - \frac{\gamma {x_r}^2}{2} - \frac{d}{2}\left[2\left(\frac{A-t}{3}\right) - (1+\beta)\left(\frac{2t}{\gamma}\right) - 2x_r\right]^2\;\; .$$

$$\frac{\partial TW}{\partial t} = -\frac{2A}{3} + \frac{4(A-t)}{9} - d\left(-\frac{2}{3} - \frac{2(1+\beta)}{\gamma}\right)\left(\frac{2(A-t)}{3} - 2x_r - \frac{2t(1+\beta)}{\gamma}\right) - \frac{2t}{\gamma}. \tag{43}$$

$$\frac{\partial TW}{\partial x_r} = 2d\left(\frac{2(A-t)}{3} - 2x_r - \frac{2t(1+\beta)}{\gamma}\right) - \gamma x_r \quad . \tag{44}$$

Solving (43) and (44), we find equilibrium levels of t and x_r :

$$t = \frac{A\gamma(2d+6d\beta-\gamma+2d\gamma)}{54d+36d\beta+18d\beta^2+9\gamma+20d\gamma+12d\beta\gamma+2\gamma^2+2d\gamma^2} \tag{45}$$

$$x_r = \frac{4Ad(4+\beta+\gamma)}{54d+36d\beta+18d\beta^2+9\gamma+20d\gamma+12d\beta\gamma+2\gamma^2+2d\gamma^2}\;\; . \tag{46}$$

Substituting (45) and (46) in (39) and (41), we get the equilibrium x_i and q_i.

$$x_i = \frac{A(2d+6d\beta-\gamma+2d\gamma)}{54d+36d\beta+18d\beta^2+9\gamma+20d\gamma+12d\beta\gamma+2\gamma^2+2d\gamma^2}\;,\;\; i = 1,2. \tag{47}$$

$$q_i = \frac{A[\gamma(3+\gamma)+2d(3(3+\gamma)+\beta(6+3\beta+\gamma))]}{\gamma(9+2\gamma)+2d(27+9\beta^2+6\beta(3+\gamma)+\gamma(10+\gamma))}, i = 1,2. \tag{48}$$

Total welfare is

$$TW = \frac{A^2(\gamma(4+\gamma)+2d(3(4+\gamma)+2\beta(4+2\beta+\gamma)))}{\gamma(9+2\gamma)+2d\left(27+9\beta^2+6\beta(3+\gamma)+\gamma(10+\gamma)\right)} \ . \quad (49)$$

2.4.1.2. R&D cooperation

Now, we assume that firms cooperate in emission-reducing R&D. Therefore, there is full information sharing between firms. So, the abatement is as follow

$$\omega_i = x_i + x_j \ , \quad i,j = 1,2, \ \ i \neq j \ . \quad (50)$$

The profit function of each firm is

$$\pi_i = \left(a - q_i - q_j\right)q_i - cq_i - t(q_i - x_i - x_j) - \frac{\gamma {x_i}^2}{2} \ , \quad i,j = 1,2, \ \ i \neq j \, . \quad (51)$$

Stage 3. Firms behave competitively in the output market. Each firm solves the following maximization problem:

$$\max_{q_i} \ \pi_i \quad , i = 1,2.$$

Equilibrium output is

$$q_i = \frac{A-t}{3} \ , i = 1,2 \, . \quad (52)$$

Stage 2. In the R&D stage, as firms cooperate in R&D, they maximize their joint profit:

$$\max_{x_i} \sum_{i=1}^{2} \pi_i = \left(a - q_i - q_j\right)q_i - cq_i - t\left(q_i - x_i - x_j\right) - \frac{\gamma {x_i}^2}{2} \, . \quad (53)$$

This yields

$$x_i = \frac{2t}{\gamma} \ i = 1,2 \, . \quad (54)$$

Stage 1. In this stage, the government maximizes welfare with respect to the emission tax:

$$max_t\, TW = 2\, Aq_i - 2{q_i}^2 - \gamma {x_i}^2 - \frac{d}{2}\left[2q_i - 2(x_i + x_j)\right]^2 . \tag{55}$$

Differentiating (55) and solving for *t* and x_i yields

$$t = \frac{A\gamma(24d-\gamma+2d\gamma)}{2(144d+18\gamma+24d\gamma+\gamma^2+d\gamma^2)} \tag{56}$$

$$x_i = \frac{A(24d-\gamma+2d\gamma)}{144d+18\gamma+24d\gamma+\gamma^2+d\gamma^2},\ i = 1,2 . \tag{57}$$

Substituting (56) and (57) into (52) and (54) we get equilibrium output and welfare:

$$q_i = \frac{A(12+\gamma)(8d+\gamma)}{2d(12+\gamma)^2+2\gamma(18+\gamma)},\ i = 1,2. \tag{58}$$

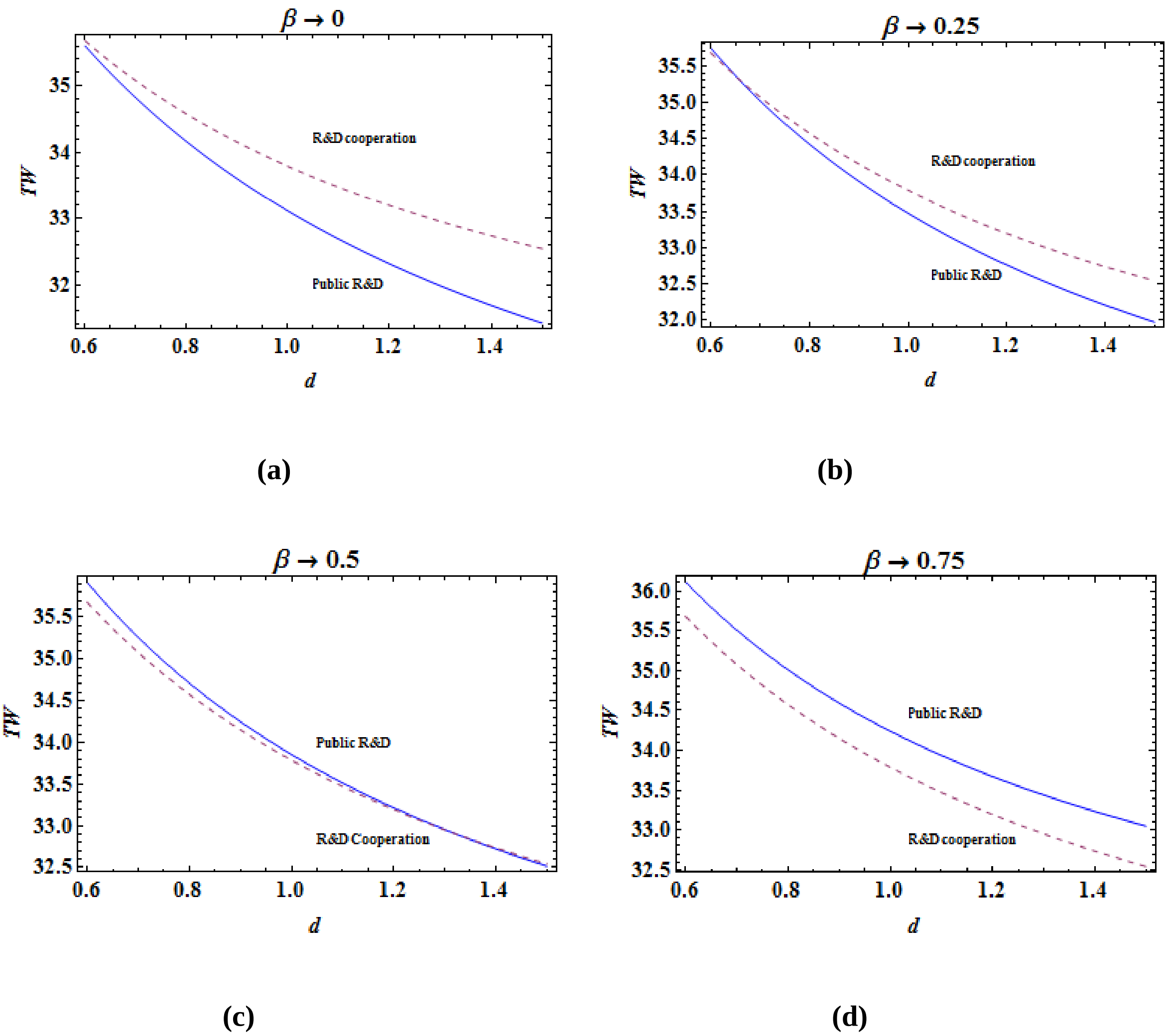
$$TW = \frac{A^2(16+\gamma)(8d+\gamma)}{2d(12+\gamma)^2+2\gamma(18+\gamma)}. \tag{59}$$

2.4.1.3. Comparing R&D cooperation and public R&D

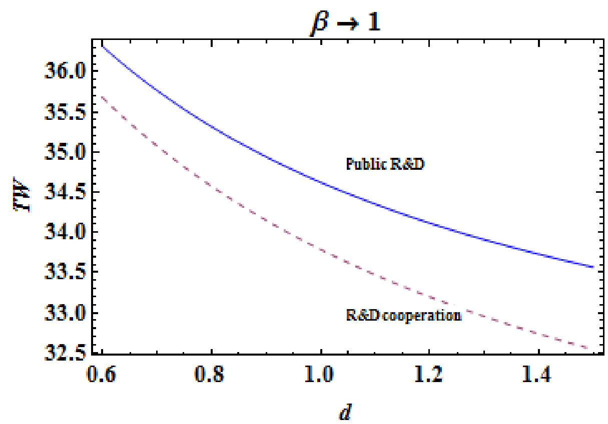
Using numerical simulations (for the same parameter values as before) and plotting welfare as a function of the damage from emissions for different levels of R&D spillovers (see figure 4), we see that for small enough spillovers welfare under R&D cooperation is higher than under public R&D. For higher R&D spillovers welfare is greater with public R&D for all levels of environment damages.

With R&D competition and public R&D, firms benefit from an additional source of R&D and this is most useful when *d* is high .With R&D cooperation, the gain is from high information sharing and this advantage is higher when β is low. When β increases, the benefit from information sharing decreases and public R&D becomes a better policy.

Figure 4. Total welfare comparison under R&D Cooperation and public R&D investment[1]



[1] The horizontal axis starting point is 0.6 to ensure positive values for all variables.



(e)

2.4.2 Regulator acts following firms' R&D decision

In this section we assume the regulator cannot commit not to modify its policy after observing firms' R&D investment. For example observing low x_i may trigger the government to choose a high t.

2.4.2.1 R&D competition and public research

In this section, we consider the following three stage game. First, firms choose their R&D level. Second, the government decides on the level of emission tax and public research level. Finally, firms set the level of output. Based on the *ratchet effect* (explained by Puller (2006) and Hepburn (2006)), in this case where the regulator commitment power in choosing the emission tax is such that firms can decide on R&D investment before the regulator, this will give firms motivation to invest more in emission-reducing R&D to influence the regulation decision on emission tax.

Stage 3. Each firm solves the following problem:

$$max_{q_i}\ \pi_i \quad i = 1,2.$$

which yields

$$q_i = \frac{A-t}{3} \ \ , i = 1,2, \tag{60}$$

where A=a-c .

