



uOttawa

L'Université canadienne
Canada's university

FACULTÉ DES ÉTUDES SUPÉRIEURES
ET POSTDOCTORALES



FACULTY OF GRADUATE AND
POSTDOCTORAL STUDIES

Jianping Mu

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

M.Sc. (Systems Science)

GRADE / DEGRÉE

Systems Science

FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

Technology Policy and R&D Cooperation in a Global Economy

TITRE DE LA THÈSE / TITLE OF THESIS

Tet Yeap

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Voicu Groza

Nguyen Van Quyen

Gary W. Slater

LE DOYEN DE LA FACULTÉ DES ÉTUDES SUPÉRIEURES ET POSTDOCTORALES /
DEAN OF THE FACULTY OF GRADUATE AND POSTDOCORAL STUDIES

**TECHNOLOGY POLICY AND R&D COOPERATION
IN A GLOBAL ECONOMY**

A THESIS
SUBMITTED IN ACCORDANCE WITH THE REQUIREMENTS
FOR THE DEGREE OF

MASTER OF SCIENCE

AT

THE UNIVERSITY OF OTTAWA

BY

JIANPING MU

JANUARY 2005

© JIANPING MU, OTTAWA, CANADA, 2005



Library and
Archives Canada

Bibliothèque et
Archives Canada

Published Heritage
Branch

Direction du
Patrimoine de l'édition

395 Wellington Street
Ottawa ON K1A 0N4
Canada

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file *Votre référence*

ISBN: 0-494-11358-8

Our file *Notre référence*

ISBN: 0-494-11358-8

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protègent cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.


Canada

Abstract

This thesis uses an international economic framework to analyze the strategic role that R&D cooperation can play in international competitions. There are two firms located in different countries and competing in output. Each firm can invest in cost-reducing R&D. There are R&D spillovers, meaning that a portion of the research results of each firm leaks out to the other firm. Two basic setups are considered. In the first setup, one of the firms benefits from an R&D subsidy from its government. In the second setup, firms collaborate in R&D. Multi-stage game-theoretic models are adopted, and the equilibrium concept used is subgame perfectness¹ [36].

The two setups are compared in terms of innovation, profits, and welfare. Moreover, the impact of spillovers on firms' and the government's decisions are considered. It is found that the subsidy declines with spillovers, because spillovers reduce the benefit of the innovation to the domestic firm. The subsidy boosts R&D investment by the domestic firm, because it reduces the net cost of R&D. The subsidy results in lower production costs for both the domestic and foreign firm. The profits of the domestic firm are always higher with the subsidy, while the foreign firm benefits from the subsidy when spillovers are high, because in this case it benefits substantially from the increase in R&D by the domestic firm due to spillovers. The subsidy increases the output of the domestic firm, but

¹ Subgame perfectness is a requirement that decisions be rational at every stage of the game.

reduces the output of the foreign firm. The subsidy is always beneficial to consumers, and always increases total welfare, defined as the sum of domestic profits and domestic consumer surplus, minus the cost of the subsidy.

The thesis also considers the impact of uncertainty in R&D on the optimal R&D subsidy. A new type of R&D subsidy is introduced, which is conditional on the success of the R&D project. This subsidy is considered in conjunction with, as well as a substitute for, the traditional unconditional R&D subsidy. It is found that the optimal conditional subsidy declines with the probability of success, meaning that riskier R&D projects should be subsidized at a higher rate. This is to compensate the firm undertaking a risky R&D project for the lower probability of obtaining the subsidy. When both conditional and unconditional R&D subsidies are used jointly, different combinations of the two can lead to the socially optimal level of innovation. Both endogenous and exogenous probabilities of success of the R&D project are considered. Moreover, both conditional and unconditional subsidies are found to decline with spillovers.

KEY WORDS: R&D, R&D cooperation, R&D subsidies

Acknowledgements

I am indebted to a very long list of people who supported me during this journey. A big thank you goes to

- Dr. TET YEAP, who sparked my interest in this research and was a great supervisor.

- My family, especially my husband BIN CHEN for his long-lasting understanding and support during the entire project.

- My friends and colleagues for their support, love and patience.

Table of Contents

Abstract.....	2
Acknowledgements	4
Chapter 1: Introduction.....	11
1.1 Motivation	11
1.2 Thesis objective	12
1.3 Thesis layout.....	14
Chapter 2: Background.....	15
2.1 International R&D cooperation with or without subsidies.....	15
2.2 Conditional R&D subsidies with uncertainty.....	17
Chapter 3: Methodology.....	20
3.1 R&D cooperation with subsidy	21
3.2 R&D cooperation without subsidy	25
Chapter 4: Analysis	29
4.1 Subsidy	30
4.2 R&D investment by domestic firm.....	31
4.3 R&D investment by foreign firm.....	32
4.4 Cost of domestic firm	33
4.5 Cost of foreign firm	35

4.6 Profit of domestic firm	36
4.7 Profit of foreign firm	38
4.8 Output of domestic firm	40
4.9 Output of foreign firm	40
4.10 Price	41
4.11 Consumer surplus	42
4.12 Social welfare	43
 Chapter 5: R&D Uncertainty with Conditional or Unconditional Subsidies	 47
5.1 Background.....	47
5.2 Model.....	48
5.2 Analysis	54
 Chapter 6: Endogenous Probability of Success.....	 60
6.1 Endogenous probability of success with conditional subsidies.....	60
6.2 Endogenous probability of success with unconditional subsidies.....	64
 Chapter 7: Conclusions and Discussions.....	 68
 References	 74
Appendix 1	78
Solutions to the cooperative case with R&D subsidy.....	78
Appendix 2	83
Solutions to the cooperative case without R&D subsidy	83

Figures

Figure 4.1: Optimal Subsidy.....	30
Figure 4.2: R&D Investment by Domestic Firm	31
Figure 4.3: R&D Investment by Foreign Firm	32
Figure 4.4: Cost of Domestic Firm.....	34
Figure 4.5: Cost of Foreign Firm.....	35
Figure 4.6: Profit of Domestic Firm	36
Figure 4.7: Profit of Foreign Firm	38
Figure 4.8: Output of Domestic Firm	40
Figure 4.9: Output of Foreign Firm	40
Figure 4.10: Price	41
Figure 4.11: Consumer Surplus	42
Figure 4.12: Social Welfare.....	44
Figure 5.1 : Effect of Spillovers on the Optimal Subsidy ($\theta = 0.75$)	58
Figure 5.2 : Effect of Probability of Success on the Optimal Subsidy ($\beta = 0.5$)	59

Tables

Table 1: Glossary	9
Table 4.1: Results of the Cooperative Case with/without R&D Subsidies	46
Table 5.1: Optimal Subsidy with t_u and t_c	53
Table 6.1: Optimal θ with t_c only.....	62
Table 6.2: Optimal θ with t_u only.....	66

Table 1: Glossary

c_d	Marginal cost of domestic firm
c_d^s	Marginal cost of domestic firm in R&D cooperation with subsidy scenario
c_d^c	Marginal cost of domestic firm in R&D cooperation scenario
c_f	Marginal cost of foreign firm
c_f^s	Marginal cost of foreign firm in R&D cooperation with subsidy scenario
c_f^c	Marginal cost of foreign firm in R&D cooperation scenario
x	Exogenous R&D investment (model with uncertainty only)
x_d	R&D output of domestic firm
x_d^s	R&D output of domestic firm in R&D cooperation with subsidy scenario
x_d^c	R&D output of domestic firm in R&D cooperation scenario
x_f	R&D output of foreign firm
x_f^s	R&D output of foreign firm in R&D cooperation with subsidy scenario
x_f^c	R&D output of foreign firm in R&D cooperation scenario
y_d	Output of domestic firm
y_d^s	Output of domestic firm in R&D cooperation with subsidy scenario
y_d^c	Output of domestic firm in R&D cooperation scenario
y_f	Output of foreign firm
y_f^s	Output of foreign firm in R&D cooperation with subsidy scenario
y_f^c	Output of foreign firm in R&D cooperation scenario
pr_d	Profit of domestic firm
pr_d^s	Profit of domestic firm in R&D cooperation with subsidy scenario
pr_d^c	Profit of domestic firm in R&D cooperation scenario

pr_f	Profit of foreign firm
pr_f^s	Profit of foreign firm in R&D cooperation with subsidy scenario
pr_f^c	Profit of foreign firm in R&D cooperation scenario
p	Price
p^s	Price of the product in R&D cooperation with subsidy scenario
p^c	Price of the product in R&D cooperation scenario
W	Social welfare
W^s	Social welfare in R&D cooperation with subsidy scenario
W^c	Social welfare in R&D cooperation scenario
CS	Consumer surplus
CS^s	Consumer surplus in R&D cooperation with subsidy scenario
CS^c	Consumer surplus in R&D cooperation scenario
t	Subsidy
t_c	Conditional subsidy
t_u	Unconditional subsidy
β	Spillover
A	Intercept of the inverse demand curve
γ	R&D cost parameter
α	Initial cost
λ	Parameter of the probability of success cost function
θ	Probability of success

Chapter 1: Introduction

1.1 Motivation

Technological cooperation is now a common practice among firms in industrialized economies. Hagedoorn et al. (2000) find that, in the 1970s, around 30-40 technology partnerships were taking place per year, and this increased to around 600 in the 1980s and 1990s. Firms cooperate on innovation to achieve a number of goals: sharing R&D costs, sharing the risks associated with innovative outcomes, pooling technological know-how, etc.

The optimal technology policy comprises an R&D subsidy to correct the R&D market failure (too little investment in R&D) and R&D cooperation to internalize R&D spillovers. An R&D subsidy is granted to a domestic firm to make it more aggressive in the world market. It is still an optimal policy for individual governments in the case of R&D cooperation, and the subsidy is larger for higher degrees of cooperation. R&D cooperation is welfare-improving for both countries. Suppose that there are effects of spillovers on effective cost reduction, profits and welfare. When firms choose their R&D strategically, they have a tendency to over-invest in R&D as they attempt to gain an advantage over their rivals.

It is increasingly important for developing countries to attract foreign investment, and some of these foreign investments involve R&D. Therefore, R&D globalization has become a trend that is no longer restricted to developed countries, for the developing economies are becoming increasingly involved in internationalization.

1.2 Thesis objective

To examine these issues, we set the analysis in an international economic framework to analyze the strategic role that R&D cooperation can play in international competition. We present a homogeneous good model of cost-reducing R&D. The world is composed of two countries, one developed country and one developing country. There is one firm in each country. The two countries are integrated, so that firms face a single market, whose consumers are represented by citizens of both countries.

The purpose of this approach is to examine two different set-ups concerning technology policy with respect to R&D. One is subsidized R&D with cooperation, while the other is cooperative R&D only. With R&D subsidies, technology policy takes the form of subsidizing cost-reducing R&D expenditures while allowing R&D cooperation to maximize joint profits. In the first stage, the government sets the subsidy, then firms choose the cost-reducing R&D simultaneously while at the same time receiving a subsidy, t , on their R&D costs. They then compete in Cournot. In cooperative R&D, technology policy takes the form of encouraging R&D by allowing firms to cooperate at the R&D stage and

compete in output in the second stage. In this model, R&D cooperation means that firms set their R&D cooperatively to maximize joint profits.

It is shown that, in most cases, providing the R&D subsidy is more effective than merely allowing for R&D cooperation. Moreover, considering the implementation of both R&D technology policies simultaneously reveals that the preferred R&D policy is to optimally subsidize R&D.

