Cooperative R&D between Heterogeneous Firms

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Abstract

In this paper I consider a two stage model of cooperative R&D where heterogeneous firms invest in product innovation. Firms invest to improve product quality in the first stage and compete *ă la* Bertrand in the second stage. Firms are heterogeneous in product quality *ex ante* and *ex post*. R&D outcomes are stochastic with a success probability an increasing function of R&D expenditure. R&D efforts are subject to spillovers. Using this model I analyze three R&D regimes: R&D competition, RJV cartelization, and RJV competition. In R&D competition, firms invest in R&D unilaterally to maximize their own profits. In RJV cartelization, firms fully share outcomes of R&D, and coordinate their R&D expenditures to maximize joint profit. In RJV competition, firms fully share outcomes of R&D as in RJV cartelization, but maximize individual profits. I compare the three regimes, focusing on R&D expenditure, the expected consumer surplus, and net profit. My analysis shows that firms benefit from cost savings but should give up an opportunity to exceed a rival firm in the RJV regimes. It also shows that consumers benefit from lower price but have new products less frequently in the RJV regimes than in R&D competition.

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1 Introduction

While the US government prohibits firms from colluding in the product market, it allows cooperation in research and development (R&D). The National Cooperative Research Act was enacted in 1984, providing government support to joint research ventures (RJV). As long as the venture's membership is not over-inclusive, meaning that a sufficient number of firms are left outside the venture, firms are allowed to co-operate in R&D. A prominent example of such an RJV is SEMATECH, a joint research consortium in the semiconductor industry.

Literature on cooperative R&D supports this policy. D'Aspremont and Jacquemin (1988) (hereafter AJ) show that both firms and consumers are better off when firms cooperate in R&D than when they unilaterally invest in R&D. They use a two-stage game model where two identical firms invest to reduce the cost of production in the first stage and compete *á la* Cournot in the second stage. A cost function is defined such that a dollar of R&D expenditure reduces the unit cost by one dollar and reduces a rival firm's cost by less than a dollar. Cooperative R&D is defined as coordinating R&D expenditure to maximize joint profits. They show that with a high level of spillover cooperative R&D results in higher R&D expenditures, profits, and consumer surplus than competitive R&D.

Kamien, Muller, and Zang (1992) (hereafter KMZ) extend AJ model. In particular, they compare four R&D regimes: R&D competition, R&D cartelization, RJV competition, and RJV cartelization. They define RJV as a regime where a spillover rate takes its maximum value, and cartelization as a regime where firms maximize joint profits. Hence, in R&D competition the spillover rate is less than the maximum and firms unilaterally invest in R&D, while in R&D cartelization the spillover rate is less than the maximum but firms coordinate their R&D expenditures to maximize joint profits. They show that profits and total surplus are higher in RJV cartelization than the other three regimes.

In these two models firms are identical *ex ante,* producing homogeneous products at the same unit cost. R&D is for the process innovation and its outcomes are deterministic. While this setting is mostly favored for analytical convenience, a model of heterogeneous firms investing in product innovation has been scarcely explored.[1]

[1] The case of heterogeneous firms investing for process innovation is analyzed by Roller et.al. (2002) and Dakhlia et.al.

In this paper I consider a two stage model of research joint ventures where heterogeneous firms invest in product innovation. Firms invest to improve product quality in the first stage and compete *á la* Bertrand in the second stage. Firms are heterogeneous in terms of product quality *ex ante* and *ex post*. My model can accommodate the process innovation with slight modifications, in which case firms invest to reduce the unit cost and are heterogenous in terms of the unit cost.

Following Ericson and Pakes (1995) and Pakes and McGuire (1994), I use state variables to represent firm heterogeneity. A firm's state is a level of its product quality, and its profit is determined by its current state as well as its rivals'.

I model R&D success as a stochastic event with its probability being an increasing function of R&D expenditure. Each firm decides how much to spend in R&D to maximize its expected net profit, which is equal to the expected profit in the second-stage minus R&D expenditure in the first stage. The equilibrium R&D expenditure, in turn, determines the probability of R&D success. A firm's state changes depending on R&D outcomes, and a higher R&D expenditure ensures a more favorable distribution of states.

Marjit (1991) and Combs (1992) examine how the probability of R&D success affects firms' incentives to cooperate in R&D. However, both authors treat the probability of R&D success as an exogenous variable so it does not depend on how much firms invest. Choi (1993) treats the probability of R&D success as an increasing function of R&D expenditure. Cooperative R&D in his model corresponds to R&D cartelization in KMZ. His analysis focuses on imitation in the product market and is confined to symmetric equilibrium.

In my model firms benefit from other firms' R&D efforts by spillover. A spillover parameter is incorporated into the probability function such that an increase in a firm's R&D expenditure raises the probability of the other firm's R&D success. Hence, the probabilities of two firms' R&D success are correlated, while they are independent of each other without spillover.

I analyze three R&D regimes: R&D competition, RJV cartelization, and RJV competition. In R&D competition, each firm invests in R&D unilaterally to maximize its own profit. In RJV cartelization, firms fully share outcomes of R&D, and coordinate their R&D expenditures to maximize the sum of profits. In RJV competition, firms fully share outcomes of R&D as in RJV cartelization, but set R&D expenditures to

(2003). Roller et.al. (2002) consider RJVs between firms with different marginal costs, based on KMZ model. Dakhlia et.al. (2003) analyze asymmetric equilibria in two stage process innovation games, extending AJ and KMZ models.

maximize individual profits.

I follow KMZ to distinguish between RJV cartelization and RJV competition. That is, in RJV cartelization participating firms maximize joint profits, while in RJV competition participants maximize their own profits. However, I distinguish RJV regimes from R&D competition differently from their model. In KMZ model the spillover rate takes the maximum value in RJV regimes so that firms fully benefit from other firms' R&D efforts. In my model, RJV participants share outcomes of R&D by sharing a single probability of R&D success.

A few remarks are in order. First, as RJV participants share a single probability of R&D success, there are only two events in the second stage of the RJV regimes: either (1) both firms succeed or (2) neither succeed. In R&D competition there are four possible events in the second stage: (1) firm 1 succeeds and firm 2 fails, (2) firm 1 fails and firms 2 succeeds, (3) both firms succeed, and (4) neither firms succeed.

Second, I set up the probability function in the RJV regimes such that the industry-wide probability of R&D success is the same as in R&D competition if the total R&D expenditure is the same. This includes all cases where firms fully share stochastic outcomes of R&D, whether they run a single research lab or two separate research labs.

Third, I consider the degree of spillover as a characteristic of technology so it does not vary among different regimes. For example, generic technology may lead to more spillover than applied technology whether firms cooperate or not. It is analogous to AJ model, but different from KMZ model in which the degree of spillover is higher in the RJV regimes.

Last, I assume that firms compete in the product market in all regimes. Although some research has been done on whether an RJV facilitates the product market collusion among participants, I do not consider this possibility in this paper.[2]

In order to compare my model with the previous literature, I first analyze the symmetric equilibrium where firms are identical *ex ante* in the R&D stage. The analysis of the pure-strategy subgame-perfect Nash equilibrium shows that R&D expenditure is highest in R&D competition and the second highest in RJV cartelization. It also shows that the industry-wide probability of R&D success is highest in R&D competition,

[2] Lambertini, et.al. (2002), Martin (1995), and Miyagiwa (2005) consider this issue.

followed by RJV cartelization.

However, higher R&D expenditure does not necessarily lead to higher (expected) consumer surplus, or to higher (expected) net profits. Unless firms' states are in a "high" range of states, RJV cartelization generates the highest consumer surplus and R&D competition generates the lowest consumer surplus. And the net profit is highest in RJV cartelization and lowest in R&D competition for all states. The results are, to some extent, consistent with those of AJ and KMZ which also show that both consumers and firms are better off when firms cooperate in R&D.

An important difference is that my results do not depend on the spillover effect. In AJ and KMZ models, cooperative R&D solves the underinvestment problem by internalizing the spillover effect. However, in my model the effect of eliminating R&D duplications, which lowers R&D expenditure, dominates the effect of internalizing externalities, which as a result increases R&D expenditure.

To analyze asymmetric equilibrium, I compute the subgame-perfect Nash equilibrium R&D expenditure for all combinations of state variables. I consider two extreme cases regarding how a firm improves its product quality. In one case, which I call a no-leapfrogging case, a firm improves product quality by one unit when its R&D is successful. In the other case, which I call a leapfrogging case, a firm with lower product quality can improve product quality up to the highest level with successful R&D. The highest level is one unit higher than the current product quality of the other firm.

Numerical analysis shows that the two cases have different implications for consumer surplus and profit. For example, in the no leapfrogging case a low quality firm is always better off in the RJV regimes than in R&D competition because its cost saving in RJVs is greater than its (expected) gain from solely succeeding in R&D in R&D competition. In the leapfrogging case, on the other hand, a high quality firm is always better off in the RJV regimes since it is protected from being leapfrogged in RJVs.

My model can be extended to a dynamic model where the two-stage game is repeated infinitely and firms maximize the net expected value of future cash flow. Song (2005) applies a dynamic version of this model to assess firms' research cooperation in the semiconductor industry. Firms' states are estimated using product market data, and additional state variables are introduced to mimic the evolution of the semiconductor industry.

In this paper I consider the two period model but analyze firms' behaviors under more general circumstances instead of confining them to estimated states. Also, I compare the model to other cooperative R&D models which are usually presented in two period settings.

The rest of the paper is organized as follows: Section 2 describes the model. Section 3 analyzes symmetric equilibrium, followed by analysis of asymmetric equilibrium in section 4. Section 5 concludes.

2 Model

Consider a two stage game in which two firms invest in R&D in the first stage and compete in the product market in the second stage. R&D outcomes are stochastic with the probability of R&D success being a function of how much they invest in the first stage. Firms compete *á la* Bertrand with different quality products. A firm's payoff is equal to the expected profit from the product market minus R&D expenditures in the first stage.

Firm heterogeneity is represented by states, and successful R&D puts a firm in a more favorable state. Since R&D outcomes are stochastic, a higher R&D expenditure, instead of guaranteeing for a more favorable state, ensures a more favorable distribution in the product market.

I limit the number of firms to two. An interesting extension of the model is to increase the number of firms to three or more, and analyze the choice of R&D partners and its effect on firms left outside joint ventures. I also limit my analysis to no collusion in the product market.

2.1 R&D Investment

I consider three regimes of R&D investment: R&D competition (case N), RJV cartelization (case CJ), and RJV competition (case NJ). In R&D competition, each firm makes R&D decisions unilaterally to maximize the expected discounted value of profits. In the RJV cartelization, firms fully share the cost and result of their R&D efforts, and coordinate their R&D expenditures to maximize the sum of their profits. In RJV competition, firms decide on R&D expenditures to maximize their individual profits, but fully share the cost and result of their R&D efforts.