Stage 2. The government chooses the level of emission tax and public R&D investment to maximize welfare.

$$TW = 2Aq_i - 2q_i^2 - \frac{d}{2}(2q_i - (1+\beta)(x_i + x_j) - 2x_r)^2 - \frac{\gamma x_i^2}{2} - \frac{\gamma x_j^2}{2} - \frac{\gamma x_r^2}{2}. \tag{61}$$

Substituting from (60) into (61) yields

$$TW = \frac{2}{3}A(A-t) - \frac{2}{9}(A-t)^2 - \frac{d}{2}\left[\frac{2(A-t)}{3} - 2x_r - (1+\beta)\left(x_i + x_j\right)\right]^2 - \frac{\gamma \mathrm{xi}^2}{2} - \frac{\gamma \mathrm{xj}^2}{2} - \frac{\gamma \mathrm{xr}^2}{2}. \tag{62}$$

We differentiate (64) with respect to t and x_r:

$$\frac{\partial TW}{\partial t} = -\frac{2A}{3} + \frac{4(A-t)}{9} + \frac{2}{3}d(\frac{2(A-t)}{3} - 2x_r - (1+\beta)(x_i + x_j)) \ . \tag{63}$$

$$\frac{\partial TW}{\partial x_r} = 2d\left(\frac{2(A-t)}{3} - 2x_r - (1+\beta)\left(x_i + x_j\right)\right) - \gamma x_r \ . \tag{64}$$

Equilibrium levels of emission tax and public R&D are found to be

$$t = -\frac{A(4d+\gamma-2d\gamma)+3d\gamma(1+\beta)\left(x_i+x_j\right)}{2(4d+\gamma+d\gamma)} \ . \tag{65}$$

$$x_r = \frac{2d(A-(1+\beta)(x_i+x_j))}{4d+\gamma+d\gamma} \ . \tag{66}$$

Stage 1. Firms choose their R&D investment by separately maximizing their profits, anticipating the government's reaction functions given by (65) and (66). So the equilibrium R&D is

$$x_i = \frac{A(8d^2(-1+\beta)-2d(3+d-\beta+3d\beta)\gamma+(-1+d(2+2d+\beta))\gamma^2)}{\gamma(4d^2(11-3\beta^2)+d(25+3\beta(4+\beta)+d(23+\beta(8+\beta)))\gamma+2(1+d)^2\gamma^2)}\ , i = 1,2\ . \qquad (67)$$

Substituting back (67) into (60), (65) and (66) the equilibrium output, emission tax and public R&D respectively are

$$q_i = \frac{A(-8d^2(-5+\beta^2)+d(23+4d(3+\beta)+\beta(10+3\beta))\gamma+2(1+d)\gamma^2)}{8d^2(11-3\beta^2)+2d(25+3\beta(4+\beta)+d(23+\beta(8+\beta)))\gamma+4(1+d)^2\gamma^2}\ ,\ i = 1,2, \qquad (68)$$

$$t = \frac{A(-2\gamma^2+d\gamma(-19-3\beta(2+\beta)+2\gamma)+2d^2(-16+\gamma(5+\beta(2+\beta)+2\gamma)))}{8d^2(11-3\beta^2)+2d(25+3\beta(4+\beta)+d(23+\beta(8+\beta)))\gamma+4(1+d)^2\gamma^2}\ , \qquad (69)$$

$$x_r = \frac{2Ad(2\gamma(1+\beta+\gamma)+d(4+\beta^2(-4+\gamma)+4\beta\gamma+\gamma(11+2\gamma)))}{\gamma(4d^2(11-3\beta^2)+d(25+3\beta(4+\beta)+d(23+\beta(8+\beta)))\gamma+2(1+d)^2\gamma^2)}\ . \qquad (70)$$

2.4.2.2 R&D cooperation

In this part, everything is as in section 4.2.1 except that firms cooperate in R&D, and there is no public research lab.

Stage 3. Firms determine the output level as above by competitively maximizing their profits with respect to output.

$$max_{q_i}\, \pi_i\ , i = 1,2.$$

The equilibrium output is

$$q_i = \frac{A-t}{3}\ , i = 1,2\ . \qquad (71)$$

Stage 2. Maximizing total welfare with respect to the emission tax, the regulator finds the optimal level of the emission tax

$$max_t\, TW = 2\,Aq_i - 2q_i^{\,2} - \frac{d}{2}\left[2q_i - 2(x_i + x_j)\right]^2 - \frac{\gamma \mathrm{xi}^2}{2} - \frac{\gamma \mathrm{xj}^2}{2}. \qquad (72)$$

$$t = \frac{A(2d-1)-6d(x_i+x_j)}{2(1+d)} \ . \tag{73}$$

Stage 1. Firms maximize their joint profits with respect to R&D:

$$max_{x_i} \sum_{i=1}^{2} \pi_i = \left(a - q_i - q_j\right)q_i - cq_i - t\left(q_i - x_i - x_j\right) - \frac{\gamma {x_i}^2}{2}, \tag{74}$$

which yields

$$x_i = \frac{A(-1+d(3+2d))}{8d(3+2d)+(1+d)^2\gamma} \ , \ i = 1,2. \tag{75}$$

By substituting (75) into (71) and (73) we can find equilibrium output, emission tax and total welfare.

$$q_i = \frac{A(\gamma+d(20+8d+\gamma))}{16d(3+2d)+2(1+d)^2\gamma}, \ i = 1,2 \ , \tag{76}$$

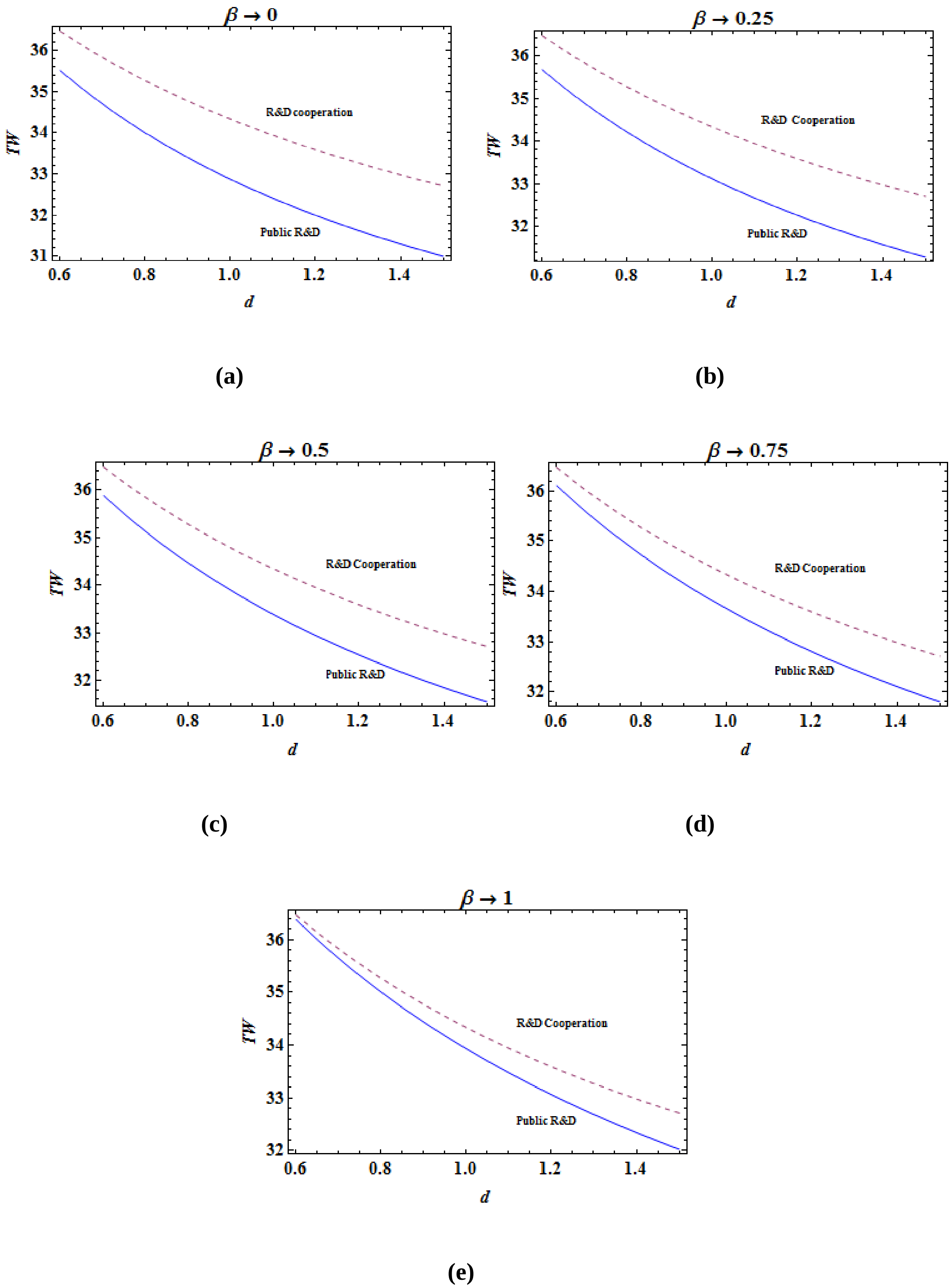
$$t = \frac{A(-\gamma+d(-12+\gamma+2d(4+\gamma)))}{16d(3+2d)+2(1+d)^2\gamma} \ , \tag{77}$$

$$TW = \frac{A^2(16d(-1+d(31+4d(10+3d)))+2(-1+d(26+d(43+4d(6+d))))\gamma+(1+d)^3\gamma^2)}{2(8d(3+2d)+(1+d)^2\gamma)^2} \ . \tag{78}$$

2.4.2.3 Comparing R&D cooperation and public R&D

We use numerical simulations to compare welfare under public R&D and R&D cooperation. As figure 5 indicates, for all spillover levels, welfare is higher under R&D cooperation although the gap shrinks as spillover increase, because a higher β reduces the gain from information sharing. Another motive for high investment under cooperation is to induce the government to choose a lower *t*.

Figure 5. Total welfare comparison under R&D Cooperation and public R&D investment[1]



[1] The horizontal axis starting point is 0.6 to ensure positive values for the variables of model.

2.5 R&D investment effect of commitment

In this section, we compare the effect of the regulator's commitment R&D investment. Public R&D investment is depicted in figure 6 for the case where the regulator sets the emission tax and public R&D before R&D investment by firms (commitment) and the case where the regulator chooses the emission tax and public R&D after firms' decision on R&D investment (no commitment) (for the same parameter values as previous sections). As the figure shows, R&D investment by the regulator is higher under no commitment than under commitment for all values of d and β.

Figure 6. Public R&D investment under commitment and no commitment[1]

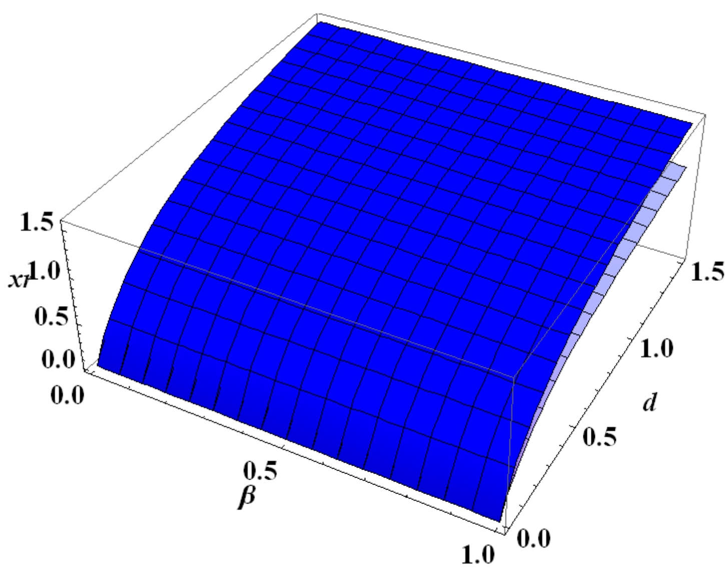


Figure 7 compares firms' R&D investments under commitment and no commitment in the case of public R&D. As the figure illustrates for all enironmental damage and spillover levels, commitment results in higher R&D by firms compared with no commitment.