We also consider the case where the success of the R&D project is uncertain, and the granting of the subsidy is made conditional on this success. There may be benefits to relating the provision of an R&D subsidy or its level to the success of an R&D project or to the level of risk associated with the project. Such a scheme, by rewarding success, may induce firms to perform better research to increase the chances of success of the project and/or the quality of the outcome. Moreover, with firms having different research capabilities, R&D subsidies linked to success may select the best firms and eliminate those performing the least successful research. With limited government funds available for subsidies, it may make sense to allocate those budgets to the best R&D projects and to the best performers.

Using the same model as above, we determine the optimal subsidy as a function of the probability of the success of the project. In addition, we introduce a new type of R&D subsidy, which is conditional on the success of the R&D project. The domestic firm gets the subsidy if the R&D project succeeds and does not get it if the project fails. We call

this type of subsidy a *conditional* R&D subsidy. We consider the use of conditional and unconditional subsidies separately, as well as the case where both are used jointly. Moreover, we allow the firm to choose the probability of success of the R&D project (instead of the size of the project).

1.3 Thesis layout

Chapter 2 reviews the literature on R&D cooperation and R&D subsidies. The next chapter presents the methodology of the model. The results are then analyzed from the point of view of the impact of spillovers, R&D subsidization and R&D levels in Chapter 4. After that, we introduce uncertainty into the model and allow the subsidy to be conditional on the success of the R&D project. In Chapter 5, firms choose R&D investments, and the government chooses two types of subsidies: an unconditional subsidy, which the domestic firm obtains in all cases; and a conditional subsidy, which the domestic firm obtains only if its R&D project succeeds. In Chapter 6, we change the choice variable of the model: now the firm chooses the probability of success, but the size of the R&D project is fixed exogenously. In this model, the government uses only a conditional subsidy. Finally, the probability of success is endogenous, but the government uses only unconditional subsidies; this allows us to compare the welfare effects of conditional versus unconditional subsidies. Chapter 7 concludes this thesis.

Chapter 2: Background

A large amount of literature dealing with R&D cooperation and technological partnerships has emerged. That literature has dealt with different facets of R&D cooperation, including process vs. product R&D, the stability of research consortia, government policy in terms of antitrust and R&D subsidization, and the appropriability of innovations, such as spillovers. That literature has come up with a number of findings regarding the desirability of cooperation, what the government of the developing country should do to encourage R&D, the identity of the cooperating partners, and the impact of spillovers and spillovers on the incentives for innovation.

Petrakis and Poyago-Theotoky (2002) consider the impact of two different policies, R&D subsidization and R&D cooperation, in a duopoly model with cost-reducing R&D and spillovers. In the case of R&D subsidization, welfare in the case of R&D cooperation is lower than welfare in the case of R&D subsidization.

2.1 International R&D cooperation with or without subsidies

The number of international R&D cooperation agreements has been increasing at an unparalleled rate. A survey article by Chesnais (1988) contains much information on various forms of R&D cooperation in a wide range of industries. For instance, between 1982

and 1985, there were 1,061 inter-firm agreements in high technology industries where the product markets are characterized by imperfect competition. Among those agreements, a large portion was for R&D cooperation, and more than half were for international cooperation. Even rival firms competing in the same final product markets may cooperate in R&D investment. Government support for both domestic and international R&D cooperation has also become more frequent. It was estimated that Airbus benefited from subsidies totaling US\$2.5 billion between 1968 and 1982 (Krugman, 1984).

Spencer and Brander (1983) demonstrated that, through subsidizing the domestic firm, a government can achieve the same strategic outcomes otherwise obtained under direct export subsidies. Spencer and Brander and all subsequent studies address this issue and have the following two results. First, a government should subsidize the domestic firm's R&D activity when the firm cooperates with its foreign partner. Second, if a subsidy is optimal, then it is larger for cooperative R&D than for non-cooperative R&D.

Among those studies on R&D globalization, it comes into view that, although not yet truly globalized, R&D cooperation is experiencing a process of globalization (Howells, 1992), and its progress differs across sectors and economies (Casson and Singh, 1993; Dunning, 1994).

A rising trend has been revealed by Reddy (2000) in terms of the international R&D cooperation in developing countries. Reddy highlighted those factors underlying this trend. They include the rising R&D costs, the increasing demand for R&D personnel, and a

shortage of R&D personnel in industrialized countries, as well as the comparative advantages of the less-advanced host countries.

Barba Navaretti (1996) analyzes the determinants of R&D cooperation between industrial and developing countries – that is, between firms with asymmetric endowments of knowledge. She develops a model in which two firms choose one option to cooperate in R&D. Their model shows that the choice of cooperating in R&D increases both the profitability and stability of the joint venture. The common starting point of the literature on hierarchical transfers of technology (see, for instance, Ethier, 1986; Wright, 1993; Ethier and Markusen, 1991) is R&D activities that create a firm specific asset, which can be a new product, a reduction in production costs or the improvement of product quality.

A framework will be developed in the following section with which both R&D subsidy and R&D cooperation can be analyzed. It is shown that, in most cases, providing R&D subsidies is more effective than merely allowing for R&D cooperation. Moreover, considering the implementation of both R&D technology policies simultaneously reveals that the preferred R&D policy is to optimally subsidize R&D.

2.2 Conditional R&D subsidies with uncertainty

The thesis also deals with conditional R&D subsidies, which are granted only when the project succeeds. Empirically, there is evidence that some countries incorporate some form of conditionality into their support for R&D. Tanayama et al. (2004) find that, in

Finland, R&D subsidies are increasing in technical challenge; this can be interpreted as a policy whereby the government grants higher R&D subsidies to more risky or difficult projects.² Fölster (1991) analyzes the different types of R&D subsidies in use. One type of R&D support is a loan that is repaid to the government only if the R&D project is successful. This is equivalent to an R&D subsidy based on failure. Fölster also identifies royalty grants, which are paid to the government based on the sales from the invention; hence, the higher the (commercial) success of the project, the lower the real subsidy rate. Or the government, in exchange for the subsidy, receives a stock option, which can be exercised if the stock value rises significantly, i.e., if the project is commercially successful. Moreover, based on a sample of Swedish firms, Fölster finds that Aselective@ subsidies (such as royalty grants, conditional loans and stock options) induce more private R&D than more traditional subsidies, such as tax incentives, project grants and project loans.

Given that some form of conditionality in the support of R&D is being used by several countries, there is a gap in the economic literature, which is the study of the properties and consequences of such conditional subsidies. To fill this gap in our understanding of the impact of R&D policies, this thesis proposes an R&D subsidy that is conditional upon the success of the project: if the R&D project succeeds, the firm obtains the subsidy; if

² In Finland, during the evaluation of subsidy provision, R&D projects are classified based on several criteria. One of these criteria is the risk associated with the R&D project; the projects are ranked from 0 to 5, with 0 representing the low risk@ projects, and 5 representing the most challenging projects. Rejected projects were, on average, safer than all other applications (Tanayame et al., 2004).

the R&D project fails, the firm has to cover all the expenses itself. Moreover, the simultaneous use of conditional and unconditional R&D subsidies is considered.

There is a small amount of literature on R&D uncertainty. Poyago-Theotoky (1998) analyses the role of a public firm in a mixed duopoly under uncertainty. Miyagiwa and Ohno (2002) analyze cooperative R&D in an oligopoly with spillovers and uncertainty. Lambertini (2004) studies the impact of demand uncertainty on R&D. However, the interaction between uncertainty and R&D subsidization has not been analyzed.

Chapter 3: Methodology

There are two firms, a domestic firm and a foreign firm, competing on the domestic market in Cournot³ [36]. Each firm can invest in process innovation to reduce its production costs and improve its competitive position. Such innovations are subject to technology spillovers between the domestic firm and the foreign firm.

We consider two different games with perfect and complete information. Those two models are based on d'Aspremont and Jacquemin (1988).

- 1) In the first game, R&D costs are subsidized by the government, which moves first by setting the subsidy rate so as to maximize total welfare in the first stage, while firms choose how much to spend in cost-reducing R&D in the second stage. In the third stage, the firms compete in output.
- 2) In the second game, there are no R&D subsidies, but firms cooperate in setting their cost-reducing R&D so as to maximize joint profits. Then in the second stage, they compete in Cournot.

³ A Cournot model is a generalization of the Cournot game to describe industry structure. Each of N firms will choose a quantity of output. Price is a commonly known decreasing function of total output. All firms know N and take the output of the others as given. Each firm has a cost function $c_i(q_i)$. Usually the cost functions are treated as common knowledge. Often the cost functions are assumed to be the same for all firms.

The main equilibrium concept used in this paper is subgame perfectness, where the game is solved backwards to ensure that the strategies of firms are rational at every node of the game.

In the following text, the superscript letter s represents R&D cooperative equilibrium with subsidy, while the superscript letter c means cooperative only. The subscript letter d represents the domestic firm, the subscript letter f , the foreign firm.

Firms invest in R&D in two scenarios: R&D cooperation with subsidy and R&D cooperation only.

3.1 R&D cooperation with subsidy

Firms face the inverse linear demand

$$p^s = A - y_d^s - y_f^s \quad (1)$$

where p^s is the price of the product, A is the intercept of the inverse demand curve (it represents the price at which the quantity demanded would be zero), and y_d^s and y_f^s are the domestic and foreign firms' outputs respectively.

The unit cost of production of the domestic firm is

$$c_d^s = \alpha - x_d^s - \beta x_f^s \quad (2)$$

where c_d^s is the marginal cost of the domestic firm, α is the initial cost of the product, $\beta \in [0,1]$ is spillovers between the domestic firm and the foreign firm and x_d^s and x_f^s represent the R&D investment of the domestic firm and that of the foreign firm respectively.

The unit cost of production of the foreign firm c_f^s is

$$c_f^s = \alpha - x_f^s - \beta x_d^s \quad (3)$$

The dollar cost of x units of R&D for the domestic firm is $\gamma x_d^{s^2}$, the dollar cost of x units of R&D for the foreign firm is $\gamma x_f^{s^2}$, where $\gamma > 0$ is an R&D cost parameter.

Thus the firms' profits are given by

$$pr_d^s = (p^s - c_d^s)y_d^s - (1-t)\gamma x_d^{s^2} \quad (4)$$

$$pr_f^s = (p^s - c_f^s)y_f^s - \gamma x_f^{s^2} \quad (5)$$

where pr_d^s is the profit of the domestic firm, pr_f^s is the profit of the foreign firm, and t is R&D subsidy given by the domestic government to the domestic firm.

The consumer surplus is defined as the area between the demand curve and the price level. Given that the local government cares only about the consumers in its own country, we define consumer surplus as half that area, hence considering the benefits of only half of total consumers.

$$CS^s = (A - p^s)(y_d^s + y_f^s)/4 \quad (6)$$

where CS^s is consumer surplus.

The social welfare of the domestic country, which is equal to the sum of the domestic producer's profits and consumer surplus minus the cost of the subsidy, is given by

$$W^s = CS^s + pr_d^s - t\gamma x_d^{s^2} \quad (7)$$

where W^s is social welfare.

We solve this game starting from the last stage, followed by stage 2 and stage 1.