I assume that the probability of R&D success is an increasing concave function of R&D expenditures, x, with $p(0) = 0$ and $\lim_{x\to\infty} p(x) = 1$. Although any probability functions that satisfy these properties can be used, I pick up the following function for the analytical and computational convenience.

Assumption 1 *Given firm j's R&D expenditure, x_j, the probability of firm i's R&D success is*

$$p_i = \frac{a_i x_i + \sigma a_i a_j x_i x_j}{1 + a_i x_i + a_j x_j + \sigma a_i a_j x_i x_j}, \tag{1}$$

where x_i is firm i's R&D expenditure, which is constrained to take non-negative values, a_i is firm i's efficiency level, and σ represents a degree of spillover with $\sigma \geq 1$.

The efficiency level represents a firm's ability to transfer R&D expenditure into the likelihood of R&D success. A more efficient firm attains a higher probability of R&D success with the same R&D expenditure.

The degree of spillover indicates how much one firm benefits from the other firm's R&D expenditure. With $\sigma > 1$, firm i's probability of R&D success increases as firm j increases its R&D expenditure.[3] The probability functions of the two firms, *i.e.*, p_i and p_j, are positively correlated by the presence of σ, and the level of σ indicates how closely they are correlated.[4] When there is no spillover, *i.e.*, $\sigma = 1$, the probability function becomes

$$p_i = \frac{a_i x_i}{1 + a_i x_i}, \tag{2}$$

which implies that the two firms' probabilities of R&D success are independent of each other.

When firms form a research joint venture (RJV), I assume that participants share the single probability function of R&D success, which has the following functional form.

Assumption 2 *When firms form a research joint venture (RJV), the probability of R&D success is*

$$p^J = \frac{a_i x_i + a_j x_j + \sigma a_i a_j x_i x_j}{1 + a_i x_i + a_j x_j + \sigma a_i a_j x_i x_j}. \tag{3}$$

This functional form ensures that the industry-wide probability of R&D success is the same, whether firms compete or cooperate in R&D, if the total R&D expenditure is equal. In other words, for the same

[3] One can verify this by showing that

$$\frac{\partial p_i}{\partial x_j} = \frac{(\sigma - 1) a_i a_j x_i}{(1 + a_i x_i + a_j x_j + \sigma a_i a_j x_i x_j)^2} \geq 0, \text{ for } \sigma \geq 1.$$

[4] While, in both AJ and KMJ models, one firm's R&D expenditure directly contributes to reducing the other firm's marginal cost of production, in my model one firm's R&D expenditure only affects the likelihood of the other firm's R&D success.

research expenditures by two firms,

$$p^J(x_1, x_2) = p_1(x_1, x_2) + p_2(x_1, x_2) - p_b(x_1, x_2) \tag{4}$$

where p_b is the probability that both firms succeed at the same time in R&D competition.

There are only two events in the second stage of the RJV case. Either (1) both firms succeed or (2) neither succeed. In R&D competition there are four possible events in the second stage, which are (1) firm 1 succeeds and firm 2 fails, (2) firm 1 fails and firms 2 succeeds, (3) both firms succeed, or (4) neither succeed.

R&D Competition (Case N) A firm's objective function is equal to the expected profits minus R&D expenditure.

$$V_1^N = -x_1 + \beta\left(p_1\pi_1^1 + p_2\pi_2^1 + p_{both}\pi_{both}^1 + p_{none}\pi_{none}^1\right) \tag{5a}$$

$$V_2^N = -x_2 + \beta\left(p_1\pi_1^2 + p_2\pi_2^2 + p_{both}\pi_{both}^2 + p_{none}\pi_{none}^2\right) \tag{5b}$$

where

$$\begin{aligned}
p_1 &= \Pr(\text{firm 1 succeeds, firm 2 fails}) = \frac{a_1x_1}{1 + a_1x_1 + a_2x_2 + \sigma a_1a_2x_1x_2}, \\
p_2 &= \Pr(\text{firm 2 succeeds, firm 1 fails}) = \frac{a_2x_2}{1 + a_1x_1 + a_2x_2 + \sigma a_1a_2x_1x_2}, \\
p_{both} &= \Pr(\text{both firms succeed}) = \frac{\sigma a_1a_2x_1x_2}{1 + a_1x_1 + a_2x_2 + \sigma a_1a_2x_1x_2}, \\
p_{none} &= \Pr(\text{neither firms succeed}) = \frac{1}{1 + a_1x_1 + a_2x_2 + \sigma a_1a_2x_1x_2},
\end{aligned}$$

π_1^i is firm i's variable profit when firm 1 succeeds and firm 2 fails in R&D, π_2^i is firm i's variable profit when firm 2 succeeds and firm 1 fails in R&D, π_{both}^i is firm i's variable profit when both firms succeed in R&D, π_{none}^i is firm i's variable profit when none succeed in R&D, and β is a discount rate.

Differentiating V_i with respect to x_i gives the first order conditions as

$$
\begin{aligned}
1 &= a_1 p_{none}^2 \triangle\pi^1, && (6a)\\
1 &= a_2 p_{none}^2 \triangle\pi^2, && (6b)
\end{aligned}
$$

where $\triangle\pi^1 = [(1+a_2x_2)\left(\pi_1^1 + a_2x_2\sigma\pi_{both}^1\right) - (1+a_2x_2\sigma)\left(a_2x_2\pi_2^1 + \pi_{none}^1\right)]$ and $\triangle\pi^2 = [(1+a_1x_1)\left(\pi_2^2 + a_1x_1\sigma\pi_{both}^2\right) - (1+a_1x_1\sigma)\left(a_1x_1\pi_1^2 + \pi_{none}^2\right)]$.

The equilibrium R&D expenditures are solutions to equations ($6a$) and ($6b$), and they satisfy the following relationship.

$$x_i^N = \max\left\{\frac{1}{a_i(1+a_jx_j^N\sigma)}\sqrt{a_i\beta\triangle\pi^i} - \frac{1+a_jx_j^N}{a_i(1+a_jx_j^N\sigma)},\ 0\right\}, \tag{7}$$

where $\triangle\pi^i = [(1+a_jx_j^N)\left(\pi_i^i + a_jx_j^N\sigma\pi_{both}^i\right) - (1+a_jx_j^N\sigma)\left(a_jx_j^N\pi_j^i + \pi_{none}^i\right)]$, and superscript N represents R&D competition (case N). When there is no spillover, the equilibrium R&D expenditure is simplified to

$$x_i^N = \max\left\{\frac{\sqrt{\beta\left(\left(\pi_i^i - \pi_{none}^i\right) + a_jx_j^N\left(\pi_{both}^i - \pi_j^i\right)\right)}}{\sqrt{a_i\left(1+a_jx_j^N\right)}} - \frac{1}{a_i},\ 0\right\} \tag{8}$$

RJV Cartelization (Case CJ) In RJV cartelization firms participating to an RJV cartel solve the following problem in determining R&D expenditure.

$$\max\left[-x_1 - x_2 + \beta\left(p^J\left(\pi_{both}^1 + \pi_{both}^2\right) + \left(1-p^J\right)\left(\pi_{none}^1 + \pi_{none}^2\right)\right)\right] \tag{9}$$

where $p^J = \frac{a_1x_1 + a_2x_2 + \sigma a_1a_2x_1x_2}{1 + a_1x_1 + a_2x_2 + \sigma a_1a_2x_1x_2}$.

Given that R&D expenditure is non-negative, the equilibrium R&D expenditure levels are determined by the following first order conditions.

$$
\begin{aligned}
1 &= \beta a_1\left(1+\sigma a_2x_2^{CJ}\right)\left(1-p^{CJ}\right)^2\left(\left(\pi_{both}^1 - \pi_{none}^1\right) + \left(\pi_{both}^2 - \pi_{none}^2\right)\right), && (10a)\\
1 &= \beta a_2\left(1+\sigma a_1x_1^{CJ}\right)\left(1-p^{CJ}\right)^2\left(\left(\pi_{both}^1 - \pi_{none}^1\right) + \left(\pi_{both}^2 - \pi_{none}^2\right)\right). && (10b)
\end{aligned}
$$

where $p^{CJ} = \frac{a_1 x_1^{CJ} + a_2 x_2^{CJ} + \sigma a_1 a_2 x_1^{CJ} x_2^{CJ}}{1 + a_1 x_1^{CJ} + a_2 x_2^{CJ} + \sigma a_1 a_2 x_1^{CJ} x_2^{CJ}}$ and CJ represents RJV cartelization. These conditions give a rule for how much each firm contributes to RJV as

$$x_2^{CJ} = x_1^{CJ} + \frac{1}{\sigma}\left(\frac{1}{a_1} - \frac{1}{a_2}\right). \tag{11}$$

It implies that a firm whose R&D efficiency, a_i, is higher should spend $\frac{1}{\sigma}\left(\frac{1}{a_j} - \frac{1}{a_i}\right)$ more for R&D, where $a_i \geq a_j$.

Equation (11) shows that a firm's contribution to RJV does not depend on its gain from R&D success. Instead, it is determined by which firm is more efficient in transferring R&D efforts to R&D success. This is because firms in RJV cartel are only concerned about the total benefit, not the individual profit, from R&D success.

The equilibrium R&D expenditure for firm 1 is obtained by solving (11) and (10a) simultaneously, and it satisfies

$$1 = \frac{\beta\sigma^2 a_1^2 a_2 \left(1 + \sigma a_1 x_1^{CJ}\right)\left[\left(\pi_{both}^1 - \pi_{none}^1\right) + \left(\pi_{both}^2 - \pi_{none}^2\right)\right]}{\left(\left(\sigma - 1\right) a_1 + a_2 + 2a_1 a_2 \sigma x_1^{CJ} + \sigma^2 a_1^2 a_2 \left(x_1^{CJ}\right)^2\right)^2}. \tag{12}$$

Then equation (11) determines the equilibrium R&D expenditure for firm 2.