[1] Dark surface depicts the no commitment case and the light surface shows the commitment case.

Figure 7. Firms' R&D under commitment and no commitment with public R&D[1]

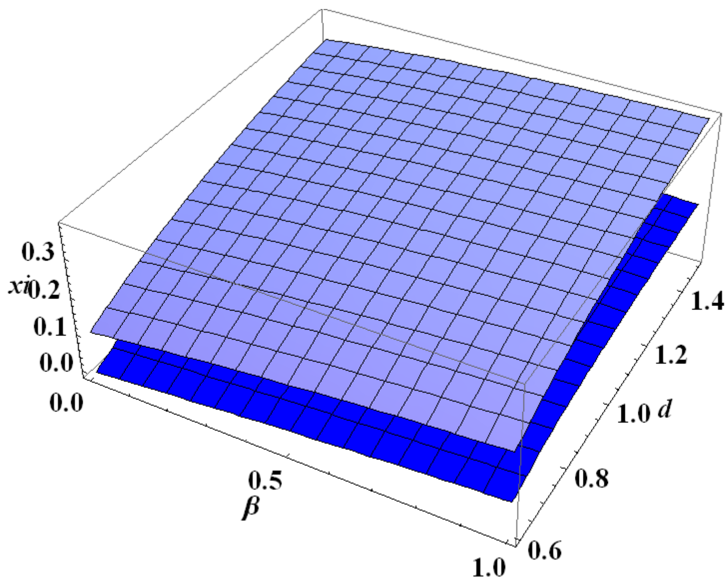
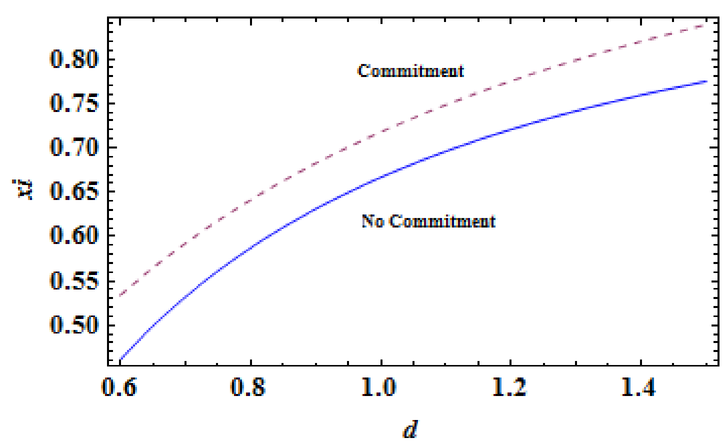


Figure 8 compares firms' R&D investment under commitment and no commitment in the case of R&D cooperation. In this case, firms' R&D investment is higher under commitment than no commitment.

Figure 8. Firm R&D under commitment and no commitment with R&D cooperation



[1] Dark surface shows the no commitment case and light surface shows commitment case.

Table 1 summarises the effect of commitment on R&D investment.

Table 1. Effect of regulator's commitment on R&D

		R&D competition	R&D cooperation
Effect of commitment on	Public R&D	-	NA
	Private R&D	+	+

In sum, commitment by the regulator always induces firms to increase private R&D investment. This induces the regulator to reduce its expenditure on public R&D (where applicable).

2.6 Conclusion

In this study, we investigated a duopoly Cournot model where firms' production causes environmental damage. First, we considered the case where firms invest in cost reducing R&D and the emission tax is set exogenously. We found and compared the welfare effect of two policies: R&D cooperation encouragement, and R&D competition with presence of public R&D. The results showed that when the emission tax is low and environmental damage is high, welfare is higher under R&D cooperation. But when the emission tax is high, public R&D yields higher welfare than R&D cooperation. Also comparing the findings of this paper with the results of Petrakis and Poyago-Theotoky (2002) on R&D subsidisation lead us to conclude that for most parameter values public R&D leads to greater welfare than R&D subsidisation.

After that, we considered two scenarios, in both of which firms instead of process R&D undertake environmental R&D and the emission tax is set by the regulator endogenously. While in the first scenario, the regulator determines the emission tax and public R&D before firms' choice of R&D investment level (commitment), in the second scenario, the regulator decides on the level of the emission tax and public R&D investment after firms' decision on R&D investment (no commitment). In the former case, for low levels of R&D spillovers welfare is higher under R&D cooperation than under public R&D. When the R&D spillover is high enough, for all levels of environmental damage, welfare is greater in the case of public R&D than R&D cooperation. In the second scenario, R&D cooperation results in higher welfare for all levels of R&D spillovers and environmental damage.

In the last section of the paper, we compared R&D investment with and without the regulator's commitment. The results showed that when the regulator decides after firms (no commitment), public R&D investment is higher than with commitment. Comparing firms' R&D investment under commitment and no commitment indicates that for both cases of R&D cooperation and public R&D, commitment leads to higher R&D investment by firms.

In this paper we studied two cases of R&D cooperation and public R&D separately and then compared them. For future studies, the case with both technology policies of R&D cooperation and public R&D could be investigated. Also, we assumed public R&D has the same effect on the cost reduction as firms' R&D investment; public R&D with different effects can be studies in the future studies.

References

Hepburn, C., 2006, "Regulation by prices, quantities, or both: A review of instrumental choice", *Oxford Review of Economic Policy*, Vol. 22, No. 2, pp. 226-247.

Kamien, M.I., Muller,E. and Zang,I., 1992, "Research Joint Ventures and R&D Cartels", *American Economic Review*, Vol. 82, pp. 1293-1306.

Ouchida, Y., Goto, D., 2014, *Environmental Research Joint Ventures and Time-Consistent Emission Tax.*

Petrakis, E., Poyago-Theotoky, J., 2002, "R&D Subsidies versus R&D Cooperation in a Duopoly with Spillovers and Pollution", *Australian Economic Papers*, Vol. 41, No. 1. pp. 37-52.

Poyago- Theotoky, J., 2003, "Optimal Environmental Taxation, R&D Subsidization and The Role of Market Conduct", *Finnish Economic Papers*, Vol. 16, No.1, pp,15-26.

Poyago- Theotoky, J., 2007, "The Organization of R&D and environmental policy", *Journal of Economic Behaviour & Organization*, Vol. 62, No.1, pp. 63-75.

Puller, S., 2006, "The strategic use of innovation to influence regulatory standard", *Journal of Environmental Economics and Management*, Vol. 52, No. 3, pp. 690-706.

Robina, S., Schubert, T., 2013, "Cooperation with Public Research Institutions and Success in Innovation: Evidence from France and Germany", *Journal of Research Policy*, Vol. 42, No. 1, pp.149–166.

Chapter 3

Endogenous formation of Research Joint Ventures in a Cournot model with Coordination Costs

3.1 Introduction

Coalition formation and cost reducing information sharing among firms have been a highly debated topic in the research and development (R&D) literature. While in reality, usually more than one coalition form, most of R&D studies analyze models in which only one RJV containing all or a subset of firms can be formed. As an example of endogenous formation of coalitions, Finus et al. (2014) model and analyze the sequential formation of coalitions in international environmental agreements. Another important point which is ignored in most previous RJV studies is the existence of coordination costs in the formation and running of coalitions.

D'Aspremont and Jacquemin (1988), Kamien et al. (1992), Suzumura (1992), Poyago-Theotoky (1995, 1999) and Atallah (2003) analyze R&D cooperation of firms in a duopoly or an oligopoly framework by assuming that a group or all firms cooperate in R&D by forming at most one consortium without any coordination cost. Falvey et al. (2013) allow for the formation of only one RJV, but extend previous works by incorporating coordination costs in their R&D cooperation model.

In the current study, we consider a Cournot model where N ex ante symmetric firms may cooperate in R&D but behave competitively at the output stage. The main difference of the present analysis with other existing works is that we consider the endogenous formation of coalitions in a model where coordination costs are incorporated. In the coalition formation stage, we assume that firms follow the sequential coalition formation game introduced by Bloch (1995, 1996). From Bloch (1996) we know that the size announcement game reaches the same subgame perfect equilibrium structure as the sequential move Coalition Unanimity game, therefore in the present study we focus on size announcement formation of coalitions. In one setting, we consider the case where a coalition's members cooperate in R&D only by maximizing joint profits and there is an industry-wide R&D spillover between firms. In another setting, we assume that members of a coalition cooperate in R&D by fully sharing information among themselves and also by jointly maximizing profits. In this case, we assume no R&D spillover between members of different coalitions. In both cases, we use numerical simulations to find the stable equilibrium and welfare maximizing coalition structures under different levels of coordination costs. The main goal of this research is to investigate how the size of equilibrium and optimal coalitions which are formed based on the size announcement game change with coordination costs.

This paper shows that under endogenous formation of RJVs and industry-wide R&D spillovers, when coordination costs are high enough, the subgame perfect equilibrium is that no RJV forms. Also, with coordination costs welfare is maximized when no RJV forms. Under endogenous formation of RJVs, high enough coordination costs and full information sharing between a coalition's members, when there is no R&D spillovers the equilibrium coalition structure is more concentrated than when coordination costs are low. Welfare maximizing coalition structure under high coordination costs are less concentrated than equilibrium coalition structure and the reverse is true when there is no coordination costs.

The paper is organized as follows. In the next section, we review the existing literature on endogenous formation of coalitions, and also some papers which analyze RJVs and R&D cooperation of firms by considering endogenous formation of coalitions based on sequential and size announcement games. In section 3, we use numerical simulations to investigate the effect of changes in coordination costs on the equilibrium and welfare maximizing coalition structures in a model where the cost-reducing R&D cooperation of firms is captured by maximizing the total profits in each joint venture. In this section, we present the results under low and high levels of industry-wide R&D spillovers. In section 4, we discuss the effect of coordination costs in a model where members of a coalition benefit from joining a RJV through full information sharing with other members and also by jointly maximizing profits in choosing their R&D investment levels. Section 5 concludes.

3.2 Literature review

A number of studies of endogenous RJVs focus on the game theory rules of coalition formation. Bloch (1996) analyzes the sequential formation of coalitions and discusses the stability structure. He also explains the sequential formation of RJVs under the assumption of symmetry of players and shows that in this case the subgame perfect equilibrium of sequential formation of coalitions is the same as the equilibrium in the size announcement game.

Yi (1997) explores the stable equilibrium coalition structures for symmetric firms in three different RJV formation games of coalition formation - Open Membership game, Equilibrium Binding Agreements and the Coalition Unanimity game - for the cases with positive and negative externalities of coalitions.