In the third stage, each firm chooses its output to maximize its profits.

$$\max_{y_d^s} pr_d^s(y_d^s, y_f^s, x_d^s, x_f^s, t) \quad (8)$$

$$\max_{y_f^s} pr_f^s(y_d^s, y_f^s, x_d^s, x_f^s, t) \quad (9)$$

This yields solutions for output as a function of R&D.

$$y_d^s = \frac{1}{3}(A + 2x_d^s - x_f^s - \alpha - x_d^s\beta + 2x_f^s\beta) \quad (10)$$

$$y_f^s = \frac{1}{3}(A + 2x_f^s - x_d^s - \alpha - x_f^s\beta + 2x_d^s\beta) \quad (11)$$

In the second stage, firms choose R&D expenditures to maximize their joint profits.

$$\max_{x_d^s, x_f^s} pr_d^s(y_d^s(x_d^s, x_f^s), y_f^s(x_d^s, x_f^s), x_d^s, x_f^s, t) + pr_f^s(y_d^s(x_d^s, x_f^s), y_f^s(x_d^s, x_f^s), x_d^s, x_f^s, t) \quad (12)$$

This yields the following levels of R&D expenditures:

$$x_d^s = (\alpha - A + A\beta - \alpha\beta - \gamma\alpha + A\beta^2 - \alpha\beta^2 - \beta^3 A + \beta^3 \alpha + \gamma A + \gamma A\beta - \gamma\alpha\beta) / (1 - 8\beta t\gamma + 5\beta^2 t\gamma - 2\beta^2 + 9\gamma^2 + \beta^4 - 10\beta^2 \gamma - 9t\gamma^2 + 16\gamma\beta - 10\gamma + 5t\gamma) \quad (13)$$

$$x_f^s = (-\beta^3 A + \beta^3 \alpha + A\beta^2 - \alpha\beta^2 - \alpha\beta - \gamma\alpha\beta + \gamma A\beta - A\beta t\gamma + A\beta + \alpha\beta t\gamma + \alpha - A + \gamma A + \alpha t\gamma - A t\gamma - \gamma\alpha) / (1 - 8\beta t\gamma + 5\beta^2 t\gamma - 2\beta^2 + 9\gamma^2 + \beta^4 - 10\beta^2 \gamma - 9t\gamma^2 + 16\gamma\beta - 10\gamma + 5t\gamma) \quad (14)$$

In the first stage, the government chooses the subsidy rate, t , to maximize social welfare.

$$\max_t W(y_d^s(t), y_f^s(t), x_d^s(t), x_f^s(t), t) \quad (15)$$

This yields the optimal subsidy rate.

$$t_{optimal} = 2(5\beta^5 - 25\beta^4 + 26\beta^3 + 22\beta^3 \gamma + 14\beta^2 - 66\beta^2 \gamma - 27\gamma^2 \beta - 31\beta + 90\gamma\beta + 11 - 38\gamma + 27\gamma^2) / (13\beta^5 - 47\beta^4 - 27\beta^3 \gamma + 46\beta^3 - 9\beta^2 \gamma + 22\beta^2 - 59\beta + 135\gamma\beta - 18\gamma^2 \beta + 25 + 90\gamma^2 - 99\gamma) \quad (16)$$

Now we can calculate the level of welfare.

$$\begin{aligned}
W^s = & -\gamma(186\gamma A\alpha - 69\alpha^2\beta^2\gamma - 212\alpha\beta^2A + 120\alpha\beta^3A - 26\alpha\beta^4A \\
& + 162\alpha^2\beta\gamma - 69A^2\beta^2\gamma + 162A^2\beta\gamma - 84\alpha^2\beta + 106\alpha^2\beta^2 \\
& - 60\alpha^2\beta^3 + 13\alpha^2\beta^4 - 84A^2\beta + 106A^2\beta^2 - 60A^2\beta^3 + 13A^2\beta^4 \\
& - 93\gamma A^2 + 72\gamma^2 A^2 - 93\gamma\alpha^2 + 72\gamma^2\alpha^2 - 50A\alpha + 25A^2 + 25\alpha^2 \\
& + 138\alpha\beta^2\gamma A - 324\alpha\beta\gamma A - 144\gamma^2 A\alpha + 168\alpha\beta A) / (13\beta^6 - 34\beta^5 \\
& - 94\beta^4\gamma - \beta^4 + 224\gamma\beta^3 + 68\beta^3 + 405\gamma^2\beta^2 - 37\beta^2 - 348\beta^2\gamma \\
& - 702\gamma^2\beta + 416\gamma\beta - 34\beta + 513\gamma^2 - 214\gamma + 25 - 324\gamma^3)
\end{aligned} \tag{17}$$

3.2 R&D cooperation without subsidy

Firms face the inverse linear demand

$$p^c = A - y_d^c - y_f^c \tag{18}$$

where p^c is the price of the product, A is the intercept of the inverse demand curve and y_d^c and y_f^c are the outputs of the domestic firm and the foreign firm.

The unit cost of production of the domestic firm is

$$c_d^c = \alpha - x_d^c - \beta x_f^c \tag{19}$$

where c_d^c is the marginal cost of the domestic firm, α is the initial cost of the product, β is the spillovers between the domestic firm and the foreign firm and x_d^c and x_f^c represent

the R&D investment of the domestic firm and R&D investment of the foreign firm respectively.

The unit cost of production of the foreign firm is

$$c_f^c = \alpha - x_f^c - \beta x_d^c \quad (20)$$

where c_f^c is the marginal cost of the foreign firm.

The dollar cost of x units of R&D for domestic firm is $\gamma x_d^{c^2}$, and the dollar cost of x units of R&D for the foreign firm is $\gamma x_f^{c^2}$, where $\gamma > 0$ is the R&D cost parameter.

Thus the firms' profits are given by

$$pr_d^c = (p^c - c_d^c)y_d^c - \gamma x_d^{c^2} \quad (21)$$

$$pr_f^c = (p^c - c_f^c)y_f^c - \gamma x_f^{c^2} \quad (22)$$

where pr_d^c is the profit of domestic firm, and pr_f^c is the profit of foreign firm.

The consumer surplus CS^c is defined as the following:

$$CS^c = (A - p^c)(y_d^c + y_f^c)/4 \quad (23)$$

The social welfare of the domestic country, W^c , which is equal to the sum of the domestic producer's profits and consumer surplus minus the cost of the subsidy, is given by

$$W^c = CS^c + pr_d^c \quad (24)$$

We solve this game starting from the last stage.

In the second stage, each firm chooses its output to maximize its profits.

$$\max_{y_d^c} pr_d^c(y_d^c, y_f^c, x_d^c, x_f^c) \quad (25)$$

$$\max_{y_f^c} pr_f^c(y_d^c, y_f^c, x_d^c, x_f^c) \quad (26)$$

This yields solutions for output as a function of R&D.

$$y_d^c = \frac{1}{3}(A + 2x_d^c - x_f^c - \alpha - x_d^c\beta^c + 2x_f^c\beta^c) \quad (27)$$

$$y_f^c = \frac{1}{3}(A + 2x_f^c - x_d^c - \alpha - x_f^c\beta^c + 2x_d^c\beta^c) \quad (28)$$

In the first stage, firms choose R&D expenditures to maximize their joint profits.

$$\max_{x_d^c, x_f^c} pr_d^c(y_d^c(x_d^c, x_f^c), y_f^c(x_d^c, x_f^c), x_d^c, x_f^c) + pr_f^c(y_d^c(x_d^c, x_f^c), y_f^c(x_d^c, x_f^c), x_d^c, x_f^c) \quad (29)$$

This yields the following levels of R&D expenditures:

$$x_d^c = -\frac{(A-\alpha)(1+\beta^c)}{1+2\beta^c+\beta^{c^2}-9\gamma} \quad (30)$$

$$x_f^c = -\frac{(A-\alpha)(1+\beta^c)}{1+2\beta^c+\beta^{c^2}-9\gamma} \quad (31)$$

Now we can calculate the level of welfare.

$$W^c = -\gamma(-18\gamma A^2 + 36\gamma\alpha A - 18\gamma\alpha^2 + A^2\beta^2 - 2\alpha\beta^2 A - 4\alpha\beta A + 2A^2\beta + \alpha^2\beta^2 + 2\alpha^2\beta + \alpha^2 - 2A\alpha + A^2) / (\beta^2 + 2\beta - 9\gamma + 1)^2 \quad (32)$$

Chapter 4: Analysis

In terms of modeling, numerical simulations are often used to prevent the analytical complexity of the results. Moreover, it is easier to analyze static games; in most cases, not much is obtained by adopting a dynamic model.

We then make comparisons to find out which one is a better policy in terms of social welfare, consumer surplus, price of the product, cost of production, profits of the domestic and foreign firms, R&D investment of the domestic and foreign firms and production output of both firms: a policy of R&D subsidization or a policy of encouraging R&D cooperation.

After solving those two models, we assume some numerical values for the parameters so as to simplify analytical expressions: $A=1000$, $\gamma=60$, $\alpha=50$.⁴ [2]

⁴ The results are not sensitive to the numerical values for the parameters above. Using different numerical values would produce different levels of R&D investment, subsidies, and output, but the relationships between the variables would not change. The values in the thesis are the same as Atallah (2004).

4.1 Subsidy

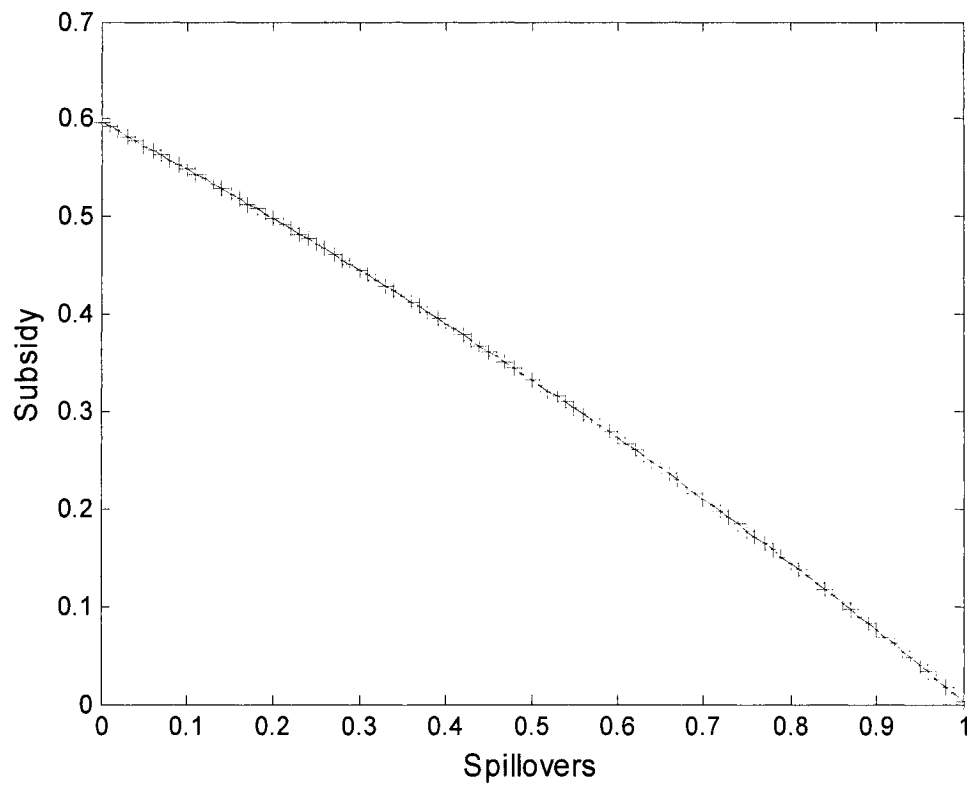


Figure 4.1: Optimal Subsidy

From Figure 4.1, we can see that the optimal subsidy declines with spillovers. The highest value, about 60% of R&D costs, is obtained when $\beta=0$. This value declines to almost zero for $\beta=1$. The reason why the subsidy declines with spillovers is that,

as spillovers increase, a larger portion of domestic R&D leaks out to the foreign firm, hence the domestic government chooses to subsidize x_d at a lower rate.