When $\sigma = 1$, equation (12) is simplified to

$$1 = \frac{\beta a_1^2 \left[\left(\pi_{both}^1 - \pi_{none}^1\right) + \left(\pi_{both}^2 - \pi_{none}^2\right)\right]}{a_2 \left(1 + a_1 x_1\right)^3}, \tag{13}$$

and the equilibrium R&D expenditures are

$$x_1^{CJ} = \max\left\{\left(\frac{\beta\left[\left(\pi_{both}^1 - \pi_{none}^1\right) + \left(\pi_{both}^2 - \pi_{none}^2\right)\right]}{a_1 a_2}\right)^{\frac{1}{3}} - \frac{1}{a_1}, 0\right\} \text{ and} \tag{14a}$$

$$x_2^{CJ} = \max\left\{\left(\frac{\beta\left[\left(\pi_{both}^1 - \pi_{none}^1\right) + \left(\pi_{both}^2 - \pi_{none}^2\right)\right]}{a_1 a_2}\right)^{\frac{1}{3}} - \frac{1}{a_2}, 0\right\}. \tag{14b}$$

RJV Competition (Case NJ) In RJV competition participating firms share the probability of R&D success as in RJV cartelization, but the equilibrium R&D expenditure is

$$x_i^{NJ} = \arg\max -x_i + \beta\left(p^J \pi_{both}^i + \left(1 - p^J\right)\pi_{none}^i\right) \tag{15}$$

where $i = 1$ and 2, and NJ represents the RJV competition case.

The first order conditions are

$$1 = \beta a_1\left(1 + \sigma a_2 x_2^{NJ}\right)\left(1 - p^{NJ}\right)^2\left(\pi_{both}^1 - \pi_{none}^1\right), \tag{16a}$$

$$1 = \beta a_2\left(1 + \sigma a_1 x_1^{NJ}\right)\left(1 - p^{NJ}\right)^2\left(\pi_{both}^2 - \pi_{none}^2\right), \tag{16b}$$

where $p^{NJ} = \frac{a_1 x_1^{NJ} + a_2 x_2^{NJ} + \sigma a_1 a_2 x_1^{NJ} x_2^{NJ}}{1 + a_1 x_1^{NJ} + a_2 x_2^{NJ} + \sigma a_1 a_2 x_1^{NJ} x_2^{NJ}}$. Given that

$$\left(\pi_{both}^i - \pi_{none}^i\right) \geq 0, \quad i = 1, 2, \tag{17}$$

the equilibrium R&D expenditure satisfies

$$\frac{a_1\left(1 + \sigma a_2 x_2^{NJ}\right)}{a_2\left(1 + \sigma a_1 x_1^{NJ}\right)} = \frac{\left(\pi_{both}^2 - \pi_{none}^2\right)}{\left(\pi_{both}^1 - \pi_{none}^1\right)}. \tag{18}$$

and this can be rewritten as

$$x_2^{NJ} = \frac{1}{\sigma}\left(\frac{1}{a_1}\frac{\left(\pi_{both}^2 - \pi_{none}^2\right)}{\left(\pi_{both}^1 - \pi_{none}^1\right)} - \frac{1}{a_2}\right) + \frac{\left(\pi_{both}^2 - \pi_{none}^2\right)}{\left(\pi_{both}^1 - \pi_{none}^1\right)} x_1^{NJ}. \tag{19}$$

It shows that, unlike in RJV cartelization, a firm's contribution to RJV depends on its relative gain from R&D success. Even when the efficiency level is the same for both firms, *i.e.*, $a_1 = a_2$, a firm with a higher gain from R&D success contributes more to RJV.

The equilibrium R&D expenditure for firm 1 is obtained by solving ($16a$) and (19) simultaneously, and equation (19) determines the equilibrium R&D expenditure for firm 2.

When $\sigma = 1$, the equilibrium R&D expenditure levels are

$$x_1^{NJ} = \begin{cases} \max\left\{ \left(\frac{\beta(\pi^1_{both} - \pi^1_{none})^2}{a_1 a_2 (\pi^2_{both} - \pi^2_{none})} \right)^{\frac{1}{3}} - \frac{1}{a_1}, 0 \right\}, & if \ \left(\pi^1_{both} - \pi^1_{none}\right) > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{20a}$$

$$x_2^{NJ} = \begin{cases} \max\left\{ \left(\frac{\beta(\pi^2_{both} - \pi^2_{none})^2}{a_1 a_2 (\pi^1_{both} - \pi^1_{none})} \right)^{\frac{1}{3}} - \frac{1}{a_2}, 0 \right\}, & if \ \left(\pi^2_{both} - \pi^2_{none}\right) > 0, \\ 0, & \text{otherwise}. \end{cases} \tag{20b}$$

2.2 Product Market

The state space is confined to one dimension with the state variable representing product quality. Successful R&D puts a firm in a more profitable state in the second stage of the game. I choose the profit function such that a higher state variable generates a higher profit. Although a firm moves to a more profitable state in multiple ways, I consider two cases regarding this transition: (1) leapfrogging and (2) no leapfrogging.

In the leapfrogging case, I assume that a firm that succeeds in R&D jumps to "the most profitable state" - the state whose level is one unit higher than the current highest state level. For example, suppose that firm 1's state is higher than firm 2's. If firm 2 succeeds in R&D and firm 1 fails, firm 2 jumps to the state that is one unit higher than firm 1's current state and firm 1 stays at its current state. If firm 1 succeeds in R&D and firm 2 fails, firm 1 moves up to the next state level and firm 2 stays at its current state. If both firms succeed in R&D, they jump to the most profitable state at the same time. In the no leapfrogging case, I assume that the state of a firm that succeeds in R&D increases by one unit. In this case a firm at a lower state level cannot "pass" a firm at a higher level with one time R&D success.

A profit function is based on a discrete choice model of differentiated product demand. The indirect utility of consumer i from buying product j is

$$u_{ij} = \delta_j - price_j + \varepsilon_{ij} \tag{21}$$

where δ_j indexes quality of product j, $price_j$ its price, and ε_{ij} a *i.i.d.* random variable drawn from the Type I extreme value distribution.

The market share of product j is defined as

$$s_j = \frac{\exp(\delta_j - price_j)}{1 + \sum_{n=1}^{N} \exp(\delta_n - price_n)} \tag{22}$$

where N is the number of products in the market. Assuming that firms produce one product each, a variable profit is

$$\pi_j = (price_j - mc_j)\, M s_j \tag{23}$$

where M is the number of consumers in the market and mc_j is the marginal cost of producing product j. The profit function ensures that higher product quality - a higher state variable - generates higher variable profit.[5]

3 Analysis of Symmetric Equilibrium

I first analyze the symmetric equilibrium where firms are at the same state level in the R&D stage. In R&D competition firms may move to different state levels in the second stage, depending on R&D outcomes. In the two RJV cases, firms are at the same state level in both stages of the game. Moreover, it makes no difference between the leapfrogging and the no leapfrogging cases.

With identical firms

[5] For an industry where firms produce homogeneous products at different unit costs and invest in R&D to reduce unit cost, a cost function should satisfy

$$\frac{\partial \pi}{\partial \omega} > 0$$
$$\frac{\partial^2 \pi}{(\partial \omega)^2} < 0$$

where ω is the state variable. An example is $mc = \exp(-\omega)$.

$$\pi_{own} = \pi_1^1 = \pi_2^2$$

$$\pi_{rival} = \pi_2^1 = \pi_1^2$$

$$\pi_{both} = \pi_{both}^1 = \pi_{both}^2 = \pi_{both}^{CJ} = \pi_{both}^{NJ}$$

$$\pi_{none} = \pi_{none}^1 = \pi_{none}^2 = \pi_{none}^{CJ} = \pi_{none}^{NJ}$$

$$cs_{both} = cs_{both}^N = cs_{both}^{CJ} = cs_{both}^{NJ}$$

$$cs_{none} = cs_{none}^N = cs_{none}^{CJ} = cs_{none}^{NJ}$$

$$a = a_1 = a_2$$

where cs_{both} denotes consumer surplus when both firms succeed in R&D and cs_{none} denotes consumer surplus when no firm succeeds in R&D.

Assumption 3 *When firms are identical ex ante,*
(i)

$$\pi_{own} > \pi_{both} > \pi_{none} > \pi_{rival}$$

(ii)

$$cs_{both} > cs_{one} > cs_{none}$$

where cs_{one} is consumer surplus when only one firm succeeds in R&D.
(iii)

$$a = 1.$$

The first part says that a firm earns the highest variable profit when it solely succeeds in R&D, the second highest variable profit when both firms succeed in R&D at the same time, and the lowest variable profit when only its rival succeeds in R&D. The second part says that consumers are better off when both firms succeed in R&D than only one firm does, and worse off when no firm succeeds. Consumers benefit from higher product quality when at least one firm succeeds but benefit more when both firms succeed because of lower price. The third assumption is merely for analytical convenience.

Proposition 1 (Existence of symmetric equilibrium) *When firms are identical ex ante,*
(i) there exists non-negative $x^N \left(= x_1^N = x_2^N\right)$ that satisfies (6a) and (6b) if $(\pi_{own} - \pi_{none}) \geq \frac{1}{\beta}$,
(ii) there exists non-negative $x^{CJ} \left(= x_1^{CJ} = x_2^{CJ}\right)$ that satisfies (10a) and (10b) if $(\pi_{both} - \pi_{none}) \geq \frac{1}{2\beta}$, and
(iii) there exists non-negative $x^{NJ} \left(= x_1^{NJ} = x_2^{NJ}\right)$ that satisfies (16a) and (16b) if $(\pi_{both} - \pi_{none}) \geq \frac{1}{\beta}$.
Proof. *See Appendix.* ■

The proposition says that, as long as $(\pi_{both} - \pi_{none})$ is not too small, there exists a non-negative equilibrium R&D expenditure in all regimes, and that the sufficient condition for all regimes to have the non-negative equilibrium R&D expenditure is $(\pi_{both} - \pi_{none}) \geq \frac{1}{\beta}$. Note that this result does not depend on how firms compete in the product market or which profit function is chosen.

Proposition 2 (Comparison of R&D expenditure) *Suppose* $(\pi_{both} - \pi_{none}) \geq \frac{1}{\beta}$. *Then,*

$$\begin{array}{lll} (i) \ \ x^{N} & > & x^{NJ} \\ (ii) \ x^{CJ} & > & x^{NJ} \\ (iii) \ x^{N} & > & x^{CJ}, \ if \ x^{N} \geq 1. \end{array}$$

Proof. *See Appendix.* ■

This proposition says that, when firms are identical *ex ante*, firms in R&D competition and RJV cartelization invest more than firms in RJV competition. Firms in R&D competition invest more than firms in RJV cartelization if $x^N \geq 1$. There are two sources of higher R&D expenditure in R&D competition. First, firms do not eliminate duplication of R&D efforts so that they invest more for the same expected profit. Second, the expected benefit from R&D success is higher because of the possibility that only one firm succeeds.