Greenlee and Cassiman (1999) consider R&D investment with quantity competition. They extend previous studies by considering the endogenous formation of coalitions in their model. In one part of their study, they assume R&D cooperation and competition of coalition members in the output stage, and in another part they assume coordination of coalition members in both R&D and output stages. The formation of RJVs in this study is based on the size announcement game introduced by Bloch (1996). In their model there are R&D

spillovers between all firms. Their results show that with endogenous formation of coalitions, the equilibrium coalition structure includes more than one RJV with different sizes. The results of welfare maximizing coalition structure show that when spillovers are large with R&D cooperation and product market competition, an industry wide RJV should be encouraged. When R&D spillovers are very high (close to 1) and R&D cost is low, cooperation in both R&D and output improves social welfare.

Yi and Shin (2000) study the endogenous formation of coalitions in a Cournot oligopoly framework with R&D spillovers among firms. They compare Open and Exclusive Membership games. The comparison of equilibrium coalition structures under these two systems of coalition formation shows that the equilibrium RJV structures under the Exclusive Membership game is more concentrated, and therefore total R&D investment is higher. Also, their analysis indicates that while the grand coalition structure improves social welfare, with high R&D spillovers, the equilibrium coalition structures under Open and Exclusive Membership are usually different from the optimal RJV structure.

Greenlee (2005) examines a Cournot framework in which multiple RJVs can form endogenously. He assumes an industry-wide R&D spillover and examines the case where a coalition's members cooperate in R&D by sharing information among themselves. He shows that when each firm maximizes its own profit and benefits from membership in a coalition only by sharing R&D with other members, firms gain higher profits when the sizes of coalitions are larger. This result is in contrast with the case where a coalition's members jointly maximize their profits. Based on the assumptions of the paper, RJVs formations increase social welfare only when spillovers are high enough.

3.3 Endogenous formation of coalitions under industry-wide spillovers

3.3.1 The model[1]

We consider N competing firms selling a homogeneous product in a Cournot oligopoly model. The inverse demand function is as follows:

$$P = A - \sum_{i=1}^{N} y_i \quad , \qquad (1)$$

where, P, A, y_i respectively stand for price, choke price and output of firm i.

In the R&D stage, we assume that firms can participate in cost-reducing R&D cooperation by joining research joint ventures, but in the output stage, they choose their output levels competitively.

In the present model, research joint ventures are considered to form endogenously and are based on the sequential game structure used by Bloch (1995, 1996). In this game, the formation of a coalition is proposed by a firm and other firms can accept or refuse to be a member of the proposed coalition. Once a coalition is formed, its members leave the game and the firm that has rejected the proposal offers the formation of another coalition. This process continues until all firms join an alliance and N firms partition between coalitions C_1, $C_2, \ldots, C_m$; where, C_1 includes n_1 members, C_2 has n_2 members, ...and C_m has n_m members . So, we can present the industry-wide partition of firms by $C = \{n_1, n_2, \ldots, n_m\}$, $\sum_{j=1}^{m} n_j = N$. Since based on Bloch (1996), sequential game has the same subgame perfect equilibrium as

[1] Formation of coalitions, assumptions regarding R&D spillovers and R&D cooperation within each coalition are similar to Greenlee (1999), with the main difference that in the present work we incorporate RJV coordination costs.

the size announcement game, (see also Greenlee et al., 1999), we use the size announcement game to analyze the model.

In this section, we assume that an industry-wide R&D spillover of $0 \leq \beta < 1$ exists between firms. The unit cost of firm *k* is

$$c_k = c - (1-\beta)x_k - \beta \sum_{i=1}^{N} x_i \ , \tag{2}$$

where x_i is the R&D output of each firm, $0 \leq \beta < 1$ is the industry-wide R&D spillovers . Each firm chooses the level of output which maximizes its profit

$$\max_{y_k} \ \ \pi_k \ . \tag{3}$$

Solving the maximization problem, the equilibrium output for firm *k* will be

$$y_k = \frac{A+\sum_{i=1}^{N} c_i-(N+1)c_k}{(N+1)} \ . \tag{4}$$

Substituting (2) into (4), y_k will be

$$y_k = \frac{A-c+(N+1)(1-\beta)x_k+(2\beta-1)\sum_{i=1}^{N} x_i}{(N+1)} \ . \tag{5}$$

The profit function for firm *k* is

$$\pi_k = \left[\frac{A-c+(N+1)(1-\beta)x_k+(2\beta-1)\sum_{i=1}^{N} x_i}{(N+1)}\right]^2 - \frac{\tau {x_k}^2}{2} \ , \tag{6}$$

where $\frac{\tau {x_k}^2}{2}$ captures firm *k*’s R&D cost and τ is R&D efficiency.

In this step, we assume that firms form coalitions endogenously and cooperate in R&D by jointly maximizing profits within each RJV. Firms still behave competitively in choosing their output in the product market.

In the R&D stage, in each coalition, members choose their R&D investment level by solving the following maximization problem

$$max_{x_k} \sum_{k \in C_k} \pi_k = \left[\frac{A-c+(N+1)(1-\beta)x_k+(2\beta-1)\sum_{i=1}^{N} x_i}{(N+1)}\right]^2 - \frac{z(n_k)x_k^2}{2} \ . \quad (7)$$

$\frac{z(n_k)\, x_k^2}{2}$ is the R&D cost of a RJV member, $z(n_k) > 0$ represents coordination costs where $z'(n_k) > 0$ and $z(1) = \tau$. This definition of $z(n_k)$ is the same as Falvey et al. (2010, 2013). $z'(n_k) > 0$ captures the fact that with the increase in size of a RJV, coordination costs increase.

From the first order condition, we obtain

$$\frac{2[(N+1)(1-\beta)+n_k(2\beta-1)]}{(N+1)2}\left[A-c+(N+1)(1-\beta)x_k+(2\beta-1)\sum_{i=1}^{N} x_i\right] - z(n_k)x_k = 0\ . \quad (8)$$

Simplifying (8) we reach

$$\left[\frac{(n+1)^2 z(n_k)-2[(N+1)(1-\beta)+n_k(2\beta-1)][(N+1)(1-\beta)]}{2[(N+1)(1-\beta)+n_k(2\beta-1)]}\right]x_k - (2\beta-1)\sum_{i=1}^{N} x_i = A-c\ . \quad (9)$$

Since *m* coalitions containing symmetric members exist we can write

$$\left[\frac{(n+1)^2 z(n_k)}{2[(N+1)(1-\beta)+n_k(2\beta-1)]} - (N+1)(1-\beta)\right]x_k - (2\beta-1)\sum_{j=1}^{m} n_j x_j = A-c\ . \quad (10)$$

According to the general solution for this type of functions explained by Greenlee (1999), the solution for x_k is

$$x_k = \frac{(A-c)}{\omega_k}\left[1 + \sum_{j=1}^{m} \frac{(1-2\beta)n_j}{\omega_j}\right]^{-1}, \tag{11}$$

or

$$x_k = \frac{(A-c)\omega_k}{1+\mu} \ , \tag{12}$$

where,

$$\omega_k = \frac{2[(N+1)(1-\beta)+n_k(2\beta-1)]}{(N+1)^2 z(n_k)-2[(N+1)(1-\beta)+n_k(2\beta-1)](N+1)(1-\beta)} \ . \tag{13}$$

and

$$\mu = (1-2\beta)\sum_{j=1}^{m} n_j\,\omega_j \ . \tag{14}$$

Substituting back the equilibrium research effort x_k into profit, we get

$$\pi_k = \frac{(A-c)^2}{(n+1)^2(1+\mu)^2}[1+(1-\beta)(N+1)\omega_k][1+(1-2\beta)n_k\omega_k] \ . \tag{15}$$

3.3.2 Equilibrium and optimal coalition structures

As explained in the previous sections, we analyze the endogenous formation of RJVs according to the size announcement game. The game of choice of coalition sizes for four symmetric players is shown in figure 1. We consider different sizes which may be announced by F_1 (firm 1) and responses of other firms to these size announcements. In general, when a coalition structure of $\{n_1, n_{2,}..., n_m\}$ forms, the profit of each firm in a coalition with n_j

members can be written as π (n_j; {n_1, $n_{2,}$..., n_m}). For example, in the case of four players, if F_1 announces size 4, then {4} forms and F_1 earns π (4; {4}). If F_1 announces 3, then {3,1} forms, F_1 earns π(3;{3,1}) and F_4 earns π(1;{3,1}). For size announcement of 2 by F_1, F_3 may announce either size 2 or 1; therefore, F_1's profit can be π(2; {2, 2}) or π(2; {2, 1, 1}). This way, we consider all possible coalition structures for announcement of size 1 by F_1. An example of the game is explained in the Appendix.

We use numerical simulations to find the equilibrium and optimal RJV structures. For this purpose, we use the same functional form as chosen by Falvey et al. (2010):

$$z(n_k) = \tau(n_k)^{\rho}, \tag{16}$$

where $$n_k \geq 1,\ \rho \geq 0.$$

Substituting (16) into (13) yields

$$\omega_k = \frac{2[(N+1)(1-\beta)+n_k(2\beta-1)]}{(N+1)^2\tau(n_k)^{\rho}-2[(N+1)(1-\beta)+n_k(2\beta-1)](N+1)(1-\beta)}\ . \tag{17}$$

We also need to initialize some values for parameters of the model, so we set parameters values as follows: A-c=20 and τ=1. Simulation results for profits of firms under different coalition structures when N=6, N=5, N=4 and R&D spillover levels are β=⅓ and β= ⅔, are presented in tables 1 through 6. We use backward induction to find the stable equilibrium coalition structure. Also, we calculate consumer surplus and welfare under low and high R&D spillovers for different levels of coordination costs. Equilibrium configurations are in bold.

Consumer surplus (CS) is

$$CS = \frac{\left(N(A-c)+(1+\beta N-\beta)\sum_{i=1}^{m} n_i x_i \ \right)^2}{2(N+1)^2} \ . \tag{18}$$

Total welfare (W) is

$$W = \sum_{i=1}^{m} n_i \, \pi_i + CS \ . \tag{19}$$

The numerical simulations results for *N*=6 and *N*=5 players are shown in tables 7 through 10. The first number in each cell represents welfare and the second one is consumer surplus. Welfare and consumer surplus are also calculated for *N*=4 and the results are available upon request.