4.2 R&D investment by domestic firm

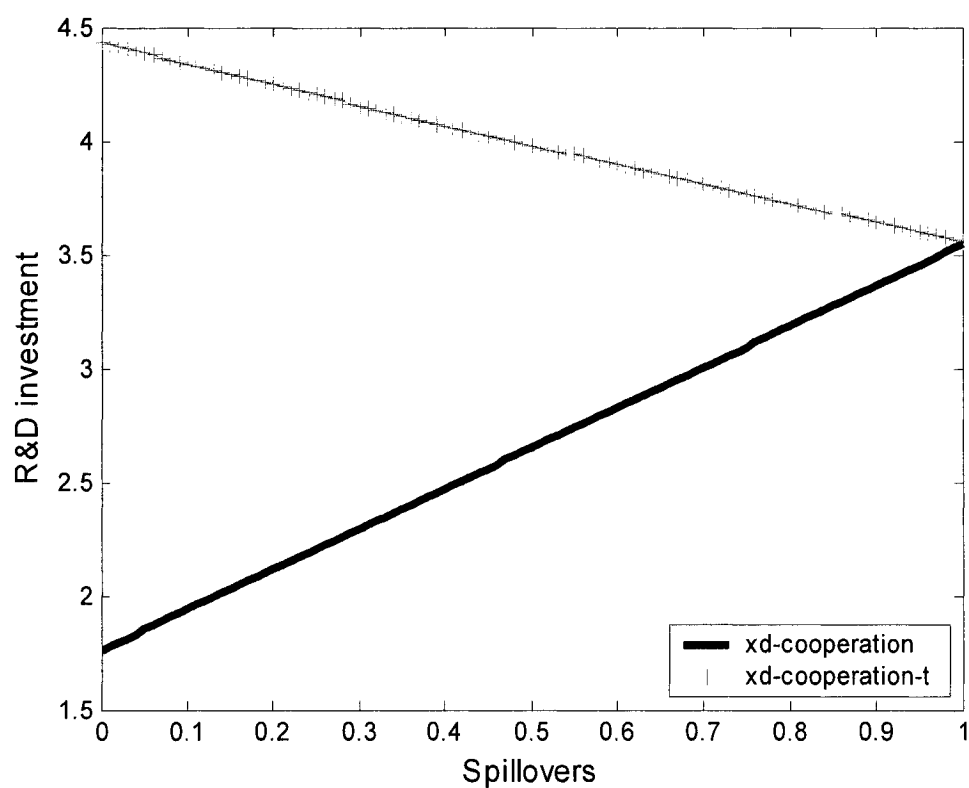


Figure 4.2: R&D Investment by Domestic Firm

In the absence of the subsidy, x_d increases with spillovers. Because firms are cooperating, the increase in spillovers increases the mutual benefits from R&D, thus increasing x_d . However, in the presence of the subsidy, x_d declines with spillovers. Be-

cause the optimal subsidy declines with spillovers, the net cost of R&D increases with spillovers, inducing a decline in R&D, in spite of the presence of cooperation. This result constitutes a major departure from the literature, where, because cooperative R&D is generally not subsidized, it increases with spillovers.

Moreover, x_d is always higher with the subsidy than without, because the subsidy reduces the net cost of R&D to the firm.

4.3 R&D investment by foreign firm

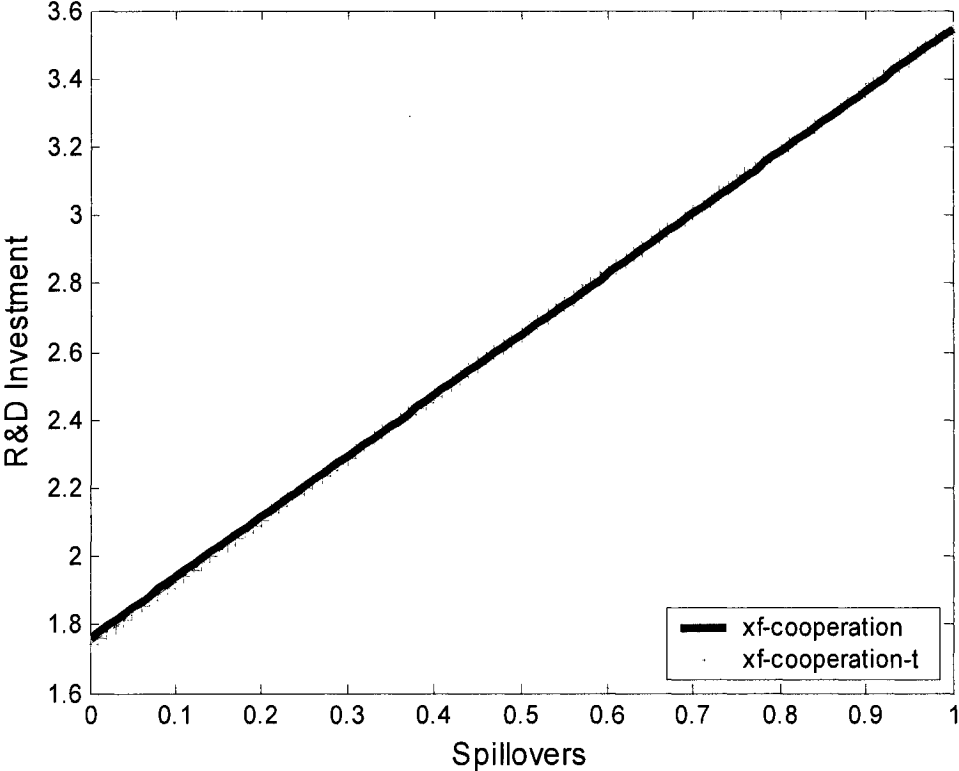


Figure 4.3: R&D Investment by Foreign Firm

x_f always increases with spillovers, with or without the subsidy provided to the domestic firm. As mentioned above, the increase in spillovers increases the mutual benefits from cooperation, increasing R&D. Because the foreign firm does not benefit from the subsidy, it is not directly affected by the fact that the subsidy declines with spillovers.

Moreover, x_f is hardly affected by the subsidy. As Figure 4.3 shows, the level of x_f is almost the same with and without the subsidy, although x_f is slightly higher without the subsidy.

4.4 Cost of domestic firm

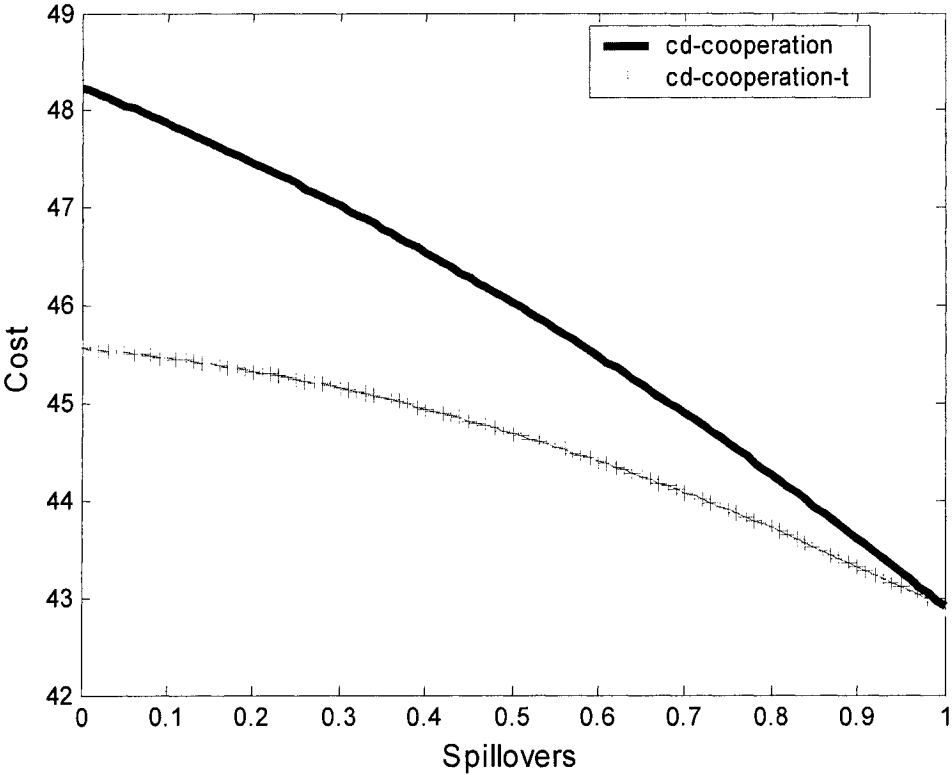


Figure 4.4: Cost of Domestic Firm

In the presence of the subsidy, the marginal cost of the domestic firm decreases with spillovers. This is due to the fact that spillovers increase x_f , and with higher spillovers, the domestic firm benefits more from any given amount of x_f . This effect on c_d dominates the effect of the decline of x_d with spillovers, which by itself would induce a positive relationship between β and x_d .

Also, c_d declines with spillovers in the absence of the subsidy. In addition to the effects of β and x_f mentioned above, x_d increases with spillovers (in the absence of the subsidy), further contributing to the decline in x_d . Notice that the decline in x_d is steeper in the absence of the subsidy, because of the fact that x_d increases with spillovers in the absence of the subsidy, but decreases with spillovers with subsidy present.

We also note that the production cost is lower with the subsidy. This is because the subsidy increases x_d .

4.5 Cost of foreign firm

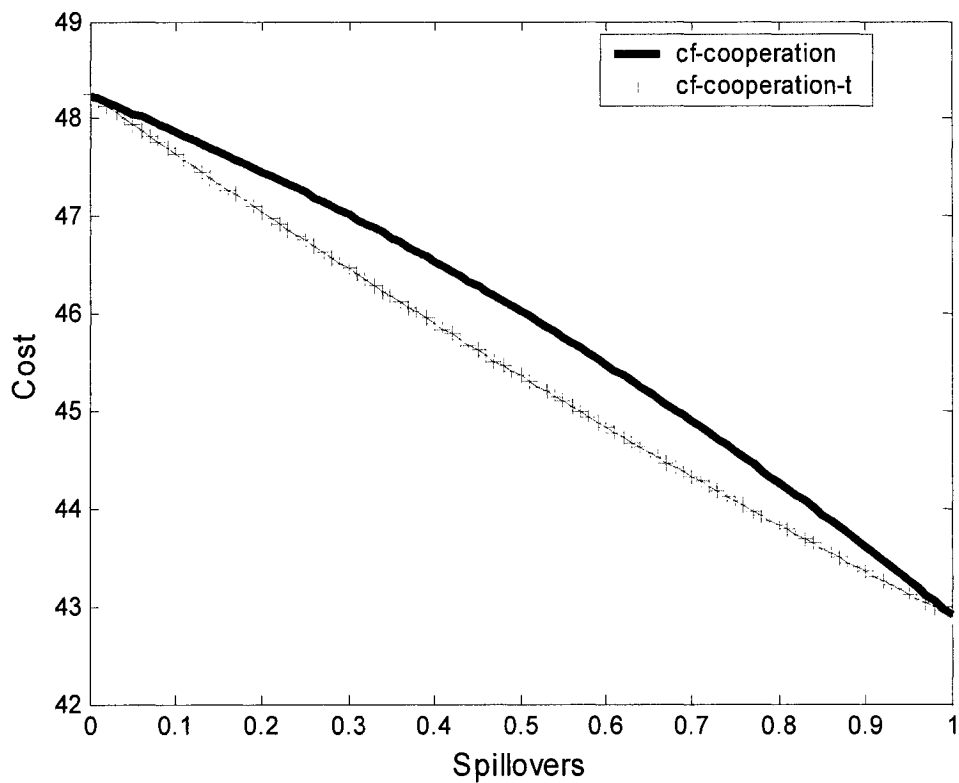


Figure 4.5: Cost of Foreign Firm

The cost of the foreign firm declines with spillovers. With and without subsidy, x_f increases with spillovers, contributing to the decline in c_f . As for the effect of x_d , it is as follows. In the absence of the subsidy, x_d increases with spillovers, contributing to the decline in c_f , both because of the higher β and the higher x_d . In the presence of the subsidy, x_d declines with spillovers, which reduces the benefits that the foreign firm gets

from x_d . But the increase in x_f more than compensates for this, resulting in a negative relationship between c_f and β .