Figure 1 shows R&D expenditure in the three regimes. It is drawn in (δ, σ) space where δ represents product quality and σ represents the degree of spillover. The marginal cost (mc_j) is set to $\delta_j/10$, the market size (M) to $3,000$ and the discount rate to 0.97. The figure shows that R&D expenditure is more sensitive to the degree of spillover in R&D competition than in the two RJV cases. A higher degree of spillover reduces firms' R&D efforts in all regimes as lower R&D efforts can achieve the same likelihood of R&D success. However, when firms compete in R&D, they do not internalize positive externalities created by the spillover effect. Hence, a firm decreases its R&D expenditure much more than in the RJV regimes to prevent its rival from benefiting from its R&D efforts.

The figure also shows that R&D expenditure is less sensitive to changes in the state level in R&D competition. R&D expenditure decreases as firms move up to higher states, because the expected return from R&D success diminishes with an increase in product quality. However, when firms compete in R&D, the expected return does not diminish as much as in the RJV regimes because of the possibility that only one firm succeeds.[6]

Figure 2 illustrates proposition 2 by comparing R&D expenditure in Figure 1 at $\sigma = 1$ and $\sigma = 10$. Although the difference becomes smaller at a higher level of σ, firms in R&D competition invest more

[6] Proposition 1 does not say anything about the uniqueness of equilibrium. However, the equilibrium is unique for the product market models I use, and, moreover, the subsequent propositions hold true even with multiple equilibria.

aggressively over the whole range of the state, and firms in the RJV regimes reduce their R&D expenditure drastically at higher state levels.

Corollary 1 *When firms are identical ex ante,*

$$\begin{aligned}(i)\ 1-p^N_{none} &> 1-p^{NJ}_{none}\\ (ii)\ 1-p^{CJ}_{none} &> 1-p^{NJ}_{none}\\ (iii)\ 1-p^N_{none} &> 1-p^{CJ}_{none},\ \text{if } x^N \geq 1,\end{aligned}$$

where $p^N_{none} = \frac{1}{1+2x^N+\sigma(x^N)^2}$, $p^{CJ}_{none} = \frac{1}{1+2x^{CJ}+\sigma(x^{CJ})^2}$, *and* $p^{NJ}_{none} = \frac{1}{1+2x^{NJ}+\sigma(x^{NJ})^2}$.

The corollary implies that the industry-wide probability of R&D success is higher when firms compete in R&D than when firms cooperate. Proposition 2 and corollary 1 show that in R&D competition firms spend more in R&D and the probability of R&D success at the industry level is higher than in the RJV regimes. This is in contrast with both AJ and KMZ models where firms spend more in R&D when they form an RJV.

However, in my model higher R&D expenditure does not necessarily result in higher consumer welfare or higher profit. Table 1 compares (the expected) consumer surplus between the RJV regimes and R&D competition, using the same parameter values as in Figure 1. $+$ indicates that consumer surplus is higher in the RJV regimes than in R&D competition. $\oplus$ indicates that it is higher in RJV cartelization but not in RJV competition than in R&D competition. $-$ indicates that it is higher in R&D competition than in the two RJV regimes. Therefore, consumer surplus is higher in RJV cartelization than in R&D competition at both $+$ and $\oplus$, and it is higher in RJV competition than in R&D competition at only $+$.

The table shows that R&D competition results in higher consumer surplus only at high state levels. Consumers prefer both higher quality and lower price. R&D competition is more likely to introduce new products, but consumers pay a higher price when only one firm succeeds in R&D. Therefore, as long as the probability of R&D success is not so much lower than in R&D competition, consumers are better off in the RJV regimes as a gain from a lower price exceeds a loss from a lower probability of having new products.

Table 2 compares (the expected) producer surplus between R&D competition and the RJV regimes in the same manner as in table 1. It shows that R&D competition results in higher producer surplus only at high state levels, although the area of higher producer surplus is much larger than that of higher consumer surplus.

Nevertheless, (the expected) net profit is always higher in the RJV regimes. This is because firms in R&D competition invest "too much" as they move up to higher states. There is a trade-off for firms in the RJV regimes. They benefit from lower R&D expenditure for the same probability of R&D success, but they do not have an opportunity to exceed a rival firm. However, the higher net profit in the RJV regimes suggests that the cost saving dominates the foregone opportunity to become a leader.

Between the two RJV regimes RJV cartelization always results in higher consumer surplus and producer surplus than RJV competition.

Proposition 3 *When firms are identical ex ante,*

$$\begin{aligned} (i)\ E\left(cs^{CJ}\right) &> E\left(cs^{NJ}\right), \\ (ii)\ E\left(ps^{CJ}\right) &> E\left(ps^{NJ}\right), \end{aligned}$$

where cs is consumer surplus and ps producer surplus.

Proof. (i) Let $cs_{both} = cs^{CJ}_{both} = cs^{NJ}_{both}$ and $cs_{none} = cs^{CJ}_{none} = cs^{NJ}_{none}$. Since $E\left(cs^l\right) = p^l cs^l_{both} + \left(1-p^l\right) cs^l_{none}$, where $l = CJ,\ NJ$,

$$\begin{aligned} E\left(cs^{CJ}\right) - E\left(cs^{NJ}\right) &= \left(p^{CJ} - p^{NJ}\right) cs_{both} - \left(p^{CJ} - p^{NJ}\right) cs_{none} \\ &= \left(p^{CJ} - p^{NJ}\right) \left(cs_{both} - cs_{none}\right) > 0. \end{aligned}$$

Hence, $E\left(cs^{CJ}\right) > E\left(cs^{NJ}\right)$.

(ii) Let $\pi_{both} = \pi^{CJ}_{both} = \pi^{NJ}_{both}$ and $\pi_{none} = \pi^{CJ}_{none} = \pi^{NJ}_{none}$. Since $E\left(ps^l\right) = p^l ps^l_{both} + \left(1-p^l\right) ps^l_{none} = 2p^l \pi^l_{both} + 2\left(1-p^l\right)\pi^l_{none}$, where $l = CJ,\ NJ$,

$$\begin{aligned} E\left(ps^{CJ}\right) - E\left(ps^{NJ}\right) &= 2\left(p^{CJ} - p^{NJ}\right)\pi_{both} - 2\left(p^{CJ} - p^{NJ}\right)\pi_{none} \\ &= 2\left(p^{CJ} - p^{NJ}\right)\left(\pi_{both} - \pi_{none}\right) > 0. \end{aligned}$$

Hence, $E\left(ps^{CJ}\right) > E\left(ps^{NJ}\right)$. ■

Firms invest more in RJV cartelization. This raises the probability of R&D success, which in turn benefits consumers. For the same reason producer surplus is higher in RJV cartelization. Higher R&D expenditure offsets higher producer surplus, but given the range of the state variable the net profit is also higher in RJV cartelization than in RJV competition.

4 Analysis of Asymmetric Equilibrium

In this section I relax the assumption of identical firms. Firms are located at different state levels in the first stage of the game. I compare R&D expenditure, the expected consumer surplus, and the expected net profits in the three regimes. Yet, I still assume that firms are equally efficient in their R&D activities by setting the efficiency level to 1, *i.e.*, $a_1 = a_2 = 1$. As in the previous section the marginal cost (mc_j) is set to $\delta_j/10$, the market size (M) to $3,000$ and the discount rate (β) to 0.97.

I consider two extreme cases regarding how a lower quality firm moves up to more profitable states. In one case, which I call a no-leapfrogging case, a lower quality firm moves up by one unit when its R&D becomes successful. In the other case, which I call a leapfrogging case, a lower quality firm can jump to "the most profitable" state by successful R&D, where the most profitable state is one unit higher than the current state of a high quality firm. In both cases, a high quality firm moves up by one unit when its R&D becomes successful.

4.1 No Leapfrogging

R&D Expenditure Figure 3 shows firm 2's R&D expenditures in the state space of (δ_1, δ_2) for the no leapfrogging case. The figure shows firm 2's R&D expenditure. Firm 2 is a high quality firm when $\delta_2 > \delta_1$ and a low quality firm when $\delta_2 < \delta_1$. The degree of spillover is fixed at 5.

In RJV cartelization firms spend in R&D equally regardless of their state levels as long as they are equally efficient in R&D (equation (11)). The total R&D expenditure is determined by the sum of the expected gains from R&D success (equation ($14a$) and ($14b$)). R&D expenditure tends to decrease as a firm moves up to higher states, given the other firm's state, which implies that the sum of the expected gains decreases.

In both R&D competition and RJV competition, a high quality firm spends more in R&D than a low quality firm, and its R&D expenditure tends to increase as it moves up to higher states, given the other firm's state. This suggests that a high quality firm gains more from R&D success and its gain increases as the quality gap widens. A difference between these two regimes is that R&D expenditure is more sensitive to changes in the other firm's states in RJV competition than in R&D competition.[7]

In symmetric equilibrium, firms invest more in R&D competition than in the RJV regimes, and more in RJV cartelization than in RJV competition. In asymmetric equilibrium with no leapfrogging, the sum of firms' R&D expenditures is still higher in R&D competition than in the RJV regimes. And, a firm spends more in R&D competition at any state levels than in RJV competition.

[7] As in the symmetric equilibrium, a higher degree of spillover reduces R&D expenditures of firms in all regimes, but it does not change shapes of graphs shown in the figure.

However, a low quality firm spends more in RJV cartelization than in R&D competition when a quality difference between two firms is large. A high quality firm spends more in RJV competition than in RJV cartelization. Furthermore, as firms become more heterogeneous, the sum of R&D expenditures becomes larger in RJV competition than in RJV cartelization.

The Expected Consumer Surplus As in the symmetric equilibrium, consumer surplus is higher in RJV cartelization than in RJV competition. This is true even when the total R&D expenditure in RJV competition exceeds the total R&D expenditure in RJV cartelization. It is because the probability of R&D success is always higher in RJV cartelization than in RJV competition.[8]

Table 3 compares consumer surplus between the RJV regimes and R&D competition. $+$, $\oplus$, and $-$ are used in the same way as in the previous tables. The table shows that the two RJV regimes generate higher consumer surplus than R&D competition unless both firms are at high state levels.

The same argument in the symmetric equilibrium is applied here. In the RJV regimes, consumers face a trade-off between a lower probability of new product introduction and a lower expected price for new products. Consumers are worse off in the RJV regimes when both firms are at high state levels, because new products are much less likely to be introduced. In all other regions, consumers are better off in the RJV regimes as their expected gain from lower new product prices outweighs their expected loss from lower probabilities of new product introductions.