Figure 1. Size announcement game for *N*=4

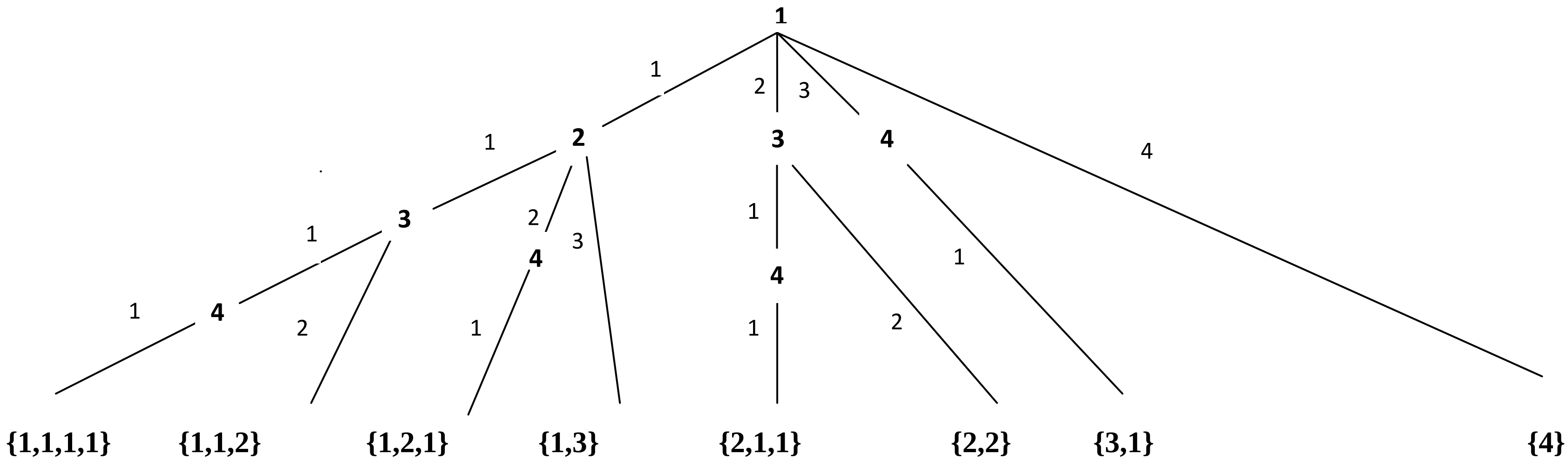


Table 1. Profits of firms in coalition structures with N=4 and β=⅓

	{1,1,1,1 }	**{2,1,1}**	**{2,2}**	**{3,1}**	**{4}**
ρ=0	17.72	17.82,18.39	18.5	18.24,19.68	**19.04**
ρ=0.25	17.72	16.68,19.15	18.07	17.03,21.15	**18.04**
ρ=0.5	**17.72**	15.82,19.73	17.72	16.2,22.18	17.39
ρ=0.75	**17.72**	15.17,20.18	17.43	15.63,22.91	16.95
ρ=1	**17.72**	14.66,20.54	17.19	15.22,23.44	16.66

Table 2. Profits of firms in coalition structures with N=4 and β=⅔

	{1,1,1,1 }	**{2,1,1}**	**{2,2}**	**{3,1}**	**{4}**
ρ=0	23.26	23.46,23.92	24.14	**24.02,25.38**	25
ρ=0.25	**23.26**	22.42,23.19	22.35	21.87,23.34	21.46
ρ=0.5	**23.26**	21.62,22.63	21.04	20.47,22.06	19.51
ρ=0.75	**23.26**	20.98,22.2	20.04	19.52,21.21	18.33
ρ=1	**23.26**	20.48,21.86	19.27	18.86,20.62	17.58

Table 3. Profits of firms in coalition structures with *N*=5 and *β*=⅓

	{1,1,1,1,1}	{2,1,1,1}	{2,2,1}	{3,1,1}	{3,2}	{4,1}	{5}
ρ=0	11.97	12.01,12.29	12.33,12.61	12.2,12.9	12.53,12.92	**12.55,13.82**	13.09
ρ=0.25	11.97	11.15,12.74	11.89,13.58	11.22,13.78	11.99,12.89	11.65,15.1	**12.36**
ρ=0.5	**11.97**	10.52,13.08	11.53,14.34	10.57,14.37	11.64,12.73	11.09,15.93	11.91
ρ=0.75	**11.97**	10.04,13.34	11.25,14.95	10.13,14.79	11.42,12.56	10.72, 16.49	11.63
ρ=1	**11.97**	9.67,13.54	11.02,15.44	9.81,15.09	11.27,12.38	10.48,16.87	11.45

Table 4. Profits of firms in coalition structures with *N*=5 and *β*=⅔

	{1,1,1,1,1}	{2,1,1,1}	{2,2,1}	{3,1,1}	{3,2}	{4,1}	{5}
***ρ*=0**	16.22	16.32,16.54	16.64,16.86	16.59,17.21	16.92,17.33	17.05,18.35	**17.73**
***ρ*=0.25**	**16.22**	15.68,16.14	15.6,16.06	15.31,16.15	15.23,15.61	15.03,16.27	14.8
***ρ*=0.5**	**16.22**	15.17,15.83	14.81,15.466	14.46,15.468	14.12,14.47	13.86,15.12	13.33
***ρ*=0.75**	**16.22**	14.77,15.59	14.21,15	13.87,15	13.36,13.68	13.14,14.44	12.5
***ρ*=1**	**16.22**	14.45,15.4	13.74,14.64	13.46,14.67	12.81,13.1	12.68,14	12

Table 5. Profits of firms in coalition structures with *N*=6 and *β*=⅓

	{1,1,1,1,1,1}	{2,1,1,1,1}	{2,2,1,1}	{2,2,2}	{3,1,1,1}	{3,2,1}	{3,3}	{4,1,1}	{4,2}	{5,1}	{6}
ρ=0	8.62	8.63,8.78	8.80,8.96	8.98	8.73,9.11	8.9,9.13,9.25	9.24	8.9,9.59	**9.09,9.62**	9.17,10.2	9.54
ρ=0.25	8.62	7.97,9.07	8.4,9.56	8.87	7.93,9.68	8.38,8.97,10.22	8.97	8.14,10.42	8.61,9.61	8.5,11.34	**8.99**
ρ=0.5	**8.62**	7.48,9.29	8.09,10.04	8.77	7.42,10.05	8.05,8.78,10.9	8.77	7.67,10.95	8.35,9.6	8.1,12	8.6
ρ=0.75	**8.62**	7.12,9.45	7.84,10.41	8.68	7.07,10.32	7.83,8.59,11.41	8.62	7.37,11.3	8.19,9.46	7.85,12.43	8.48
ρ=1	**8.62**	6.84,9.58	7.64,10.7	8.6	6.83,10.5	7.68,8.42,11.8	8.51	7.17,11.53	8.11,9.3	7.69.12,7	8.36

Table 6. Profits of firms in coalition structures with *N*=6 and *β*=⅔

	{1,1,1,1,1,1}	{2,1,1,1,1}	{2,2,1,1}	{2,2,2}	{3,1,1,1}	{3,2,1}	{3,3}	{4,1,1}	{4,2}	{5,1}	{6}
ρ=0	11.95	12,12.11	12.17,12.28	12.34	12.14,12.47	12.32,12.53,12.65	12.69	12.39,13.05	12.57,13.11	**12.75,13.91**	13.23
ρ=0.25	**11.95**	11.57,11.88	11.5,11.81	11.43	11.31,11.85	11.24,11.47,11.78	11.22	11.11,11.87	11.04,11.5	10.94,11.96	10.81
ρ=0.5	**11.95**	11.22,11.69	10.99,11.45	10.76	10.74,11.44	10.52,10.75,11.2	10.3	10.35,11.2	10.13,10.53	9.99,10.99	9.69
ρ=0.75	**11.95**	10.95,11.55	10.59,11.16	10.25	10.35,11.16	10.02,10.24,10.8	9.69	9.87,10.79	9.55,9.91	9.45,10.44	9.06
ρ=1	**11.95**	10.73,11.43	10.28,10.94	9.85	10.07,10.96	9.65,9.87,10.51	9.28	9.56,10.53	9.17,9.48	9.11,10.12	8.72

Table 7. Welfare and Consumer surplus for *N*=5 and *β*=⅓

		{1,1,1,1,1}	{2,1,1,1}	{2,2,1}	{3,1,1}	{3,2}	{4,1}	{5}
ρ=0	*W*	**298.87**	294.75	290.58	286.06	282.37	280.42	258.24
	CS	**238.98**	233.84	228.62	224.22	218.86	210.47	197.72
ρ=0.25	*W*	**298.87**	287.2	275	271.8	259.5	261.3	233.7
	CS	**238.98**	226.6	213.9	211	197.77	197.72	171.9
ρ=0.5	*W*	**298.87**	281.74	263.53	262.97	243.64	249.14	219.35
	CS	**238.98**	221.45	203,03	202.56	183.22	181.98	159.77
ρ=0.75	*W*	**298.87**	277.6	254.7	257.1	232.2	240.9	210.5
	CS	**238.98**	217.5	194.7	196.8	172.8	175.1	152.3
ρ=1	*W*	**298.87**	274.47	247.84	253.13	223.76	235.17	204.97
	CS	**238.98**	214.5	188.3	192.79	165.17	170.64	147.68

Table 8. Welfare and Consumer surplus for *N*=5 and *β*=⅔

		{1,1,1,1,1}	{2,1,1,1}	{2,2,1}	{3,1,1}	{3,2}	{4,1}	{5}
ρ=0	*W*	320.11	330.11	340.48	350.76	262.63	384.13	**442.47**
	CS	238.98	247.84	257.04	267.25	277.19	300.53	**353.8**
ρ=0.25	*W*	**320.11**	316.4	312.8	315	311.5	316.1	320.09
	CS	**238.98**	236.6	234.4	236.9	234.6	240.1	246.7
ρ=0.5	*W*	**320.11**	305.99	292.5	292.13	279.25	279.83	266.86
	CS	**238.98**	228.12	217.76	217.81	207.92	208.48	200.16
ρ=0.75	*W*	**320.11**	297.7	277	276.7	257.4	258.2	238.5
	CS	**238.98**	221.4	205.2	205	190	189.9	176
ρ=1	*W*	**320.11**	291.29	265.16	265.99	242.23	244.68	222.25
	CS	**238.98**	216.15	195.53	196.3	177.56	178.42	162.21

Table 9. Welfare and Consumer surplus for N=6 and β=⅓

		{1,1,1,1,1,1}	{2,1,1,1,1}	{2,2,1,1}	{2,2,2}	{3,1,1,1}	{3,2,1}	{3,3}	{4,1,1}	{4,2}	{5,1}	{6)
ρ=0	*W*	**303.3**	300.2	297.1	293.9	293.7	291.0	284.8	283.5	281.9	273.3	258.3
	CS	**251.6**	247.8	243.9	240.09	240.6	236.7	229.3	230.4	226.3	217.1	201.06
ρ=0.25	*W*	**303.3**	293.7	283.7	273.4	281.2	271.1	258	266.5	256.3	250.9	232.4
	CS	**251.6**	241.4	230.9	220.1	228.6	217.8	204.1	213.8	202.5	197	178.5
ρ=0.5	*W*	**303.3**	288.9	273.8	257.8	273.4	257.5	240.3	261.2	239.7	238.1	218.09
	CS	**251.6**	236.8	221.4	205.2	221.0	204.9	187.6	203.9	187.1	185.6	166.02
ρ=0.75	*W*	**303.3**	285.4	266.3	245.9	268.4	247.8	228.2	249.9	228.3	230.4	209.6
	CS	**251.6**	233.3	214.1	193.8	215.9	195.7	176.4	197.7	176.6	178.7	158.7
ρ=1	*W*	**303.3**	282	260.5	236.6	265.0	240.7	219.6	249.4	220.3	225.5	204.5
	CS	**251.6**	230.7	208.5	185.02	212.3	189.06	168.6	193.7	169.2	174.3	154.3