4.6 Profit of domestic firm

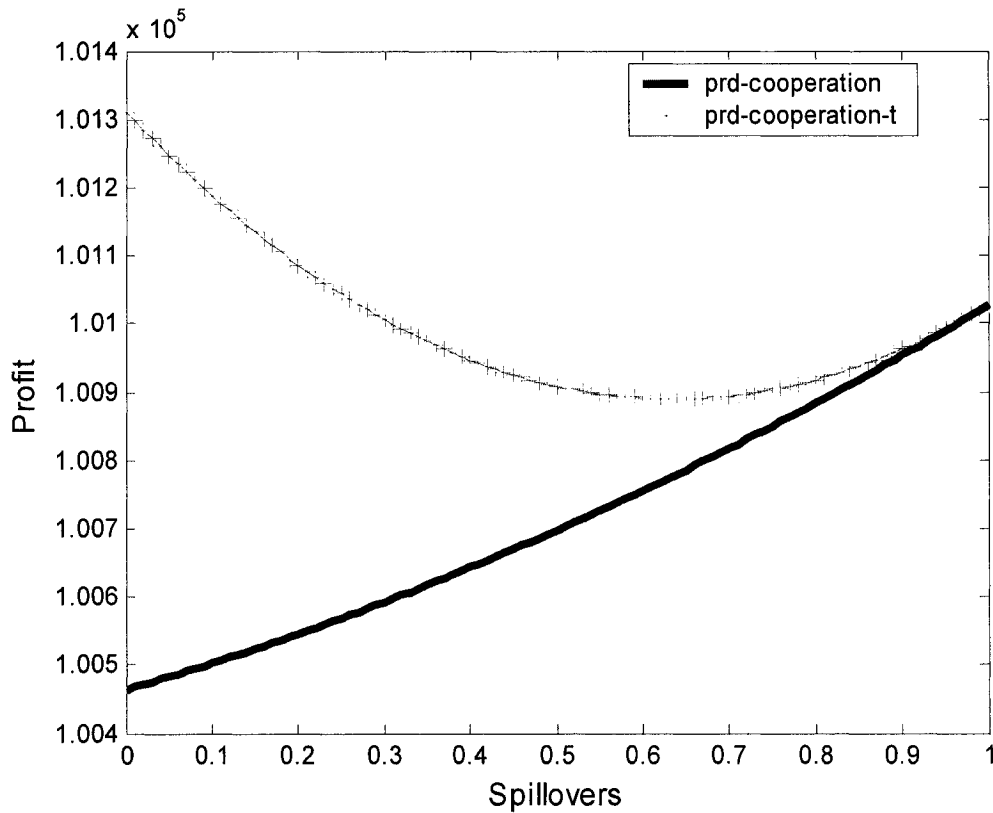


Figure 4.6: Profit of Domestic Firm

In the absence of the subsidy, the profit of the domestic firm increases with spillovers, because in this case, spillovers increase both x_d and x_f . However, with the subsidy present, there is a non-monotonic relationship between pr_d and β : pr_d first declines, then

increases with spillovers. Remember that, with the subsidy, x_d declines with spillovers, while x_f increases with spillovers. Initially, the increase in spillovers reduces x_d , which hurts the domestic firm; moreover, because spillovers are low, the domestic firm benefits little from the increase in x_f ; this explains why pr_d initially declines with spillovers. However, as spillovers increase further, the domestic firm benefits substantially from the increase in x_f , which has a positive effect on its profits. This effect is sufficiently strong to dominate the negative effect of the decline in x_d .

The profit of the domestic firm is higher in the presence of the subsidy.

4.7 Profit of foreign firm

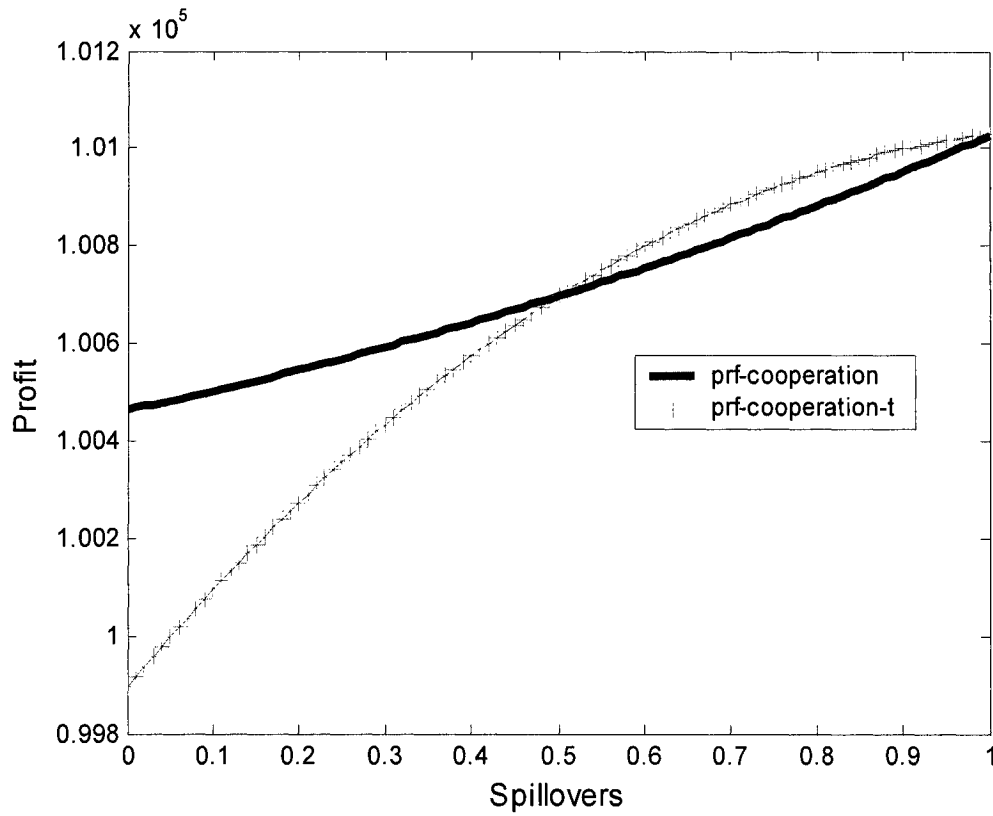


Figure 4.7: Profit of Foreign Firm

The profit of the foreign firm always increases with spillovers. The increase in spillovers benefits the foreign firm through multiple channels. In the presence of the subsidy, the increase in spillovers increases x_f and reduces x_d , which benefits the foreign firm. In the absence of the subsidy, the increase in spillovers increases x_f , which benefits the foreign firm; it also increases x_d , which by itself may hurt the foreign firm; but because of the increased diffusion rate and the increase in x_f , the net effect is to increase pr_f .

Note that the increase in pr_f is generally steeper in the presence of the subsidy, because in this case, the increase in spillovers reduces x_d , which is beneficial to the foreign firm. Only when spillovers are very high does the increase in pr_f slow down in the presence of the subsidy; this is because the high spillovers provide the domestic firm with a substantial benefit from the increase in x_f .

Moreover, whether the foreign firm benefits or loses from the subsidization of the domestic firm depends on spillovers. With low spillovers, the foreign firm makes higher profits in the absence of the subsidy. This is because the subsidy is high with low spillovers, and x_d is always higher in the presence of the subsidy. Moreover, the low spillovers provide little benefit for the foreign firm, while with high spillovers, the foreign firm actually prefers that the R&D of the domestic firm be subsidized. This is because x_d is higher with the subsidy; the high spillovers provide sufficient benefits for the foreign firm.

From the analysis of pr_d and pr_f , we can say that the foreign firm benefits most from the subsidy when spillovers are high, whereas the domestic firm benefits most when spillovers are low.

4.8 Output of domestic firm

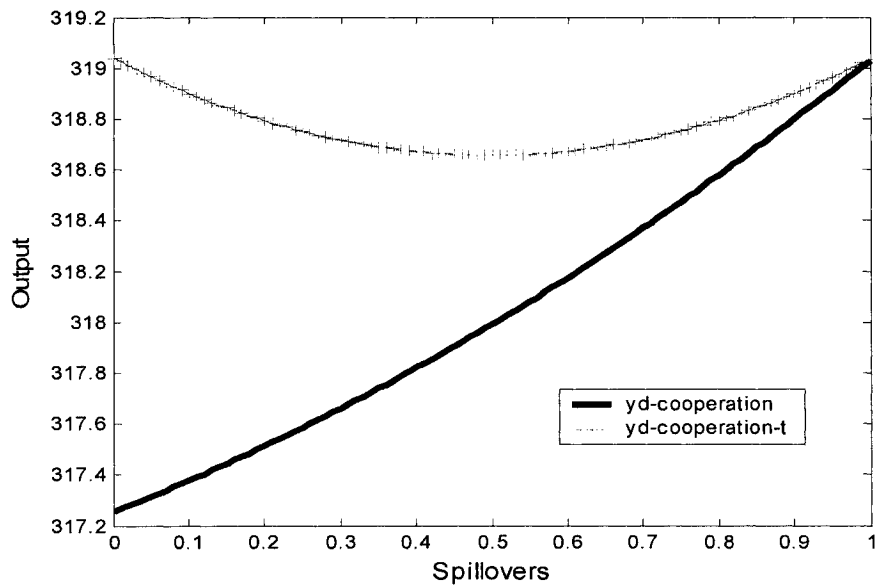


Figure 4.8: Output of Domestic Firm

4.9 Output of foreign firm

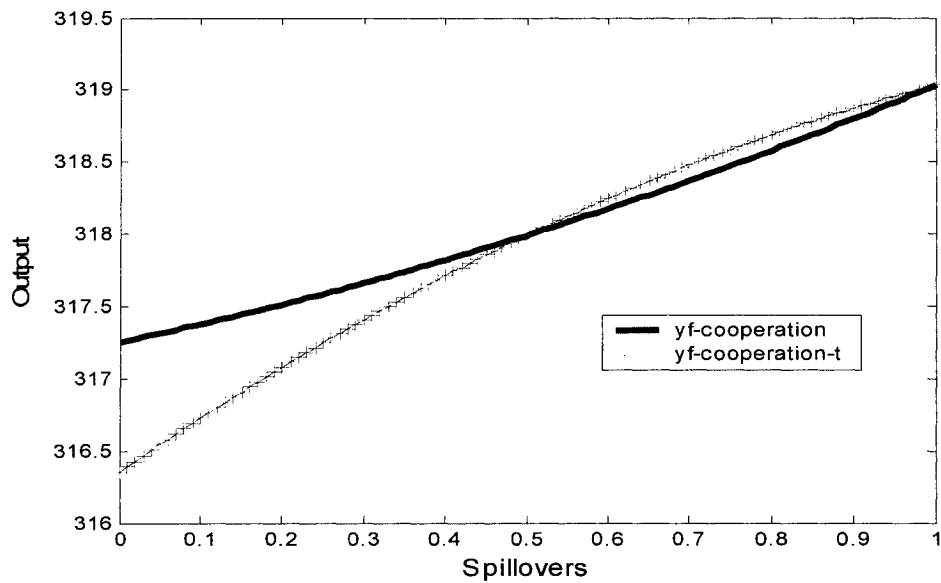


Figure 4.9: Output of Foreign Firm

The relationship between output and spillovers (Figures 4.8 and 4.9) is identical to the relationship between profits and spillovers. This is because higher output is due to a lower cost, which means a higher market share and higher profits.