The Expected Net Profit Table 4-1 compares firm 2's net profit between the RJV regimes and R&D competition. As previously, firm 2 is a high quality firm when $\delta_2 > \delta_1$ and a low quality firm when $\delta_2 < \delta_1$, and the degree of spillover is fixed at 5. $+$ indicates that firm 2's net profit is higher in the RJV regimes than in R&D competition. $\oplus$ indicates that it is higher in RJV cartelization but not in RJV competition than in R&D competition. $-$ indicates that it is higher in R&D competition than in the two RJV regimes. Therefore, firm 2's net profit is higher in RJV cartelization than in R&D competition at both $+$ and $\oplus$, and it is higher in RJV competition than in R&D competition at only $+$. Table 4-2 compares firm 2's net profit

[8] A higher total R&D expenditure does not guarantee a higher probability of R&D successs since it is possible to have

$$\sigma\left(x_1^{CJ}x_2^{CJ} - x_1^{NJ}x_2^{NJ}\right) > \left(x_1^{NJ} + x_2^{NJ}\right) - \left(x_1^{CJ} + x_2^{CJ}\right).$$

between RJV cartelization and RJV competition with + indicating net profit is higher in RJV cartelization and − that it is higher in RJV competition.

Table 4-1 shows that a low quality firm is always better off in the RJV regimes than in R&D competition. A high quality firm is also better off in the RJV regimes when two firms' state levels are close. A high quality firm is worse off in the RJV regimes when a quality gap with a low quality firm becomes widened, and the state space where a high quality firm is worse off is much larger in RJV competition than in RJV cartelization.

A firm saves R&D expenditure in the RJV regimes, but it gives up an opportunity to solely succeed in R&D. For a high quality firm a gain from the cost saving in the RJV regimes is lower than a gain from solely succeeding in R&D in R&D competition. On the other hand, a low quality firm gains more from the cost saving since its gain from R&D success is relatively small due to no leapfrogging.

Table 4-2 compares RJV cartelization with RJV competition. The table shows that a high quality firm is always better off in RJV cartelization than in RJV cartelization, while a low quality firm is better off in RJV competition. In both regimes firms move up to their next state levels from successful R&D, no matter how much they invest. However, a high quality firm incurs a higher cost in RJV competition than in RJV cartelization, while a low quality firm incurs a higher cost in RJV cartelization.

The tables show that, depending on state levels, a high quality firm may prefer R&D competition or RJV cartelization most. It is more likely to prefer RJV cartelization as a low quality firm's state level is lower and two firms' quality gap is narrower. A low quality firm, on the other hand, prefers RJV competition most, RJV cartelization next, and R&D competition least.

Lastly, I examine if the RJV regimes are sustainable when firms have a choice of not cooperating in R&D. Figure 4 shows differences of the net profit for states where both firms have either higher or lower net profits at the same time. I put zeros for states where only one firm has a higher net profit in one regime.

The figure shows both firms earn higher net profits in RJV cartelization than in R&D competition when they are close to each other in the state space. Comparing RJV competition with R&D competition, the area where both firms join an RJV becomes smaller. In comparing the two RJV regimes both firms choose RJV cartelization only when they are not much different. Note that there are no regions in the state space where both firms are better off in R&D competition than in the RJV regimes.

The results show that firms are more likely to form an RJV when they are less heterogenous. The results also show that they do not have consensus on which RJV regime is better unless their product quality is very similar, but prefer RJV cartelization to RJV competition when it is.

4.2 Leapfrogging

R&D Expenditure With leapfrogging a low quality firm can become a high quality firm when it solely succeeds in R&D competition. In the RJV regimes both firms move up to the same state level when cooperative R&D becomes successful. Figure 5 shows firm 2's R&D expenditure in the state space (δ_1, δ_2) with the degree of spillover fixed at 5.

In R&D competition a low quality firm invests more than a high quality firm, which is opposite to the no-leapfrogging case. The expected benefit of a high quality firm is lower than in the no leapfrogging case. It is because its gain is lower when both firms succeed in R&D and its loss is higher when a low quality firm solely succeeds. On the other hand, a low quality firm expects a higher profit when both firms succeed and also when it solely succeeds.

In RJV cartelization, firms do not invest unless they are close to each other in the state space. This is because the expected loss of a high quality firm dominates the expected gain of a low quality firm. They invest only when the sum of the benefits is positive. In RJV competition, a high quality firm contributes nothing to R&D while a low quality firm aggressively invests.

The Expected Consumer Surplus Table 5-1 compares consumer surplus between the RJV regimes and R&D competition with $+$, $\oplus$, and $-$ being used in the same way as in table 3. Consumer surplus is higher in R&D competition than in the two RJV regimes unless firms are close to each other and their state levels are low. In the no leapfrogging case this happens only when both firms are at high state levels. The reason is trivial for RJV cartelization where firms do not invest unless they are similar and their state levels are low. In RJV competition the probability of having a new product is not zero, but it is not high enough to generate higher consumer surplus than R&D competition. Consumers still benefit from a lower new product price in RJV competition, but this benefit is dominated by a benefit of having a new product more frequently in

R&D competition.

Table 5-2 compares consumer surplus between RJV cartelization and RJV competition. RJV cartelization does not necessarily generate higher consumer surplus than RJV competition due to no investment. Consumer surplus is higher in RJV cartelization only when R&D expenditure is positive. While the probability of having a new product is always positive in RJV competition because of a low quality firm's investment, it is zero in RJV cartelization except when both firms are at low state levels.

The Expected Net Profit Table 6-1 compares firm 2's net profit between the RJV regimes and R&D competition. As in the previous tables, firm 2 is a high quality firm when $\delta_2 > \delta_1$ and a low quality firm when $\delta_2 < \delta_1$, and the degree of spillover is fixed at 5. Table 6-2 compares firm 2's net profit between RJV cartelization and RJV competition. $+$, $\oplus$, and $-$ are used in the same manner as in tables 4-1 and 4-2.

Table 6-1 presents an opposite case of the no leapfrogging case (table 4-1.) A high quality firm is always better off in the RJV regimes than in R&D competition. A low quality firm is worse off in the RJV regimes unless two firms are close to each other. The state space where a high quality firm is better off is larger in RJV competition than in RJV cartelization.

A low quality firm is better off in R&D competition than in the RJV regimes, because it has a chance of leapfrogging a high quality firm. On the other hand, a high quality firm is better off in RJVs since it is protected from being leapfrogged.

Table 6-2 compares RJV cartelization with RJV competition. A low quality firm is better off in RJV cartelization than in RJV competition when R&D expenditure is positive, while a high quality firm is better off in RJV cartelization except when R&D expenditure is positive. No investment in RJV cartelization hurts a low quality firm as it is deprived of the chance to jump up to a higher state level. In RJV competition a low quality firm still invests and can catch up with a high quality firm at a positive probability. When R&D expenditure is positive in RJV cartelization, a low quality firm is better since it can gain the same benefit with much less cost. A high quality firm, on the other hand, benefits from no investment in RJV cartelization. When investment is positive, it is worse off than in RJV competition because the expected variable profit is the same but it incurs investment cost in RJV cartelization.

As for the no leapfrogging case I examine if the RJV regimes are sustainable when firms have a choice of not cooperating in R&D. Figure **??** is analogous to Figure 4. The figure shows that RJVs are sustainable with leapfrogging when firms are less heterogenous, but the state space where they are sustainable is much smaller than in the no leapfrogging case.

5 Conclusion

In this paper I construct a two stage model of cooperative R&D where heterogeneous firms invest in product innovation. Firms invest to improve product quality in the first stage and compete *á la* Bertrand in the second stage. Firms are heterogeneous in product quality *ex ante* and *ex post*. R&D outcomes are stochastic with a success probability an increasing function of R&D expenditure. R&D efforts are subject to spillover.

Using this model I analyze three R&D regimes: R&D competition, RJV cartelization, and RJV competition. In R&D competition, firms invest in R&D unilaterally to maximize their own profits. In RJV cartelization, firms fully share outcomes of R&D, and coordinate their R&D expenditures to maximize joint profit. In RJV competition, firms fully share outcomes of R&D as in RJV cartelization, but maximize individual profits.

In symmetric equilibrium firms invest less in the RJV regimes than in R&D competition. Lower R&D expenditure is a result of eliminating R&D duplications. Firms benefit from cost savings but should give up an opportunity to exceed a rival firm in the RJV regimes. The net effect is that firms are always better off in the RJV regimes.

R&D competition introduces new products more frequently, which benefits consumers. However, new product price is higher, which hurts consumers. Overall, consumers are more likely to be better off in the RJV regimes.

In asymmetric equilibrium I consider both the leapfrogging and the no-leapfrogging cases. Although both firms and consumers have the same trade off as in symmetric equilibrium, the welfare ranking depends on firms' states. This suggests that one should be careful in assessing benefits of RJVs in the real world. The market structure and characteristics of technology should be considered. This highlights importance of empirical studies in assessing benefits of RJVs.

Appendix: proof of propositions

Proof of proposition 1

(i) From the symmetry of firms and equations $(6a)$ and $(6b)$, x^N should satisfy

$$x^N = \frac{1}{(1+x^N\sigma)}\sqrt{\beta\triangle\pi\left(x^N\right)} - \frac{1+x^N}{(1+x^N\sigma)},$$

where $\triangle\pi\left(x^N\right) = \left(1+x^N\right)\left(\pi_{own} + x^N\sigma\pi_{both}\right) - \left(1+x^N\sigma\right)\left(x^N\pi_{rival} + \pi_{none}\right)$. Let

$$f_N\left(x\right) = \frac{1}{(1+x\sigma)}\sqrt{\beta\triangle\pi\left(x\right)} - \frac{1+x}{(1+x\sigma)} - x.$$

Then,

$$\begin{aligned} f_N\left(0\right) &= \sqrt{\beta\left(\pi_{own}-\pi_{none}\right)} - 1 \geq 0, \text{ if } \left(\pi_{own}-\pi_{none}\right) \geq \frac{1}{\beta}, \\ \lim_{x\to\infty} f_N\left(x\right) &= -\infty. \end{aligned}$$

Therefore, if $\left(\pi_{own}-\pi_{none}\right) \geq \frac{1}{\beta}$, then there exists non-negative x^N that satisfies $f_N\left(x^N\right) = 0$.

(ii) From the symmetry of firms and equations $(10a)$ and $(10b)$, x^{CJ} should satisfy

$$1 = \frac{2\beta\sigma^2\left(1+\sigma x^{CJ}\right)\left(\pi_{both}-\pi_{none}\right)}{\left((\sigma-1)+1+2\sigma x^{CJ}+\left(\sigma x^{CJ}\right)^2\right)^2}.$$

Let

$$f_{CJ}\left(x\right) = \frac{2\beta\sigma^2\left(1+\sigma x\right)\left(\pi_{both}-\pi_{none}\right)}{\left((\sigma-1)+1+2\sigma x+\left(\sigma x\right)^2\right)^2} - 1.$$

Then,

$$\begin{aligned} f_{CJ}\left(0\right) &= 2\beta\left(\pi_{both}-\pi_{none}\right) - 1, \\ \lim_{x\to\infty} f_{CJ}\left(x\right) &= -1. \end{aligned}$$

Therefore, if $\left(\pi_{both}-\pi_{none}\right) \geq \frac{1}{2\beta}$, there exists non-negative x^{CJ} that satisfies $f_{CJ}\left(x^{CJ}\right) = 0$.