Table 10. Welfare and Consumer surplus for N=6 and β=⅔

		{1,1,1,1,1,1}	{2,1,1,1,1}	{2,2,1,1}	{2,2,2}	{3,1,1,1}	{3,2,1}	{3,3}	{4,1,1}	{4,2}	{5,1}	{6}
ρ=0	*W*	327.7	330.7	338.4	346.2	345.9	354.5	371.6	369.6	380.8	410.2	**465.6**
	CS	251.6	258.3	265.1	272.2	272.6	279.8	295.4	296.3	304.2	332.5	**386.2**
ρ=0.25	*W*	**327.7**	319.53	315.77	312.06	317.15	313.54	311.32	314.41	313.23	318.77	322.53
	CS	**251.6**	248.86	246.14	243.44	247.78	245.07	244	248.78	246.05	252	250.67
ρ=0.5	*W*	**327.7**	310.7	298.7	287.2	298.3	286.7	275.2	289.4	275.2	275.1	264.5
	CS	**251.6**	241.5	231.9	222.6	231.7	222.4	213.3	222.5	213.6	214.1	206.4
ρ=0.75	*W*	**327.7**	303.9	285.7	268.6	285.39	268.32	252	271.4	251.8	251.35	235.8
	CS	**251.6**	236.8	221	207.1	220.8	206.9	193.8	206.7	193.8	193.6	181.3
ρ=1	*W*	**327.7**	298.4	275.5	254.4	276.2	255.1	236.3	259.7	236.5	237.3	219.9
	CS	**251.6**	231.2	212.5	195.3	213,2	195.9	180.7	196.7	180.8	181.6	167.6

To find the equilibrium coalition structure, for instance in the case of *N*=6, β=⅓ and *ρ*=0.5, if firm 1 announces size 1, the best response of other firms is to also announce size 1. If firm 1 announces size 2, the best response is that firms 3, 4 and 5 each announce size 1 and therefore {2,1,1,1,1} forms. When firm 1 announces 3, firms 4 and 5 each announce size 1 and {3,1,1,1} forms. When firm 1 announces size 4, {4,1,1} is the best response. And finally, if firm 1 announces 5 or 6, respectively, {5,1} and {6,1} form. Among all these coalition structures, $\{1_6\}$ (meaning 6 singleton coalitions) yields the highest profit and therefore it is the subgame perfect equilibrium.

Equilibrium and welfare maximizing coalition structures for four, five and six players in the cases of low and high R&D spillovers are presented in the following table.

Table 11. Equilibrium and welfare maximizing coalition structures[1]

ρ	*N*=6				*N*=5				*N*=4			
	B=1/3		*B*=2/3		*B*=1/3		*B*=2/3		*B*=1/3		*B*=2/3	
	E	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*
0	{2,4}	$\{1_5\}$	{1,5}	{6}	{1,4}	$\{1_5\}$	{5}	{5}	{4}	$\{1_5\}$	{1,3}	{4}
0.25	{6}	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	{5}	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	{4}	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$
0.5	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$
0.75	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$
1	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$	$\{1_5\}$

As the results show, while according to Greenee et al. (1999) in the endogenous model of coalition formation with no coordination costs, equilibrium coalition structures usually include more than one RJV with different sizes, the presence of high enough

[1] In this table, *E* and *W* respectively stand for Equilibrium and welfare maximizing coalition structures.

coordination costs in the model weakens the effect of investment coordination in the coalitions with more than one member and as a result no RJV will be formed.

Another important point which tables 7 through 10 report is that when coordination costs are considered, for any level of ρ, consumer surplus and total welfare are maximized when no RJV is formed. When coordination costs increase, the R&D investment and therefore profits of firms in RJVs with more than one member decrease and the investment and profits of firms which have not joined any RJV increase. Therefore, the socially optimal coalition structure for any strictly positive level of coordination costs is that firms do not join any coalition.

Result 1. *Under endogenous formation of RJVs and industry-wide R&D spillovers with the presence of high enough coordination costs, the subgame perfect equilibrium is that no RJV forms*.

Result 2. *In the presence of high enough coordination costs, welfare is maximized when no RJV forms*.

3.4 Endogenous formation of coalitions under intra RJV full information sharing and no industry-wide spillovers

In this section, we assume that RJVs form endogenously in a Cournot model of N ex ante symmetric firms. Within each coalition members cooperate in R&D by fully sharing information between themselves and also by jointly maximizing their profits over R&D. Also, we assume there is no R&D spillover between coalitions.

3.4.1 The model

The unit cost of a representative firm in a coalition with n_k members is

$$c_k = c - \sum_{k \in c(k)} x_k \ . \tag{20}$$

The profit function of firm *k* is

$$\pi_k = \left[\frac{A-c+(N+1)\sum_{k \in c(k)} x_k - \sum_{i=1}^{N} n_i x_i}{(N+1)}\right]^2 - \frac{z(n_k) {x_k}^2}{2} \ . \tag{21}$$

As there are *m* coalitions, each coalition solves

$$max_{x_k} \sum_{k \in C_k} \pi_k = \left[\frac{A-c+(N+1)\sum_{k \in c(k)} x_k - \sum_{j=1}^{m} n_j^2 x_j}{(N+1)}\right]^2 - \frac{z(n_k) {x_k}^2}{2} \ . \tag{22}$$

Taking the derivative of (22) with respect to x_k yeilds

$$\left[\frac{(N+1)^2 z(n_k)}{2[(N+1)n_k - {n_k}^2]} - (N+1)n_k\right] x_k + \sum_{j=1}^{m} n_j^2 x_j = A - c \ . \tag{23}$$

As in Greenlee (1999) the general solution for x_k is

$$x_k = \frac{(A-c)}{\omega_k}\left[1 + \sum_{j=1}^{m} \frac{{n_j}^2}{\omega_j}\right]^{-1}, \tag{24}$$

or

$$x_k = \frac{(A-c)\omega_k}{1+\mu} \ , \tag{25}$$

where

$$\omega_k = \frac{2\left[(N+1)n_k - n_k^2\right]}{(N+1)^2 z(n_k) - 2\left[(N+1)n_k - n_k^2\right](N+1)n_k} \,, \tag{26}$$

and

$$\mu = \sum_{j=1}^{m} n_j{}^2\, \omega_j \,. \tag{27}$$

Substituting for the variables in the profit function, the profit of a firm in a coalition with n_k members is

$$\pi_k = \frac{(A-c)^2}{(N+1)^2(1+\mu)^2}\left[1 + n_k(N+1)\omega_k\right]\left[1 + n_k{}^2\omega_k\right] \,. \tag{28}$$

3.4.2 Equilibrium and Optimal coalition structures

We use the same functional form for $z(n_k)$ as in section 3.2, so

$$\omega_k = \frac{2\left[(N+1)n_k - n_k^2\right]}{\tau(n_k)^{\rho}(N+1)^2 - 2\left[(N+1)n_k - n_k^2\right](N+1)n_k} \,. \tag{29}$$

Numerical profit outcomes for parameter values of A-c= 20, $\tau = 50$ and N=4, 5, 6 and 7, ρ= 0, 0.25, 0.5, 0.75 and 1 are presented in tables 12 through 15. According to Falvey et al. (2010), since for ρ=2 coordination costs are too high, the efficiency of formation of RJV is less than when the firm remains single. Therefore, to make sure that the formation of research joint ventures is still efficient, we assume $\rho \leq 1$.[1]

Tables 16 through 18 present the results for consumer surplus and welfare under different levels of coordination costs. The general formula for CS under the assumptions of this section is

[1] The full proof is also available in Falvey et al (2010).

$$CS = \frac{\left(N(A-c)+\sum_{i=1}^{m} n_i^2 x_i\ \right)^2}{2(N+1)^2}\ . \qquad (30)$$

Table 12. Profits of firms in coalition structures with *N*=4

	{1,1,1,1 }	{2,1,1}	{2,2}	{3,1}	{4}
ρ=0	15.89	16.26, 15.47	15.84	**16.37, 14.8**	16.2
ρ=0.25	15.89	16.18,15.57	15.86	**16.25,15.1**	16.14
ρ=0.5	15.89	16.12, 15.66	15.88	**16.16, 15.39**	16.1
ρ=0.75	15.89	16.,07, 15.73	15.9	**16.10,15.59**	16.07
ρ=1	15.89	16, 15.79	15.92	**16.05, 15.74**	16.05

Table 13. Profits of firms in coalition structures with *N*=5

	{1,1,1,1,1}	{2,1,1,1}	{2,2,1}	{3,1,1}	{3,2}	{4,1}	{5}
ρ=0	11.01	11.3,10.7	11.04,10.4	11.5,10.1	11.22,10.4	**11.4,9.6**	11.26
ρ=0.25	11.01	11.26,10.8	11.04,10.5	11.3,10.4	11.1,10.6	**11.3,10.3**	11.21
ρ=0.5	11.01	11.2,10.8	11,10.7	11.28,10.6	11.12,10.8	**11.25,10.46**	11.18
ρ=0.75	11.01	11.1,10.9	11.04,10.7	11.21,10.7	11.09,10.9	**11.16, 10.9**	11.15
ρ=1	11.01	11.1,10.9	11,10.8	11.15,10.8	11.08,10.9	**11.14,10.8**	11.14

Table 14. Profits of firms in coalition structures with *N*=6

	{1,1,1,1,1,1}	{2,1,1,1,1}	{2,2,1,1}	{2,2,2}	{3,1,1,1}	{3,2,1}	{3,3}	{4,1,1}	{4,2}	{5,1}	{6}
ρ=0	8	8.34,7.88	8.1, 7.7	7.95	8.55, 7.45	8.35, 7.7, 7.28	7.91	8.59, 6.93	8.4, 7.17	**8.47,6.61**	8.28
ρ=0.25	8	8.28,7.93	8.13,7.79	7.99	8.42,7.6	8.27,7.8,7.5	7.97	8.43,7.32	8.29,7.51	**8.35,7.16**	8.24
ρ=0.5	8	8.24, 7.97	8.13, 7.86	8.01	8.32, 7.77	8.21, 7.93, 7.67	8.02	8.33, 7.59	8.21, 7.74	**8.27, 7.53**	8.21
ρ=0.75	8	8.2,8	8.12,7.92	8.04	8.25,7.8	8.17,8,7.8	8.05	8.25,7.78	8.17,7.9	**8.22,7.78**	8.19
ρ=1	8	8.1, 8	8.1, 7.97	8.06	8.2, 7.96	8.15, 8.04, 7.9	8.08	8.2, 7.92	8.15, 8	**8.19, 7.94**	8.18

Table 15. Profits of firms in coalition structures with *N*=7

	{1$_7$}	{2,1,1,1,1,1}	{2,2,1,1,1}	{2,2,2,1}	{3,1,1,1,1}	{3,2,1,1}	{3,2,2}	{3,3,1}	{4,1,1,1}	{4,2,1}	{4,3}	{5,1,1}	{5,2}	{6,1}	{7}
ρ=0	6.1	6.4,6.04	6.26,5.9	6.12,5.7	6.6,5.7	6.4,5.9,5.5	6.3,5.7	6.12,5.2	6.1,5.2	6.5,5.4,5.1	6.24,5.6	6.67,4.8	**6.53,5**	6.51,4.68	6.34
ρ=0.25	6.1	6.3,6.07	6.24,5.9	6.14, 5.8	6.4,5.8	6.3, 6,5.7	6.2,5.9	6.15,5.5	6.17,5.5	6.4,5.7,5.4	6.2,5.8	6.5, 5.3	6.4,5.4	**6.4,5.2**	6.3
ρ=0.5	6.1	6.3,6.1	6.23,6	6.15,5.9	6.4,5.9	6.3,6,5.8	6.2,6	6.16,5.7	6.17,5.7	6.3,5.9,5.7	6.19,5.9	6.39,5.6	6.31,5.7	**6.34,5.6**	6.28
ρ=0.75	6.1	6.28,612	6.22,6.06	6.16, 6	6.3, 6	6.2,6.12,5.9	6.2, 6	6.18,5.8	6.16,5.9	6.2,6.03,5.8	6.19,6	6.3,5.8	6.27,5.9	**6.29,5.9**	6.27
ρ=1	6.1	6.2,6.14	6.21,6.1	6.17,6	6.2,6	6.2,6.1,6	6.2,6.1	6.19,5.9	6.16,6.0	6.2,6.1,6	6.19,6.1	6.28,6.02	6.24,6.09	**6.26,6.06**	6.26