4.10 Price

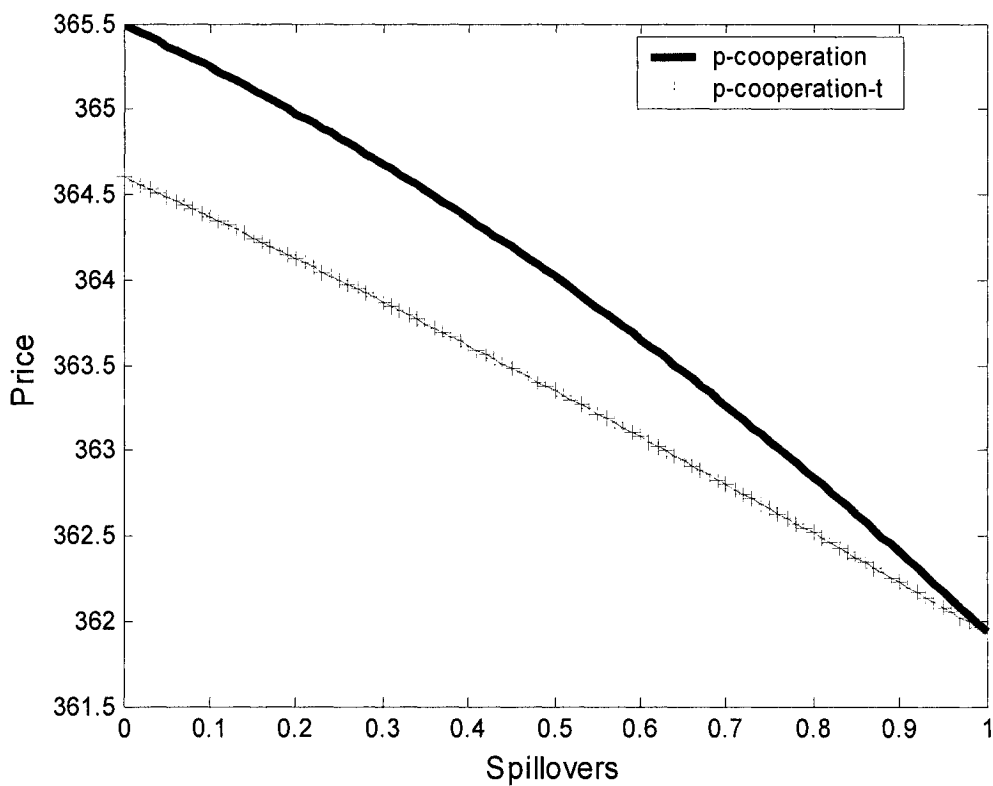


Figure 4.10: Price

The price always decreases with spillovers. This is because the production costs of both firms decline with spillovers. Moreover, the price is always lower in the presence of the

subsidy, because the production costs of both firms are lower in the presence of the subsidy.

4.11 Consumer surplus

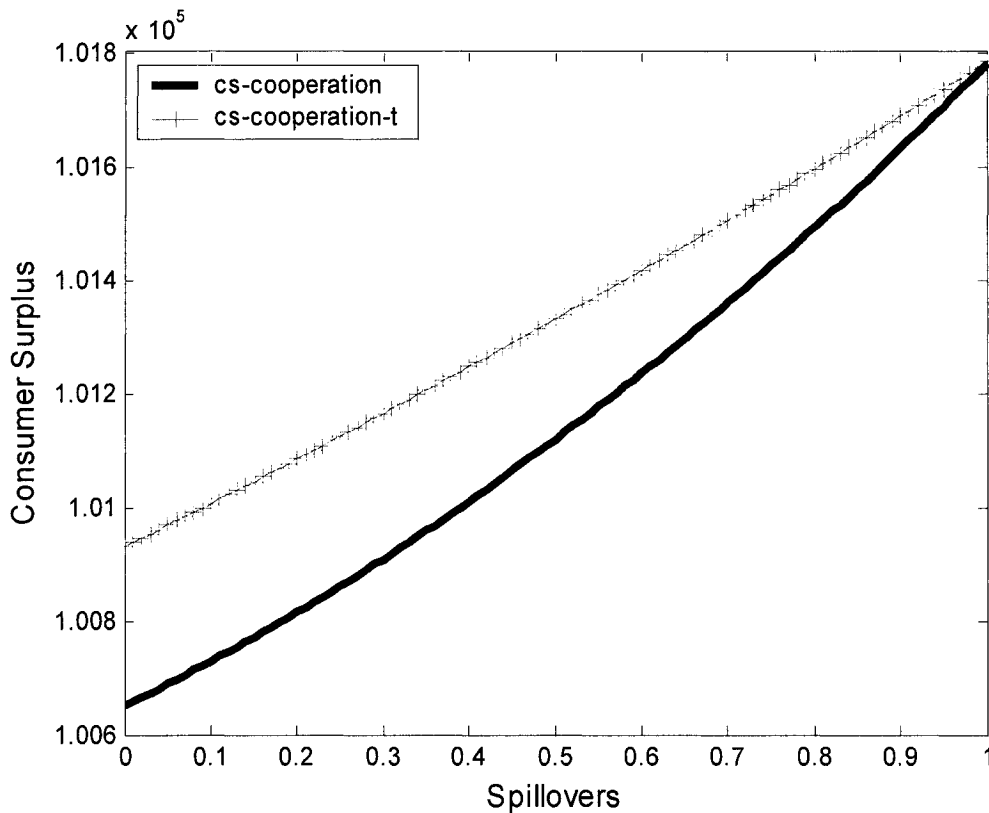


Figure 4.11: Consumer Surplus

From Figure 4.11, we can see that consumer surplus always increases with spillovers, due to the decline in the price with spillovers. Moreover, consumer surplus is always higher with the subsidy than without, because of the lower price. Consumers benefit from the higher R&D due to the subsidy.

4.12 Social welfare

We then went on to compare welfare levels between R&D cooperation with subsidy and R&D cooperation.

Difference between welfare levels ($W^t - W^c$)

$$\begin{aligned}
 & -\gamma(186\gamma A\alpha - 69\alpha^2\beta^2\gamma - 212\alpha\beta^2A + 120\alpha\beta^3A - 26\alpha\beta^4A + 162\alpha^2\beta\gamma - 69A^2\beta^2\gamma \\
 & + 162A^2\beta\gamma - 84\alpha^2\beta + 106\alpha^2\beta^2 - 60\alpha^2\beta^3 + 13\alpha^2\beta^4 - 84A^2\beta + 106A^2\beta^2 - 60A^2\beta^3 \\
 & + 13A^2\beta^4 - 93\gamma A^2 + 72\gamma^2A^2 - 93\gamma\alpha^2 + 72\gamma^2\alpha^2 - 50A\alpha + 25A^2 + 25\alpha^2 + 138\alpha\beta^2\gamma A \\
 & - 324\alpha\beta\gamma A - 144\gamma^2A\alpha + 168\alpha\beta A) / (13\beta^6 - 34\beta^5 - 94\beta^4\gamma - \beta^4 + 224\gamma\beta^3 + 68\beta^3) \quad (33) \\
 & + 405\gamma^2\beta^2 - 37\beta^2 - 348\beta^2\gamma - 702\gamma^2\beta + 416\gamma\beta - 34\beta + 513\gamma^2214\gamma + 25 - 324\gamma^3) \\
 & + \gamma(-18\gamma A^2 + 36\gamma\alpha A - 18\gamma\alpha^2 + A^2\beta^2 - 2\alpha\beta^2A - 4\alpha\beta A + 2A^2\beta + \alpha^2\beta^2 + 2\alpha^2\beta \\
 & + \alpha^2 - 2A\alpha + A^2) / (\beta^2 + 2\beta - 9\gamma + 1)^2
 \end{aligned}$$

where W^t is the social welfare in R&D cooperation with subsidy scenario, while W^c the social welfare in R&D cooperation.

The following figure illustrates the solution.

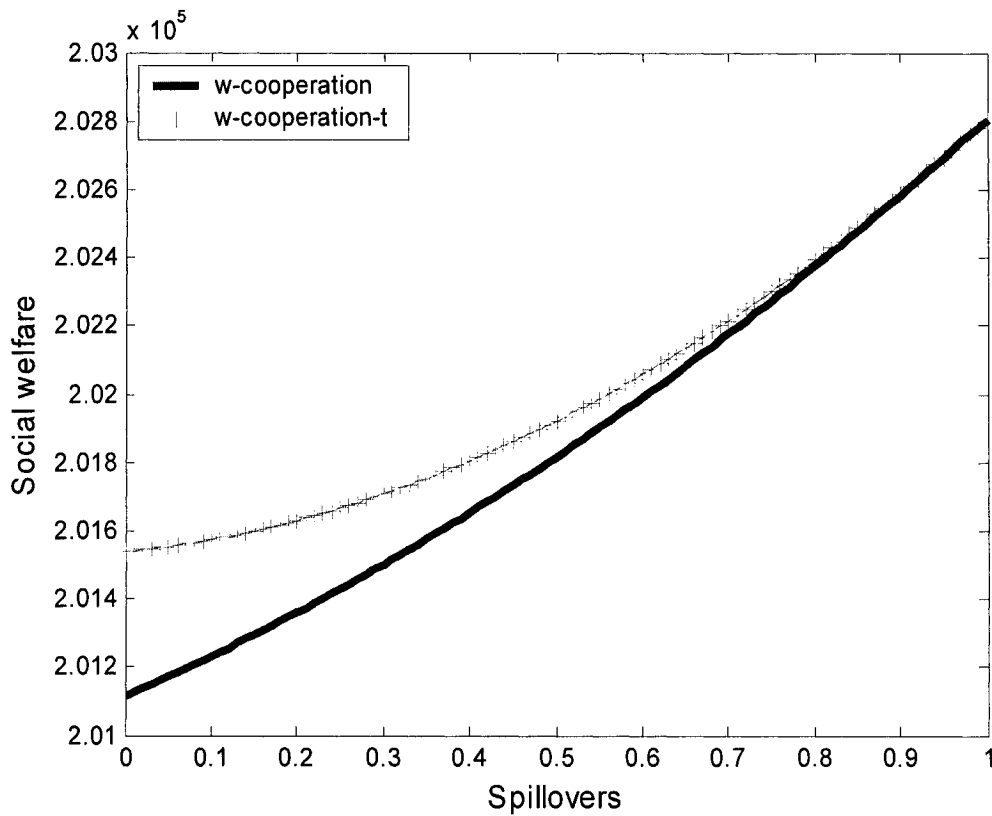


Figure 4.12: Social Welfare

Welfare is always increasing with spillovers. Welfare has three components: consumer surplus, domestic profits, and the cost of the subsidy. As explained above, consumer surplus is always increasing with spillovers. Domestic profits increase with spillovers in the absence of the subsidy, and first decrease then increase with spillovers in the presence of the subsidy. As for the cost of the subsidy, it declines with spillovers, because both domestic R&D and the subsidy rate decline with spillovers. In the absence of the subsidy, both consumer surplus and domestic profits increase with spillovers, and there is no subsidy, hence the total welfare increases with spillovers. With the subsidy present, consumer surplus and the decline in the cost of the subsidy contribute to the increase in wel-

fare; the change in domestic profits contributes positively to welfare when spillovers are high and negatively to welfare when spillovers are low. In this last case, the effects of the increase in consumer surplus and the decline in the cost of the subsidy dominate the negative effect of domestic profits, hence the total welfare increases with spillovers in the presence of the subsidy.

Welfare is always higher in the presence of the subsidy. The gap is largest when spillovers are low, and it declines with spillovers. This is because the optimal subsidy declines with spillovers, hence the gap between the two models declines with spillovers.