(iii) From the symmetry of firms and equations $(16a)$ and $(16b)$, x^{NJ} should satisfy

$$1 = \frac{\beta\sigma^2\left(1+\sigma x^{NJ}\right)\left(\pi_{both}-\pi_{none}\right)}{\left((\sigma-1)+1+2\sigma x^{NJ}+\left(\sigma x^{NJ}\right)^2\right)^2}.$$

Let

$$f_{NJ}\left(x\right) = \frac{\beta\sigma^2\left(1+\sigma x\right)\left(\pi_{both}-\pi_{none}\right)}{\left((\sigma-1)+1+2\sigma x+\sigma^2x^2\right)^2} - 1.$$

Then,

$$\begin{aligned} f_{NJ}\left(0\right) &= \beta\left(\pi_{both}-\pi_{none}\right) - 1, \\ \lim_{x\to\infty} f_{NJ}\left(x\right) &= -1. \end{aligned}$$

Therefore, if $\left(\pi_{both}-\pi_{none}\right) \geq \frac{1}{\beta}$, there exists non-negative x^{NJ} that satisfies $f_{NJ}\left(x^{NJ}\right) = 0$.

Proof of proposition 2

(i) From the symmetry and equations $(6a)$ and $(10a)$, it should hold that

$$\frac{\left(1+x^N\right)\pi_{own}-x^N\left(1+\sigma x^N\right)\pi_{rival}+x^N\sigma\left(1+x^N\right)\pi_{both}-\left(1+x^N\sigma\right)\pi_{none}}{\left(1+2x^N+\sigma\left(x^N\right)^2\right)^2}$$
$$=\quad\frac{\left(1+\sigma x^{NJ}\right)\left(\pi_{both}-\pi_{none}\right)}{\left(1+2x^{NJ}+\sigma\left(x^{NJ}\right)^2\right)^2}.$$

Suppose $x^N \leq x^{NJ}$. Since $\pi_{own} > \pi_{both} > \pi_{none} > \pi_{rival}$,

$$\frac{\left(1+x^N\right)\pi_{own}-x^N\left(1+\sigma x^N\right)\pi_{rival}+x^N\sigma\left(1+x^N\right)\pi_{both}-\left(1+\sigma x^N\right)\pi_{none}}{\left(1+2x^N+\sigma\left(x^N\right)^2\right)^2}$$
$$>\quad\frac{\left(1+x^N\right)\left(1+\sigma x^N\right)\left(\pi_{both}-\pi_{none}\right)}{\left(1+2x^N+\sigma\left(x^N\right)^2\right)^2}\geq\frac{\left(1+\sigma x^{NJ}\right)\left(\pi_{both}-\pi_{none}\right)}{\left(1+2x^{NJ}+\sigma\left(x^{NJ}\right)^2\right)^2},$$

which is a contradiction. Hence, $x^N > x^{NJ}$ to have the equality to hold.

(ii) From the symmetry and equations $(10a)$ and $(16a)$, it should hold that

$$\frac{2\left(1+\sigma x^{CJ}\right)}{\left(1+2x^{CJ}+\sigma\left(x^{CJ}\right)^2\right)^2}=\frac{1+\sigma x^{NJ}}{\left(1+2x^{NJ}+\sigma\left(x^{NJ}\right)^2\right)^2}.$$

Suppose $x^{NJ} \geq x^{CJ}$. Then

$$\frac{1+\sigma x^{NJ}}{\left(1+2x^{NJ}+\sigma\left(x^{NJ}\right)^2\right)^2}<\frac{2\left(1+\sigma x^{CJ}\right)}{\left(1+2x^{CJ}+\sigma\left(x^{CJ}\right)^2\right)^2}.$$

Therefore, $x^{CJ} > x^{NJ}$ to have the equality to hold.

(iii) From the symmetry and equations $(6a)$ and $(10a)$, it should hold that

$$\frac{\left(1+x^N\right)\pi_{own}-x^N\left(1+\sigma x^N\right)\pi_{rival}+x^N\sigma\left(1+x^N\right)\pi_{both}-\left(1+x^N\sigma\right)\pi_{none}}{\left(1+2x^N+\sigma\left(x^N\right)^2\right)^2}$$
$$=\quad\frac{2\left(1+\sigma x^{CJ}\right)\left(\pi_{both}-\pi_{none}\right)}{\left(1+2x^{CJ}+\sigma\left(x^{CJ}\right)^2\right)^2}.$$

Suppose $x^N \leq x^{CJ}$. Since $\pi_{own} > \pi_{both} > \pi_{none} > \pi_{rival}$ and $x^N \geq 1$,

$$\frac{\left(1+x^N\right)\pi_{own}-x^N\left(1+\sigma x^N\right)\pi_{rival}+x^N\sigma\left(1+x^N\right)\pi_{both}-\left(1+\sigma x^N\right)\pi_{none}}{\left(1+2x^N+\sigma\left(x^N\right)^2\right)^2}$$
$$>\quad\frac{\left(1+x^N\right)\left(1+\sigma x^N\right)\left(\pi_{both}-\pi_{none}\right)}{\left(1+2x^N+\sigma\left(x^N\right)^2\right)^2}\geq\frac{2\left(1+\sigma x^{NJ}\right)\left(\pi_{both}-\pi_{none}\right)}{\left(1+2x^{NJ}+\sigma\left(x^{NJ}\right)^2\right)^2},$$

which is a contradiction. Therefore, $x^N > x^{CJ}$ if $x^N \geq 1$.

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[Table 1] Comparison of Expected Consumer Surplus in Symmetric Equilibrium: RJV vs. R&D Competition

											σ										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	0.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	2.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	3.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	4	+	+	+	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
	4.5	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
δ	5	⊕	⊕	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	5.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	6	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	6.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	7	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	7.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	8	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	8.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	9	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	9.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	10	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

δ denotes product quality and σ denotes the degree of spillover.

$+$ indicates that consumer surplus is higher in the two RJV regimes than in R&D competition.

$\oplus$ indicates that consumer surplus is higher in RJV cartelization but not in RJV competition than in R&D competition.

$-$ indicates that consumer surplus is higher in R&D competition than in the two RJV regimes.

[Table 2] Comparison of Expected Producer Surplus in Symmetric Equilibrium: RJV vs. R&D competition

		σ																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	0.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	2.5	+	+	+	+	+	+	+	+	+	+	+	+	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
	3	+	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
	3.5	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
	4	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	4.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
δ	5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	5.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	6	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	6.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	7	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	7.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	8	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	8.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	9	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	9.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	10	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

δ denotes product quality and σ denotes the degree of spillover.

$+$ indicates that producer surplus is higher in the two RJV regimes than in R&D competition.

$\oplus$ indicates that producer surplus is higher in RJV cartelization but not in RJV competition than in R&D competition.

$-$ indicates that producer surplus is higher in R&D competition than in the two RJV regimes.

[Table 3] Comparison of Expected Consumer Surplus with No Leapfrogging: RJV vs. R&D Competition

	δ_1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
	0.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	2.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	3.5	+	+	+	+	+	+	+	+	+	⊕	⊕	⊕	⊕	⊕	+	+	+	+	+	+
	4	+	+	+	+	+	+	+	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
	4.5	+	+	+	+	+	+	+	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
δ_2	5	+	+	+	+	+	+	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−
	5.5	+	+	+	+	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	6	+	+	+	+	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	6.5	+	+	+	+	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	7	+	+	+	+	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	7.5	+	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	8	+	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	8.5	+	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	9	+	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	9.5	+	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	10	+	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−

δ_j denotes firm j's product quality.

$+$ indicates that consumer surplus is higher in the two RJV regimes than in R&D competition.

$\oplus$ indicates that consumer surplus is higher in RJV cartelization but not in RJV competition than in R&D competition.

$-$ indicates that consumer surplus is higher in R&D competition than in the two RJV regimes.

[Table 4-1] Comparison of the Expected Net Profit with No Leapfrogging: RJV vs. R&D Competition

δ_2 \ δ_1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
0.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
1.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
2.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
3.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
4.5	⊕	⊕	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
5	⊕	⊕	⊕	⊕	⊕	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
5.5	⊕	⊕	⊕	⊕	⊕	⊕	⊕	+	+	+	+	+	+	+	+	+	+	+	+	+
6	⊕	⊕	⊕	−	−	−	−	⊕	+	+	+	+	+	+	+	+	+	+	+	+
6.5	⊕	⊕	−	−	−	−	−	−	⊕	+	+	+	+	+	+	+	+	+	+	+
7	⊕	⊕	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+	+
7.5	⊕	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+
8	⊕	−	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+
8.5	⊕	−	−	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+
9	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+	+
9.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	+	+	+	+
10	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	+	+	+

δ_j denotes firm j's product quality. + indicates that net profit is higher in the two RJV regimes than in R&D competition. ⊕ indicates that net profit is higher in RJV cartelization but not in RJV competition than in R&D competition. − indicates that net profit is higher in R&D competition than in the two RJV regimes.

[Table 4-2] Comparison of the Expected Net Profit with No Leapfrogging: RJV cartel vs RJV competition

δ_2 \ δ_1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
0.5	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1.5	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
2	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
2.5	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
3	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−
3.5	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−
4	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
4.5	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−
5	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
5.5	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−
6	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−
6.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
7	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−
7.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−
8.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−
9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−
9.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
10	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

δ_j denotes firm j's product quality. + indicates that net profit is higher in RJV cartelization than in RJV competition. − indicates that net profit is higher in RJV competition than in RJV cartelization.

[Table 5-1] Expected Consumer Surplus with Leapfrogging: RJV vs. R&D Competition

	δ_1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
δ_2	0.5	+	+	⊕	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−
	1	+	+	+	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−
	1.5	⊕	+	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−
	2	⊕	⊕	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−
	2.5	⊕	⊕	⊕	⊕	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−
	3	⊕	⊕	⊕	⊕	⊕	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−
	3.5	⊕	⊕	⊕	⊕	⊕	⊕	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	4	−	−	−	−	⊕	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	4.5	−	−	−	−	−	−	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
	5	−	−	−	−	−	−	−	−	−	⊕	−	−	−	−	−	−	−	−	−	−
	5.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	6	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	6.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	7	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	7.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	8	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	8.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	9	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	9.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	10	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

δ_j denotes firm j's product quality. $+$ indicates that consumer surplus is higher in the two RJV regimes than in R&D competition. $\oplus$ indicates that consumer surplus is higher in RJV cartelization but not in RJV competition than in R&D competition. $-$ indicates that consumer surplus is higher in R&D competition than in the two RJV regimes.