Table 15. Welfare and Consumer surplus in coalition structures with *N*=4

		{1,1,1,1 }	{2,1,1}	{2,2}	{3,1}	{4}
ρ=0	*W*	192.3	193.1	193.8	194	**196.1**
	CS	128.7	129.6	130.4	131	**131.3**
ρ=0.25	*W*	192.3	199.2	193.5	194.2	**194.9**
	CS	128.7	129.4	130	130.3	**130.3**
ρ=0.5	*W*	192.3	192.8	193.3	193.9	**194**
	CS	128.7	129.2	129.7	130	**129.6**
ρ=0.75	*W*	192.3	192.7	193.1	193.3	**193.4**
	CS	128.7	129.1	129.4	129.43	**129.1**
ρ=1	*W*	192.3	192.6	192.9	**193.8**	193
	CS	128.7	129.03	129.2	**129.9**	128.8

Table 16. Welfare and Consumer surplus in coalition structures with *N*=5

		{1,1,1,1,1}	{2,1,1,1}	{2,2,1}	{3,1,1}	{3,2}	{4,1}	{5}
ρ=0	*W*	194.7	195.2	195.7	196.6	197.1	**198.6**	199.1
	CS	139.6	140.3	141	141.8	142.4	**143.1**	142.8
ρ=0.25	*W*	194.7	195.1	195.5	196.1	196.4	**197.6**	197.5
	CS	139.6	140.2	140.7	141.1	141.6	**141.9**	141.5
ρ=0.5	*W*	194.7	195	195.3	195.7	196.03	**196.7**	196.53
	CS	139.6	140	140.4	140.6	141.05	**141**	140.6
ρ=0.75	*W*	194.7	194.9	195.2	195.4	195.6	**197.6**	195.8
	CS	139.6	139.9	140.2	140.3	140.5	**140.4**	140
ρ=1	*W*	194.7	194.9	195.1	195.2	195.4	**195.5**	195.3
	CS	139.6	139.8	140	140.04	140.2	**140**	139.6

Table 17. Welfare and Consumer surplus in coalition structures with *N*=6

		{1,1,1,1,1,1}	{2,1,1,1,1}	{2,2,1,1}	{2,2,2}	{3,1,1,1}	{3,2,1}	{3,3}	{4,1,1}	{4,2}	{5,1}	{6}
ρ=0	*W*	196.1	196.4	196.8	197.1	197.6	197.8	198.8	199.4	199.7	**201.2**	201
	CS	147.6	148.2	148.8	149.3	149.5	150.1	151.3	151.2	151.7	**152.2**	151.3
ρ=0.25	*W*	196.1	196.42	196.6	196.9	197.1	197.4	198.13	198.3	198.6	**199.4**	199.1
	CS	147.6	148.1	148.5	148.9	149	149.4	150.2	150	150.4	**150.5**	149.7
ρ=0.5	*W*	196.1	196.3	196.5	196.7	196.9	197	197.5	197.6	197.8	**198.2**	197.9
	CS	147.6	147.9	148.3	148.6	148.5	148.9	149.4	149.1	149.4	**149.3**	148.7
ρ=0.75	*W*	196.1	196.3	196.4	196.6	196.6	196.8	197.1	197.1	197.3	**197.4**	197.2
	CS	147.6	147.9	148.1	148.2	148.2	148.4	148.8	148.5	148.7	**148.5**	148
ρ=1	*W*	196.1	196.2	196.4	196.5	196.5	196.6	196	196.8	196.92	**196.96**	196.7
	CS	147.6	147.8	147.9	148.1	148	148.1	148.3	148.1	148.3	**148**	147.6

Table 18. Welfare and Consumer surplus in coalition structures with *N*=7

		{1_7}	{2,1,1,1,1,1}	{2,2,1,1,1}	{2,2,2,1}	{3,1,1,1,1}	{3,2,1,1}	{3,2,2}	{3,3,1}	{4,1,1,1}	{4,2,1}	{4,3}	{5,1,1}	{5,2}	{6,1}	{7}
ρ=0	*W*	197	197.3	197.5	197.7	199	198.25	198.5	198.8	197.6	199.9	200.5	201.8	201.95	**203.24**	202.3
	CS	153	154.2	154.7	155.2	155.40	155.8	156.3	157	157.1	157.6	158.6	158.8	159.2	**159.4**	157.9
ρ=0.25	*W*	197	197.2	197.4	197.6	197.8	197.9	198.1	198.5	197.3	199.	199.4	200	200.2	**200.8**	200.2
	CS	153	154.1	154.5	154.8	154.9	155.2	155.6	156	156	156.3	157	156.9	157.2	**157.1**	156
ρ=0.5	*W*	197	197.2	197.3	197.5	197.6	197.6	197.89	198.14	197.24	198.4	198.7	198.9	199	**199.3**	198.9
	CS	153	154	154.3	154.6	154.6	157.7	155.14	155.3	155.22	155.4	155.9	155.6	155.93	**155.6**	154.9
ρ=0.75	*W*	197	197.18	197.29	197.4	197.4	197.4	197.6	197.8	197.15,	197.9	198.2	198.2	198.3	**198.4**	198.1
	CS	153	154	154.2	154.4	154.3	154.4	154.7	154.8	154.6	154.8	155.1	154.8	155	**154.7**	154.2
ρ=1	*W*	197	197.1	197.24	197.32	197.34	197.3	197.5	197.6	197	197.6	197.85	197.82	**197.9**	197.8	197.6
	CS	153	153.9	154	154.2	154.13	154.17	154.4	154.46	154.20	154.4	154.6	154.35	**154.4**	154.2	153.7

Based on the results for profits and welfare for coalition structures with different sizes (*N*=4 to *N*=11), the equilibrium and welfare maximizing coalition structures are presented in table 19.

Table 19. Equilibrium and welfare maximizing coalition structures

ρ	***N*=11**		***N*=10**		***N*=9**		***N*=8**		***N*=7**		***N*=6**		***N*=5**		***N*=4**	
	E	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*
0	{9,2}	{9,1,1}	{8,2}	{8,2}	{7,2}	{8,1}	{6,2}	{7,1}	{5,2}	{6,1}	{5,1}	{5,1}	{4,1}	{4,1}	{3,1}	{4}
0.25	{9,2}	{9,1,1}	{8,2}	{8,2}	{7,2}	{8,1}	{6,2}	{7,1}	{6,1}	{6,1}	{5,1}	{5,1}	{4,1}	{4,1}	{3,1}	{4}
0.5	{9,2}	{9,2}	{8,2}	{8,2}	{7,2}	{8,1}	{6,2}	{7,1}	{6.1}	{6,1}	{5,1}	{5,1}	{4,1}	{4,1}	{3,1}	{4}
0.75	{9,2}	{9.2}	{8,2}	{8,2}	{7,2}	{7,2}	{6.2 }	{7,1}	{6,1}	{6,1}	{5,1}	{5,1}	{4,1}	{4,1}	{3,1}	{4}
1	{10,1}	{9,2}	{9,1}	{8,2}	{8,1}	{7,2}	{7,1}	{6,2}	{6,1}	{5,2}	{5,1}	{5,1}	{4,1}	{4,1}	{3,1}	{3,1}

The results show that except for small *N* (*N*=4, 5, 6), in all cases when coordination costs are high enough (ρ=1), the equilibrium coalition structures are more concentrated than the case when coordination cost is zero or it is not very high (ρ=0.5). As explained before, accepting a new member has two effects. On one hand, RJV members benefit from information sharing with the arrival of a new member; on the other hand, the increase in coordination cost raises the cost of each RJV member.

According to Yi and Shin (2000), coalition $C=\{n_1, n_2,\ldots, n_m\}$ is a concentration of $C'=\{n_1', n_2', \ldots, n_m'\}$ when we obtain $C=\{n_1, n_2,\ldots, n_m\}$ by moving one member from n_j' *to* $n_i',$ where $n_i' \geq n_j'$.

When the coordination cost is not very high (ρ=0.5), in almost all cases the presence of coordination costs in the model does not affect the equilibrium size of the coalition structure. The reason is that the increase in the coordination costs from 0 to 0.5 increases the cost of R&D cooperation among members of a coalition with more than one member, but members still benefit from joint profit maximization and also sharing information among themselves. So, firm 1 prefers to announce the same size and the same coalition structure forms in equilibrium.

As coordination costs increase from 0.5 to 1, firm 1 announces a larger size to alleviate the effect of coordination costs by benefiting from an extra member from getting more information, and therefore, a more concentrated coalition structure forms. The reason is that with increases in coordination costs, R&D investment decreases and therefore, the newcomer is a less fierce competitor.

The following numerical example for N=7 confirms this. The equilibrium coalition structure when ρ=0 is {5,2} and for ρ=1 is {6,1}. If we consider {5,2} in both cases of low and high coordination costs, bringing in one more member raises the cost of insiders by 0.02. When ρ=0 the marginal cost of the newcomer is reduced by 0.28 while for ρ=1 its marginal cost reduces by 0.04. So, when coordination costs are high enough, there will be less reduction in the marginal cost of the new member and therefore, it will be accepted as it is a less fierce competitor.

Table 20. Changes in marginal costs of firms by adding a new member

ρ=0				Change in marginal costs
c_5	c_2	c_6	c_1	$c_6 - c_2 = -0.28$
29.5	29.8	29.52	29.96	$c_6 - c_5 = 0.02$
ρ=1				
c_5	c_2	c_6	c_1	$c_6 - c_2 = -0.04$
29.9	29.96	29.92	29.95	$c_6 - c_5 = 0.02$

Comparing these results with the results of Falvey et al. (2010) shows that when the formation of coalitions is considered endogenously and more than one coalition can form, because a RJV member takes into account the possibility of formation of other competitive RJVs, when coordination cost is very high, in equilibrium the size of coalitions is higher than the case when only one RJV can form.

Also, the results show that while the socially maximizing coalition structure in most cases ($N \geq 7$) is more concentrated than the equilibrium structure when coordination costs are zero, in the case of high coordination costs (ρ=1), it will be less concentrated than the equilibrium coalition structure.