A	α	γ	β	t	x_d	x_f	y_d	y_f	c_d	c_f	P	pr_d	pr_f	CS	W
1000	50	60	0	0.5969	4.4341	1.7425	319.0419	316.3503	45.5659	48.2575	364.6078	101312.176	99895.3544	100930.812	201538.866
1000	50	60	0		1.7625	1.7625	317.2542	317.2542	48.2375	48.2375	365.4917	100463.822	100463.822	100650.211	201114.033
1000	50	60	0.25	0.4723	4.2024	2.1989	318.7516	317.249	45.2478	46.7504	363.9994	101043.387	100356.794	101124.182	201667.135
1000	50	60	0.25		2.2055	2.2055	317.5856	317.5856	47.2432	47.2432	364.8288	100568.775	100568.775	100860.617	201429.393
1000	50	60	0.5	0.3331	3.9818	2.6499	318.6576	317.9916	44.6932	45.3592	363.3508	100908.235	100697.35	101330.556	201921.911
1000	50	60	0.5		2.6499	2.6499	317.9916	317.9916	46.0251	46.0251	364.0167	100697.35	100697.35	101118.678	201816.028
1000	50	60	0.75	0.1777	3.7683	3.0978	318.7531	318.5855	43.9083	44.0759	362.6614	100902.967	100920.916	101550.115	202301.645
1000	50	60	0.75		3.0963	3.0963	318.4728	318.4728	44.5815	44.5815	363.0544	100849.726	100849.726	101424.937	202274.664
1000	50	60	1	0.0037	3.558	3.5448	319.0343	319.0343	42.8972	42.8972	361.9314	101026.119	101028.922	101782.869	202806.176
1000	50	60	1		3.5448	3.5448	319.0299	319.0299	42.9104	42.9104	361.9403	101026.119	101026.119	101780.046	202806.165

Table 4.1: Results of the Cooperative Case with/without R&D Subsidies

Chapter 5: R&D Uncertainty with Conditional or Unconditional Subsidies

In the previous chapters, the outcome of R&D was deterministic: the firm knew with certainty how much R&D output it would obtain from a given investment in R&D. In practice, however, firms face uncertainty with respect to R&D outcomes. R&D projects may succeed or fail. In this chapter and the next ones, we analyze the optimal subsidy in the presence of R&D uncertainty.

5.1 Background

There is literature on optimal R&D under uncertainty. Poyago-Theotoky (1998) analyses the role of a public firm in a mixed duopoly under uncertainty. Miyagiwa and Ohno (2002) analyze cooperative R&D in an oligopoly with spillovers and uncertainty. Lambertini (2004) studies the impact of demand uncertainty on R&D. Matsumura (2003) analyses R&D investments under uncertainty, considering cases where firms choose the size of the R&D project and cases where firms choose the probability of success. He also considers the subsidization of R&D.

The modeling of innovation with uncertainty in this thesis is similar to Matsumura's modeling (2003). Matsumura studies cost-reducing R&D under uncertainty. Innovation efforts can either reduce production costs or increase the probability of success. Matsumura (2003) also finds that the optimal subsidy increases according to the riskiness of the project.⁵ However, in his model, all subsidies are unconditional. This section goes beyond this literature in that it considers the subsidization of R&D. It also goes beyond Matsumura (2003), since it considers a new type of R&D subsidy, to be explained shortly.

In the current chapter, we focus on uncertainty with respect to success or failure when the probability of success is exogenous. In the following chapters, we endogenize the probability of success.

5.2 Model

This model is based on Matsumura (2003). The model is the same as in the previous chapter (R&D cooperation with subsidy), except that now the R&D of the domestic firm may succeed or fail. For simplicity, we assume that the foreign firm does not face any uncertainty: its project always succeeds. This allows us to focus on the behavior of the domestic firm and the government.

⁵ He goes even further, suggesting that risky investments should be subsidized, while safer investments should be taxed. This is because, in his model, when firms choose the probability of success, they invest too much in safe projects.

Let $\theta \in [0,1]$ ⁶ be the probability that the R&D of the domestic firm succeeds, and $1-\theta$ the probability that it fails. If the project succeeds, the domestic firm gets a cost reduction, x_d (chosen in the second stage), and the foreign firm benefits from this R&D output through spillovers, as before. If the R&D of the domestic firm fails, it only gets the spill-over benefit from the foreign firm, and the foreign firm only obtains the cost reduction from its own R&D.

The demand function is the same as above.

$$p = A - y_d - y_f \quad (34)$$

The expected cost functions become

$$c_d = \alpha - \theta x_d - \beta x_f \quad (35)$$

$$c_f = \alpha - x_f - \beta \theta x_d \quad (36)$$

Because of the presence of R&D uncertainty, the government may wish to make part of the R&D subsidy conditional on the success of the project. To consider that option, we let the government choose two subsidies. The first one is t_u , which is given to the firm in all cases, whether the project succeeds or fails. The second one is t_c , which is conditional on the success of the project: the firm gets it if the project succeeds and does not get it if the project fails. In general, such a subsidy may give the firm incentives to increase the chances of success (see next chapter). Moreover, such a conditional subsidy allows the

⁶ The thesis considers two cases of innovations outcomes: the size of the innovation and the probability of success. For the probability of success, this takes into account that many R&D projects may succeed or fail. A project succeeds with a certain probability. The firm can try to improve the chances of success by putting in more resources and more people into a project.

government to reward success and select the best firms and the best projects over time.

The total subsidy cannot exceed the cost of the project, hence $t_u + t_c \leq 1$.

Expected profits become

$$pr_d = (p - c_d)y_d - (1 - t_u - \theta t_c)\gamma x_d^2 \quad (37)$$

$$pr_f = (p - c_f)y_f - \gamma x_f^2 \quad (38)$$

and expected welfare becomes

$$W = CS + pr_d - (t_u + \theta t_c)\gamma x_d^2 \quad (39)$$

Using this framework, we solve the model starting from the last stage. In the third stage, firms choose output. At that stage, uncertainty is resolved, and firms know whether the project has succeeded or failed. In the case of success ($\theta=1$), the optimal output is

$$y_{dg} = \frac{1}{3}(A - \alpha + 2x_d - \beta x_d - x_f + 2\beta x_f) \quad (40)$$

$$y_{fg} = \frac{1}{3}(A - \alpha + x_d - 2\beta x_d + 2x_f - \beta x_f) \quad (41)$$

In the case of failure ($\theta=0$), the optimal output is

$$y_{db} = \frac{1}{3}(A - \alpha - x_f + 2\beta x_f) \quad (42)$$

$$y_{fb} = \frac{1}{3}(A - \alpha + 2x_f - \beta x_f) \quad (43)$$

where g denotes a “good” outcome, and b denotes a “bad” outcome.

Because there is still uncertainty in the second and first stages, the firm and the government will base their choices in those stages on expected output, which is given by

$$\begin{aligned} y_d &= \theta y_{dg} + (1 - \theta) y_{db} \\ &= \frac{1}{3} \theta (A - \alpha + 2x_d - \beta x_d - x_f + 2\beta x_f) + \frac{1}{3} (1 - \theta) (A - \alpha - x_f + 2\beta x_f) \end{aligned} \quad (44)$$

$$\begin{aligned} y_f &= \theta y_{fg} + (1 - \theta) y_{fb} \\ &= \frac{1}{3} \theta (A - \alpha + x_d - 2\beta x_d + 2x_f - \beta x_f) + \frac{1}{3} (1 - \theta) (A - \alpha + 2x_f - \beta x_f) \end{aligned} \quad (45)$$

We now turn to the second stage. In this stage, firms maximize expected profits, because they do not know yet whether the project will succeed or not, and hence whether the domestic firm will obtain the subsidy or not. The optimal investments in R&D are given by

$$\begin{aligned} x_d &= -((1 + \beta)(A - \alpha)(1 - 2\beta + \beta^2 - \gamma)\theta / \\ &((-1 + \beta^2)^2 \theta^2 - 9\gamma^2(-1 + t_u + t_c \theta) + (5 - 8\beta + 5\beta^2)\gamma(-1 + t_u + t_c \theta - \theta^2))) \end{aligned} \quad (46)$$

$$\begin{aligned} x_f &= -((1 + \beta)(A - \alpha)((1 + \beta)^2 \theta^2 + \gamma(-1 + t_u + t_c \theta)) / \\ &((-1 + \beta^2)^2 \theta^2 - 9\gamma^2(-1 + t_u + t_c \theta) + (5 - 8\beta + 5\beta^2)\gamma(-1 + t_u + t_c \theta - \theta^2))) \end{aligned} \quad (47)$$

In the first stage, the government chooses t_u and t_c . Note that, even though t_c is paid only after the project takes place (in the case of success), the government can commit initially to both t_u and t_c . Maximizing welfare with respect to t_u and t_c yields the following condition:

$$t_u + t_c = (191825 - 1963\theta^2 + \beta^4(5 - 55\theta^2) + \beta^5(-7 + 17\theta^2) + 2\beta^3(877 + 469\theta^2) - 2\beta^2(1715 + 2231\theta^2) + \beta(-189187 + 5525\theta^2)) / (318085 - 56759\beta - 518\beta^2 - 1574\beta^3 - 47\beta^4 + 13\beta^5) \quad (48)$$

It turns out that the solution to this problem is not unique. This is why we obtain one equation with two unknowns, t_u and t_c . This means that there are several combinations of t_u and t_c which can allow the government to maximize welfare. The left-hand side of the last equation represents the expected subsidy rate to the firm. This expected subsidy rate must be equal to a certain function, which depends on the parameters of the model, in particular β and θ . In what follows, we analyze how the optimal subsidies depend on these two parameters.

θ	β	$t_u + \theta t_c$	Combination 1		Combination 2		Combination 3		W	pr_d	x_d	
			t_u (min)	t_c (max)	t_u (med)	t_c (med)	t_u (max)	t_c (min)				
0.25	0	0.602676	0.470234667	0.529765333	0.4821408	0.4821408	0.4821408	0.602676	0	200441	99990.8	1.10028
0.25	0.5	0.333754	0.111672	0.888328	0.2670032	0.2670032	0.2670032	0.333754	0	201034	100317	0.990596
0.25	1	0.0037037	0	0.0148148	0.00296296	0.00296296	0.00296296	0.0037037	0	202097	101025	0.886388
0.5	0	0.601519	0.203038	0.796962	0.401012667	0.401012667	0.401012667	0.601519	0	200659	100254	2.20383
0.5	0.5	0.333624	0	0.667248	0.222416	0.222416	0.222416	0.333624	0	201211	100435	1.98313
0.5	1	0.0037037	0	0.0074074	0.002469133	0.002469133	0.002469133	0.0037037	0	202238	101025	1.77402
0.75	0	0.599591	0	0.799454667	0.342623429	0.342623429	0.342623429	0.599591	0	201025	100694	3.31397
0.75	0.5	0.333406	0	0.444541333	0.190517714	0.190517714	0.190517714	0.333406	0	201507	100632	2.97955
0.75	1	0.0037037	0	0.004938267	0.0021164	0.0021164	0.0021164	0.0037037	0	202474	101026	2.66414
1	0	0.596891	0	0.596891	0.2984455	0.2984455	0.2984455	0.596891	0	201539	101312	4.43405
1	0.5	0.333101	0	0.333101	0.1665505	0.1665505	0.1665505	0.333101	0	201922	100908	3.98183
1	1	0.0037037	0	0.0037037	0.00185185	0.00185185	0.00185185	0.0037037	0	202806	101026	3.558

Table 5.1: Optimal Subsidy with t_u and t_c

5.2 Analysis

Obtaining analytical results for the effects of β and θ turns out to be difficult. For that, we rely on numerical simulations. Table 5.1 presents the optimal subsidies for different combinations of spillovers and probability of success. For any given values of β and θ , there is an infinity of combinations of t_u and t_c allowing the government to achieve the optimum. To focus on our ideas, we calculate three levels of optimal subsidies. The first one is such that t_u is set as low as possible, and t_c is set as high as possible. This scheme would be useful to a government that wants to rely as much as possible on conditional subsidies. The second scheme is such that $t_u = t_c$. This is useful when the government wants the unconditional and conditional subsidies to be equal. The last one is such that t_u is set as high as possible, and t_c as low as possible. This is relevant when a government wants to minimize the use of conditional subsidies.