[Table 5-2] Expected Consumer Surplus with Leapfrogging: RJV cartel vs. RJV competition

	δ_1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
δ_2	0.5	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−
	1	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−
	1.5	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
	2	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
	2.5	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
	3	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−
	3.5	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−
	4	−	−	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−
	4.5	−	−	−	−	−	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−
	5	−	−	−	−	−	−	−	+	+	+	+	−	−	−	−	−	−	−	−	−
	5.5	−	−	−	−	−	−	−	−	−	+	+	−	−	−	−	−	−	−	−	−
	6	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−	−
	6.5	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−
	7	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−	−	−
	7.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−	−
	8	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−	−
	8.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	−
	9	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−
	9.5	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−
	10	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+

δ_j denotes firm j's product quality. $+$ indicates that consumer surplus is higher in RJV cartelization than in RJV competition. $-$ indicates that consumer surplus is higher in RJV competition than in RJV cartelization.

[Table 6-1] Comparison of the Expected Net Profit with Leapfrogging: RJV vs. R&D Competition

δ_2 \ δ_1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
0.5	+	+	⊕	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−
1	+	+	+	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−
1.5	+	+	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−	−
2	+	+	+	+	⊕	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−
2.5	+	+	+	+	+	⊕	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−
3	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−	−
3.5	+	+	+	+	+	+	+	⊕	⊕	−	−	−	−	−	−	−	−	−	−	−
4	+	+	+	+	+	+	+	+	⊕	−	−	−	−	−	−	−	−	−	−	−
4.5	+	+	+	+	+	+	+	+	+	⊕	−	−	−	−	−	−	−	−	−	−
5	+	+	+	+	+	+	+	+	+	+	⊕	−	−	−	−	−	−	−	−	−
5.5	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−
6	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−
6.5	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−
7	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
7.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−
8.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−
9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−
9.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−
10	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

δ_j denotes firm j's product quality. $+$ indicates that net profit is higher in the two RJV regimes than in R&D competition. $\oplus$ indicates that net profit is higher in RJV cartelization but not in RJV competition than in R&D competition. $-$ indicates that net profit is higher in R&D competition than in the two RJV regimes.

[Table 6-2] Comparison of the Expected Net Profit with Leapfrogging: RJV cartel vs. RJV competition

δ_2 \ δ_1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
0.5	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−
1	−	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−
1.5	−	−	+	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
2	−	−	−	+	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
2.5	−	−	−	−	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−
3	−	−	−	−	−	+	+	+	+	−	−	−	−	−	−	−	−	−	−	−
3.5	−	−	−	−	−	−	+	+	+	−	−	−	−	−	−	−	−	−	−	−
4	+	+	−	−	−	−	−	+	+	+	−	−	−	−	−	−	−	−	−	−
4.5	+	+	+	+	+	−	−	−	+	+	−	−	−	−	−	−	−	−	−	−
5	+	+	+	+	+	+	+	−	−	+	+	−	−	−	−	−	−	−	−	−
5.5	+	+	+	+	+	+	+	+	+	−	+	+	−	−	−	−	−	−	−	−
6	+	+	+	+	+	+	+	+	+	+	−	+	−	−	−	−	−	−	−	−
6.5	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−
7	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−	−
7.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−	−
8	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−	−
8.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−
9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−
9.5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−
10	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

δ_j denotes firm j's product quality. $+$ indicates that net profit is higher in RJV cartelization than in RJV competition. $-$ indicates that net profit is higher in RJV competition than in RJV cartelization.

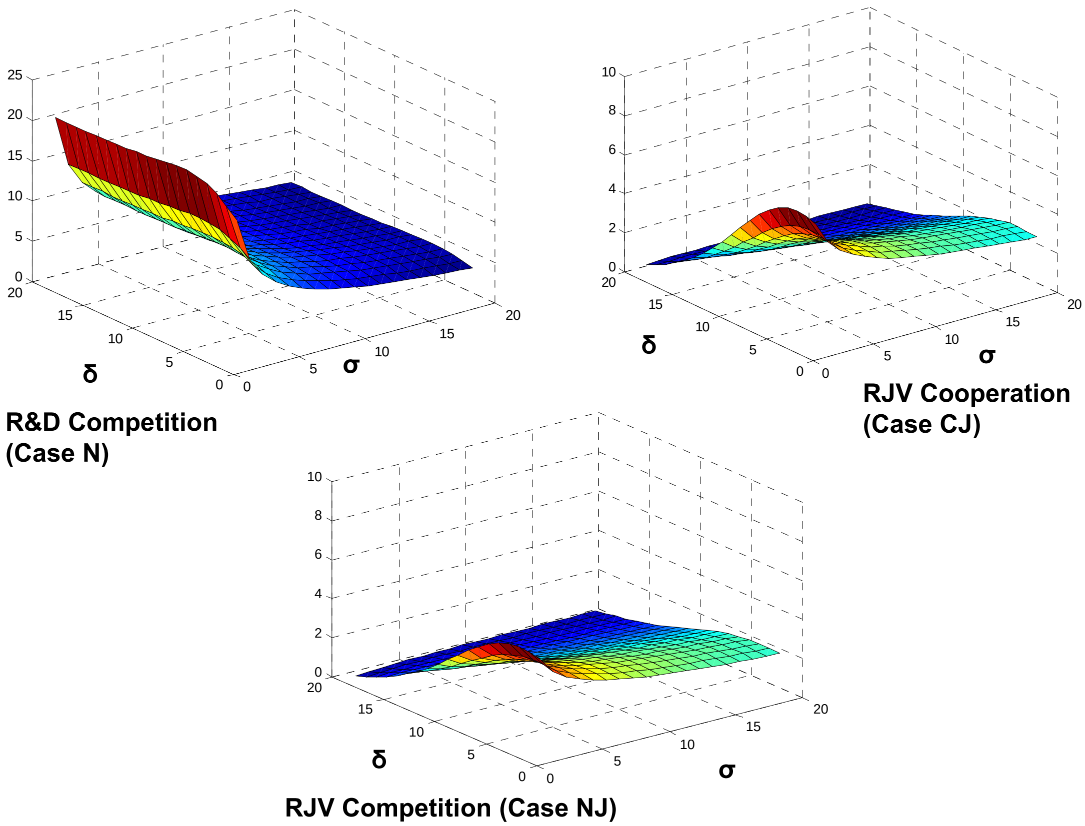
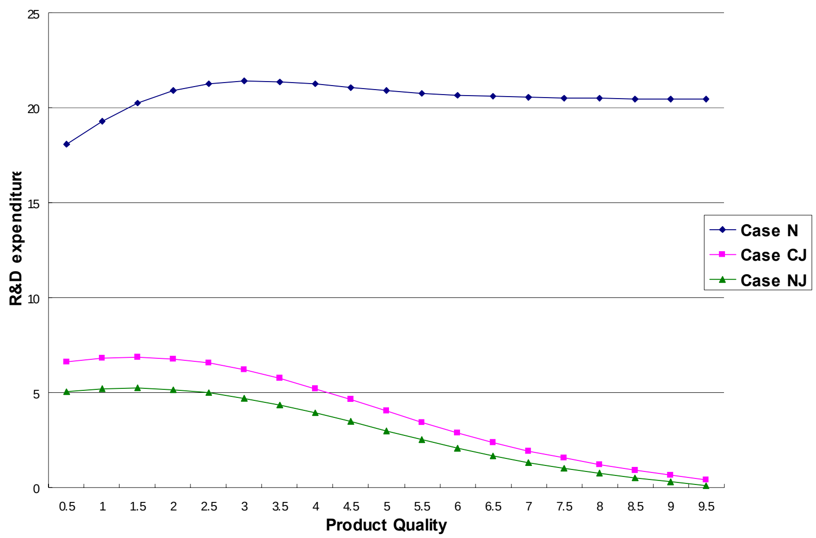
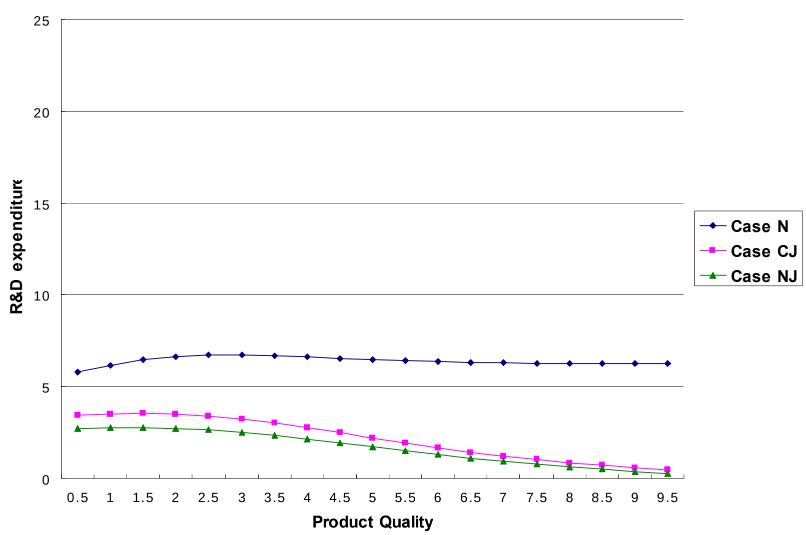