Result 3. *With endogenous formation of RJVs, when there is full information sharing between a coalition's members and no R&D spillovers between different coalitions, in the presence of high enough coordination costs and for N≥7, the equilibrium coalition structure is more concentrated than when coordination costs are low.*

Result 4. *With the endogenous formation of RJVs, when there is full information sharing between a coalition's members and no R&D spillovers between different coalitions, in the presence of high enough coordination costs and for N≥7, the welfare maximizing coalition* *structure is less concentrated than the equilibrium coalition structure. The reverse is true for the case when there is no coordination costs in the model.*

Result 5. *When more than one coalition can form endogenously under high enough coordination costs, the equilibrium size of the coalition structure is higher than when only one RJV can form.*

3.5 Conclusion

The focus of this paper was on investigating the effect of changes in coordination costs on the equilibrium and optimal coalition structures, where coalitions can form endogenously based on the size announcement game. Fist, we assumed an industry-wide R&D spillover where a coalition's members cooperate in R&D by jointly maximizing profits. The numerical simulations results indicate that with high enough coordination costs the equilibrium and optimal coalition structure is that no RJV forms. Second, we analyzed the case of intra-coalition full R&D cooperation and no industry-wide R&D spillovers. Applying numerical simulations showed that with high enough coordination costs, the equilibrium coalition structure is more concentrated than under low coordination cost. Also, with endogenous formation of coalitions under high enough coordination costs the size of the coalition structure is greater than when only one coalition is allowed to form. When coordination costs are high enough, the equilibrium coalition structure is more concentrated than the optimal coalition structure, while the opposite is true for low coordination costs.

References

Atallah, G., 2003, "Information sharing and the stability of cooperation in research joint ventures", *Economics of Innovation and New Technology*, Vol. 12, No. 6, pp. 531-554.

Bloch, F., 1996, "Sequential formation of coalitions with externalities and fixed payoff division", *Games and Economic Behavior*, Vol. 14, No. 1, pp. 90-123.

D'Aspremont, C. and Jacquemin, A., 1988, "Cooperative and non-cooperative R&D in duopoly with spillovers", *American Economic Review*, Vol. 78, No. 5, pp. 1133-1137

Falvey, R., Poyago-Theotoky, J. and Teerasuwannajak, K.T., 2010, *Costly research joint ventures : the role of coordination costs.*

Falvey, R., Poyago-Theotoky, J., Teerasuwannajak, K.T., 2013, "Coordination costs and research joint ventures", *Economic Modelling*, Vol. 33, pp. 965-976.

Finus, M., Rundshagen, B., Eyckmans, J., 2014, "Simulating a sequential coalition formation process for the climate change problem: first come, but second served?", *Annals of Operations Research*, Vol. 220, No. 1, pp. 5-23.

Greenlee, P. and Cassiman, B., 1999, "Product market objectives and the formation of research joint ventures", *Managerial and Decision Economics*, Vol. 20, No. 3, pp. 111-130.

Kamien, M.I., Muller, B. and Zang, I., 1992, "Research joint ventures and R&D Cartels", *American Economic Review*, Vol. 82, No. 5, pp. 1293-1306.

Poyago-Theotoky, J., 1995, "Equilibrium and optimal size of a research joint venture in an oligopoly with spillovers", *The Journal of Industrial Economics*, Vol. 43, No.2, pp. 209-225.

Poyago-Theotoky, J.,1999, "A note on endogenous spillovers in a non-tournament R&D duopoly", *Review of Industrial Organization*, Vol. 15, No. 3, pp. 253-262.

Suzumura, K., 1992, "Cooperative and noncooperative R&D in an oligopoly with spillovers", *American Economic Review*, Vol. 82, No. 5, pp. 1307-1320.

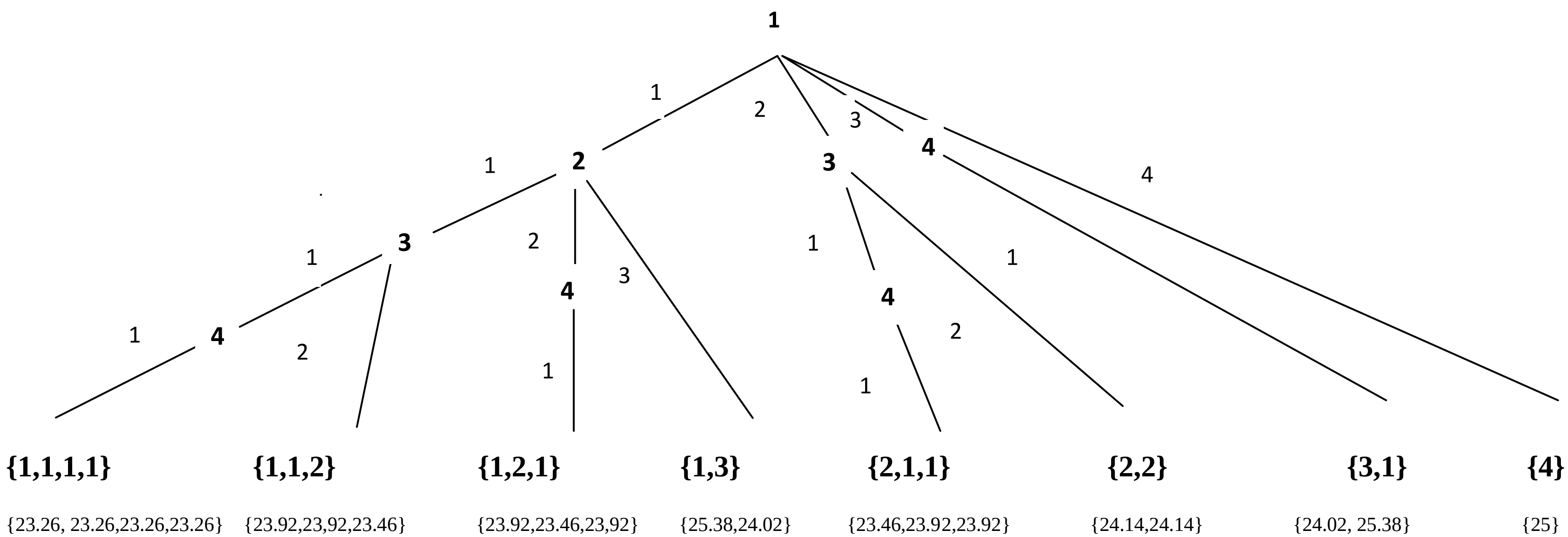
Yi, S., 1997, "Stable coalition structures with externalities", *Games and Economic Behavior*, Vol. 20, No. 2, pp. 201-237.

Greenlee, P., 2005, "Endogenous formation of competitive research sharing joint ventures", *The Journal of Industrial Economics*, Vol. 53, No. 3, pp. 355-391.

Yi, S. and Shin, H. 2000, "Endogenous formation of research coalitions with spillovers", *International Journal of Industrial Organization*, Vol. 18, No. 2, pp. 229-256.

Appendix

Figure 1. Size announcement game for N=4



A. Firm 1 announces size 4, an RJV with size 4 forms and the profit of each member is 25.

B. Firm 1 announces size 3, {3,1} forms, the profit of each firm inside the RJV is 24.02 and for the single firm is 25.38.

C. Firm 1 announces size 2, the next firm can announce either 2 or 1 and therefore {2,2} and {2,1,1} can form, but as the profit of the third firm under {2,1,1} is less than {2,2} (23.92<24.14), {2,1,1} will never form.

D. Firm 1 announces size 1, firm 2 can announce either 3, 2 or 1. If firm 2 announces size 1 the third firm can choose 2 or 1, but since the profit of the third firm under {1,1,1,1} is less than under {1,1,2} (23.26<23.46), {1,1,1,1} will not form. If firm 2 announces size 2, {1,2,1} forms and if it announces 3, {1,3} forms. Comparing {1,1,2}, {1,2,1} and {1,3}, firm 2 will achieve the highest profit under {1,3} (25.38>23.46, 25.38>23.92). So, if firm 1 announces size 1, {1,3} will always form.

Comparing the profit of RJVs under *A*, *B*, *C* and *D*, firm 1 will announce size 1 and the second firm will announce size 3. So, {1,3} is the subgame perfect Nash equilibrium.

General conclusion

In the first chapter of the thesis we studied a Stackelberg model in R&D and production markets. We incorporated coordination costs and considered the same functional form and assumptions for R&D cost function as Falvey et al. (2010). Then, we used numerical simulations to find the effects of R&D cooperation on R&D investments, production and profits of firms under different levels of coordination costs. The results indicate that with linear production costs, full information sharing and no R&D spillover, insiders gain higher profits compared with R&D competition. Moreover, the cooperative regime always yields higher welfare compared with no cooperation. The R&D investment incentives and profits of RJV members decrease with coordination costs. We also studied the effect of changes in coordination costs on the equilibrium and optimal sizes of the RJV. For a large enough number of leaders, the equilibrium size of the RJV is less than the optimal size. Except for large number of leaders and high coordination costs, in most cases the optimal size of the RJV is independent from coordination costs, but the equilibrium size of the RJV always decreases with them. These results remain unchanged when more followers are added to the model.

In the next step, as an extension of the model we assumed that RJV members cooperate in R&D only by jointly maximizing profits. Also, we assumed R&D spillovers between all leaders and from leaders to followers. The numerical simulations results showed that in this case, profits of RJV members are lower than outsider leaders, and therefore, they do not have an incentive to join the RJV and no RJV forms. In the last part, we discussed how the previous results change if production costs are convex. In this case, profits of insiders are always greater than outsiders' and their profits increase with accepting new members in the RJV. This means that outsiders always have an incentive and also are allowed by insiders to join the RJV. Therefore, an RJV containing all leaders forms.

In chapter two, we argued that firms' production may lead to environmental damage. For this purpose we studied a duopoly Cournot model. First, we studied the case where firms invest in product R&D and the emission tax is set exogenously. The results indicated that when the emission tax is low, for high levels of environmental damage and low R&D spillovers welfare is higher under cooperation; but when the emission tax is high for all levels of environmental damage and R&D spillovers, public R&D yields higher welfare than R&D cooperation. In the next part, we compared our findings with Petrakis and Poyago-Theotoky (2002) on R&D subsidisation. This comparison showed that for most parameter values public R&D leads to greater welfare than R&D subsidisation.

Further we discussed two scenarios where firms instead of process R&D undertake environmental R&D and the emission tax is set endogenously by the regulator. In the first scenario, the regulator determines the emission tax and public R&D before firms' choice of R&D investment (commitment). In this case, for low levels of R&D spillovers welfare is higher under public R&D than R&D cooperation and the reverse is true for high R&D spillovers. When the R&D spillover is high enough, for all levels of environmental damage, welfare is greater in the case of public R&D than R&D cooperation. In the second scenario, the regulator decides on the level of emission tax and public R&D investment after firms' decision on R&D investment (no commitment). In this scenario, R&D cooperation results in higher welfare with R&D cooperation for all levels of R&D spillovers and environmental damage. We compared R&D investment with and without the regulator's commitment. The results showed that under no commitment public R&D investment is higher than under commitment. Comparing commitment and no commitment also showed that commitment increases private R&D.

The third chapter analyzed a Cournot model where coalitions can form endogenously based on the size announcement game. Fist, we assumed that a coalition's members cooperate in R&D by maximizing their joint profit and that there are industry-wide R&D spillovers. The numerical simulations results indicate that with high enough coordination costs the equilibrium and optimal coalition structure is that no RJV forms. Second, we analyzed the case of intra-coalition full R&D cooperation and no industry-wide R&D spillovers. Based on numerical results, with high enough coordination costs, the equilibrium coalition structure is more concentrated than under low coordination cost. Also, with endogenous formation of coalitions under high enough coordination costs the size of the coalition structure is greater than when only one coalition is allowed to form exogenously. When coordination costs are high enough, the equilibrium coalition structure is more concentrated than the optimal coalition structure, while the opposite is true for low coordination costs.