Figure 1: R&D expenditure in symmetric equilibrium



(i) σ =1



(ii) σ =10

Figure 2: Comparison of R&D expenditure in symmetric equilibrium

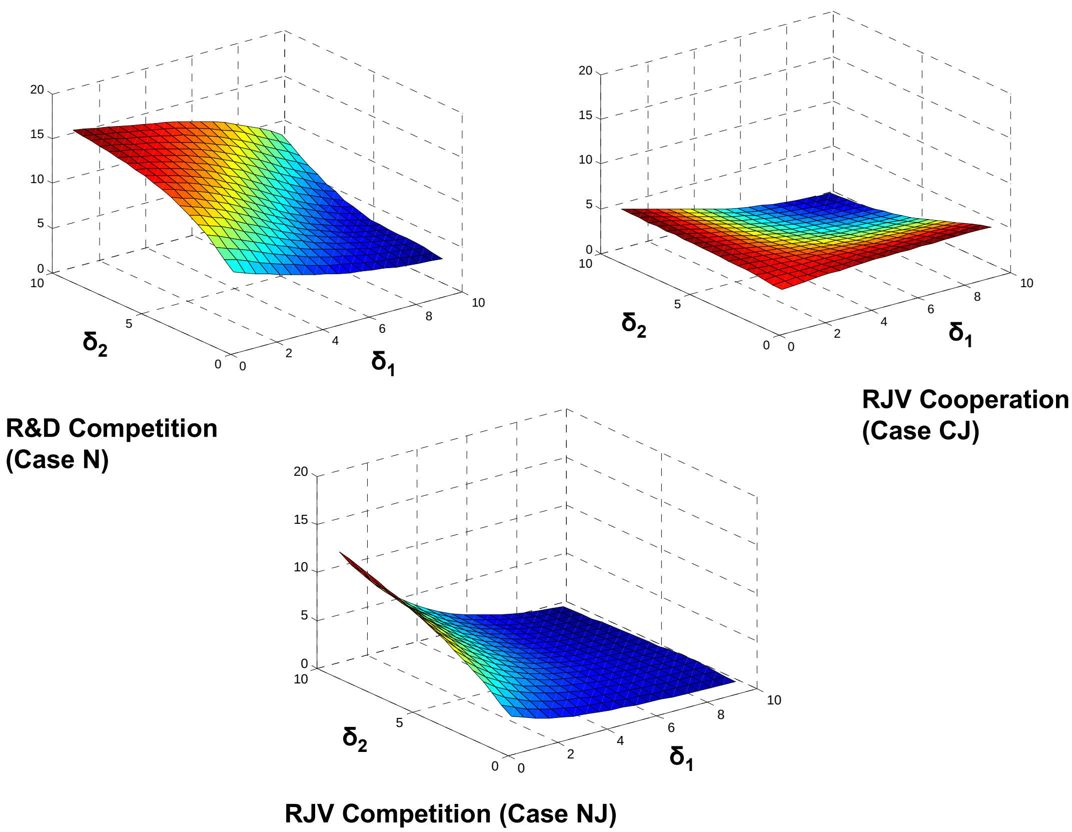


Figure 3: R&D expenditure in the no leapfrogging case

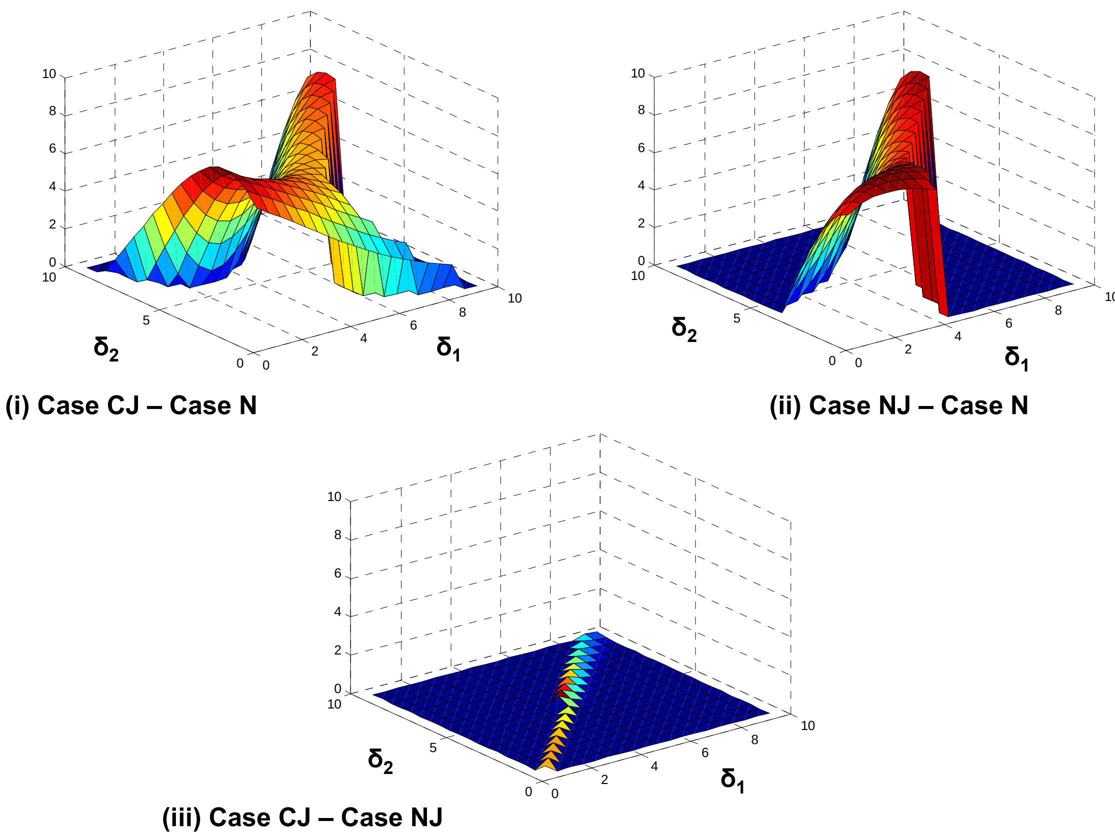


Figure 4: Incentive compatibility in the no leapfrogging case

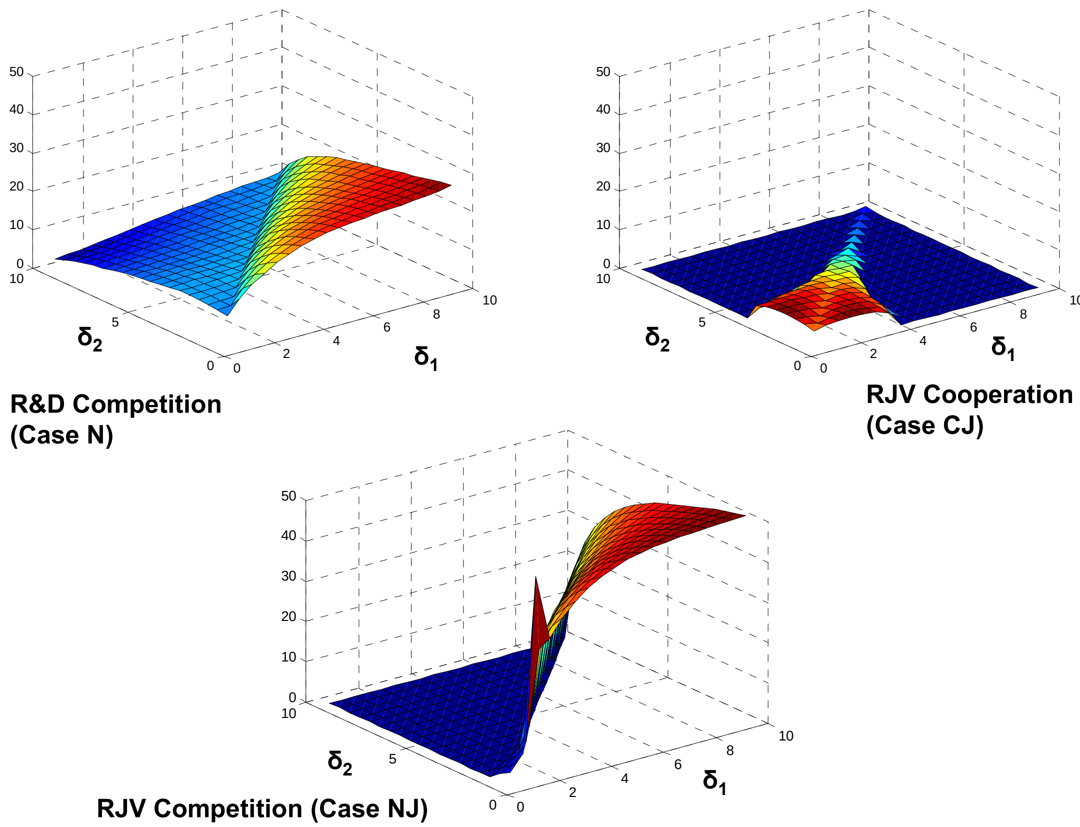


Figure 5: R&D expenditure in the leapfrogging case

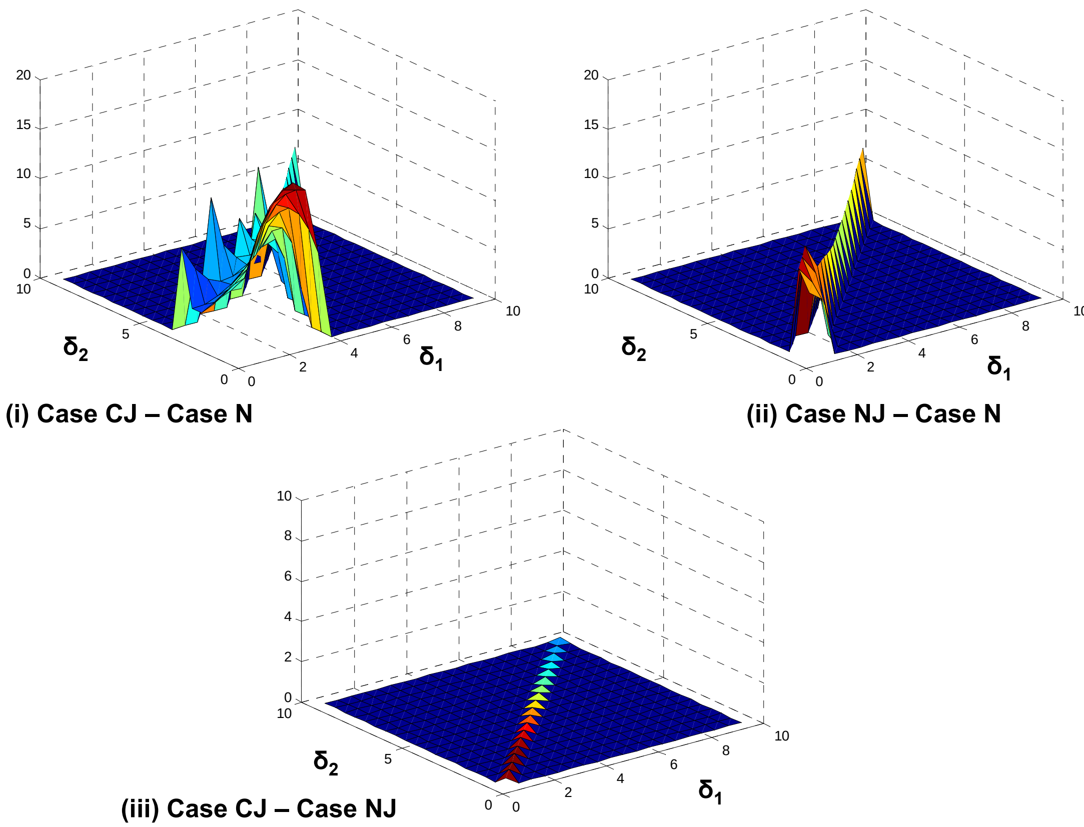


Figure 6: Incentive compatibility in the leapfrogging case