The table shows that, for any combination used, the optimal subsidy (t_u , t_c , or both) declines with spillovers. This is reminiscent of the results obtained in Chapter 4. As spillovers increase, the benefits to the foreign firm increase, and the optimal subsidy declines. Therefore, the presence of uncertainty and the use of conditional subsidies do not alter the basic relationship between the optimal subsidy to a domestic firm and spillovers.

The table also shows that the optimal subsidy declines with θ , meaning that, as the R&D project becomes less risky, the optimal subsidy declines. This means that R&D projects with a higher risk should get a larger subsidy. The reason for that counter-intuitive result is that firms invest too little in risky R&D projects. The higher the risk, the lower the R&D investment. The government needs to compensate for the higher risk by providing a higher subsidy rate.

The goal of the government is to induce the optimal level of R&D. The optimal level is induced by an optimal level of the expected subsidy. As θ increases, the probability of obtaining the subsidy increases; to restore the optimal subsidy to its optimal level, the government reduces the subsidy. Conversely, when θ decreases, the probability of obtaining the subsidy declines; to restore the expected subsidy to its optimal level, the government increases the subsidy.

Matsumura (2003) also finds that risky investments should be subsidized, while safe investments should be taxed. This is because firms invest too little in risky investments, and too much in safe investments.

We now turn to the choice between the different combinations. When the first combination is used, where t_c is set as high as possible, t_u is positive when θ is low, but nil when θ is intermediate or high. When θ is low, the project is very risky, and a conditional subsidy alone cannot give the firm sufficient incentives to perform the appropriate

level of R&D. Therefore, the government needs to set a strictly positive level of t_u . As θ increases, it becomes possible to rely only on t_c , and to set $t_u=0$.

The advantage of the second combination, where $t_u=t_c$, is its simplicity. It may be simpler for the government and for firms when there is a unique subsidy rate, which is obtained in all cases and which is obtained again in cases of success.

The last combination is such that t_c is as low as possible. In this case, it is always possible to set $t_c=0$ and use only t_u . This is equivalent to the model presented in the previous section.

Note that, for any given level of β and θ , the expected subsidy is the same, irrespective of the scheme used. This means that, irrespective of the combination used, the level of all variables (R&D, output, etc.) is the same. This is not surprising. Given that the firm is risk-neutral, it only cares about the expected subsidy, irrespective of its distribution between t_u and t_c . This is true because θ is exogenous. When θ is endogenous, however, as in the next section, this is no longer the case.

The table also shows how domestic R&D, domestic profits, and welfare are affected by spillovers and by the presence of uncertainty. Domestic R&D declines with spillovers, because the subsidy declines with spillovers.

When the probability of success is low, domestic profits increase with spillovers; in spite of the decline in the subsidy, the firm gets a larger benefit from the R&D of the foreign firm, which increases its profits. And because the probability of success is not too high, the domestic firm does not lose too much (in expectation) from the increase in spillovers, because there is a significant probability that the foreign firm does not receive any information. When the probability of success is high, however, domestic profits first decrease, then increase with spillovers. They first decrease with spillovers because there is a significant chance that the foreign firm obtains the information. However, as spillovers increase further, the benefit the domestic firm receives from the foreign firm is more important than the loss from the leakage of its own technology (remember that x_d declines with spillovers, but x_f increases with spillovers), hence pr_d increases with spillovers when the probability of success is sufficiently high.

As for welfare, it always increases with spillovers. Spillovers result in increased consumer surplus (because of the lower price) and may increase or decrease domestic profits (see above). But the positive effect on consumer surplus always dominates, resulting in an increase in total welfare.

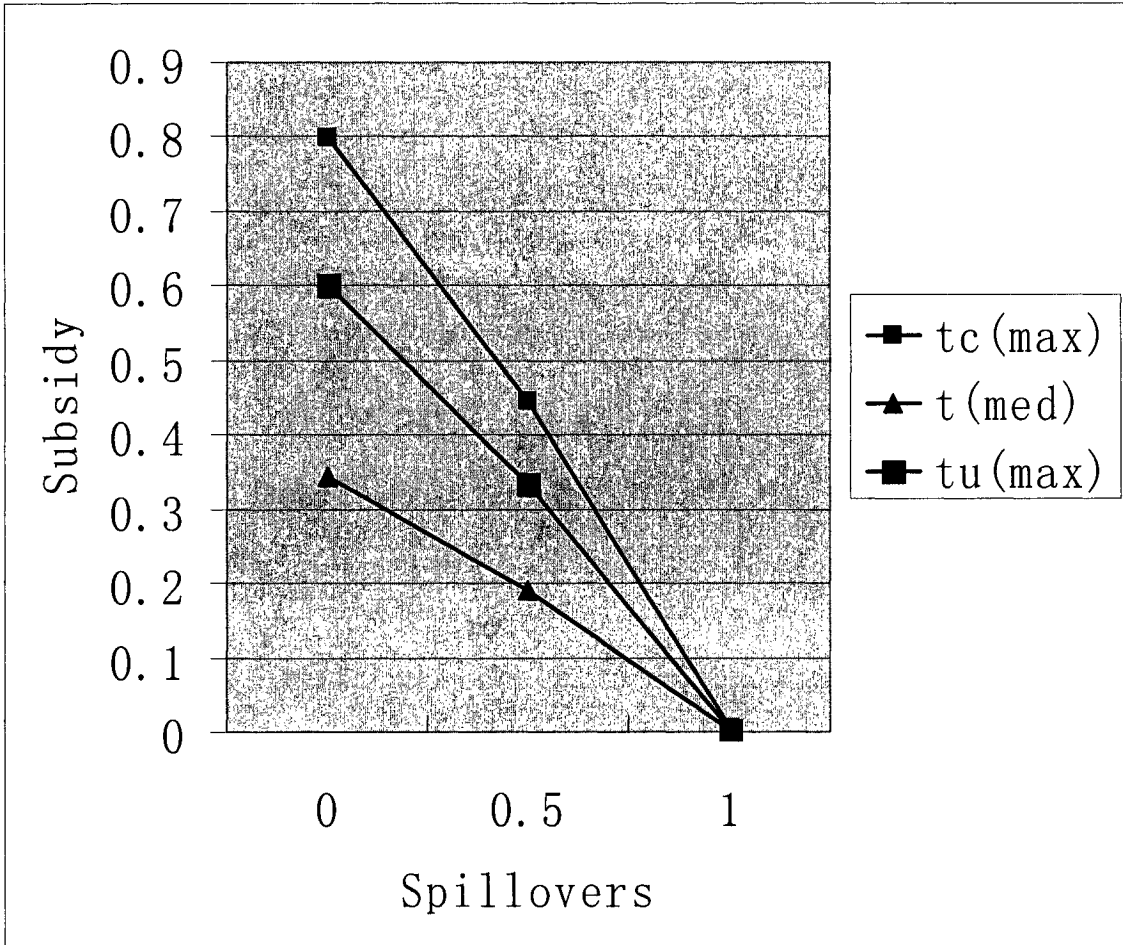


Figure 5.1: Effect of Spillovers on the Optimal Subsidy ($\theta = 0.75$)

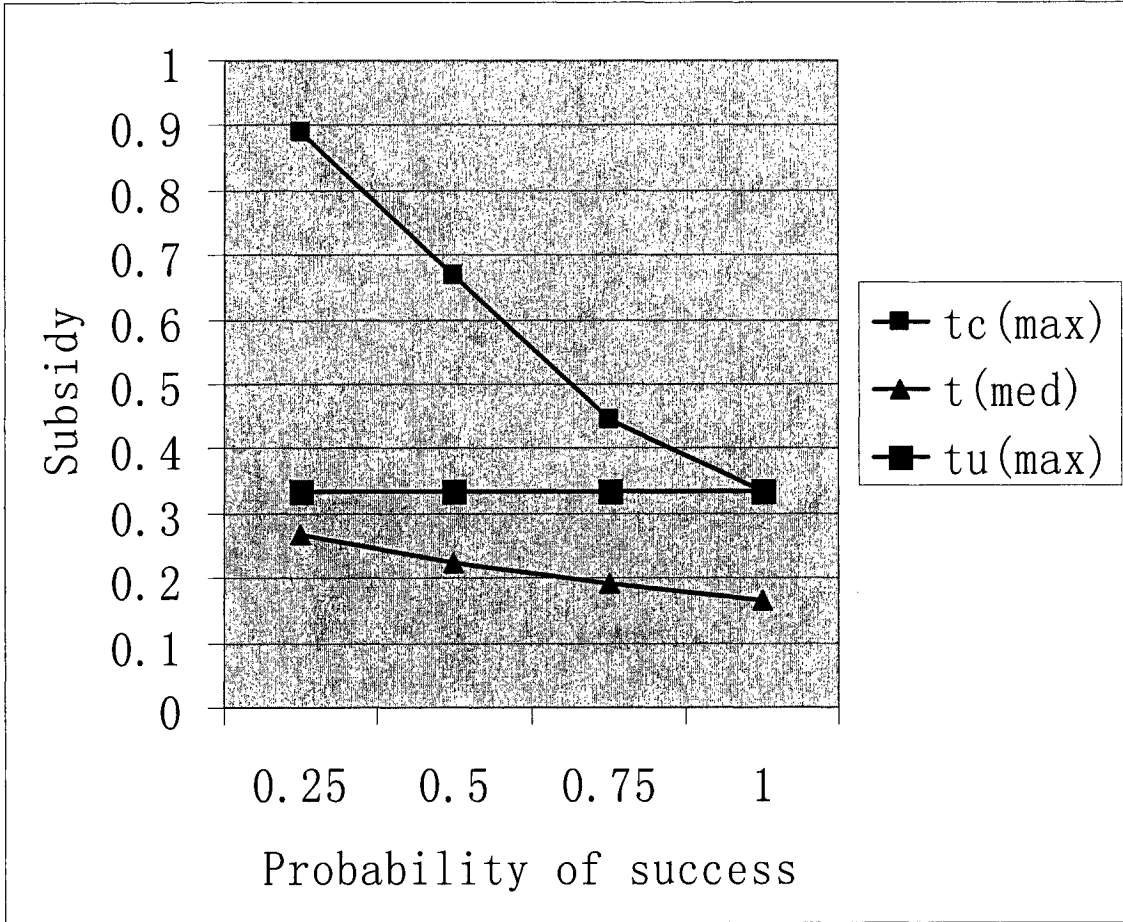


Figure 5.2: Effect of Probability of Success on the Optimal Subsidy ($\beta = 0.5$)

Chapter 6: Endogenous Probability of Success

6.1 Endogenous probability of success with conditional subsidies

In this section we allow for R&D uncertainty but let the firm choose the probability of success, θ . This allows us to analyze the interaction between the conditional subsidy and the efforts made by the firm. This endogenization comes at the cost of some simplifications, however. First, while it would be useful to allow the firm to choose both x and θ , this turns out to be difficult analytically. Therefore, x is now exogenous, and the firm chooses only θ . Second, as in the previous chapter, there is no uncertainty for the foreign firm, which hence does not make any decisions in the second stage (but there is still R&D cooperation). Finally, it is tedious to solve for the optimal subsidies when the government can choose both t_u and t_c . For that reason, we assume that the government only chooses t_c , and hence that there is no unconditional subsidy.

The demand function is the same as above. We call x the exogenous R&D output. The cost functions become

$$c_d = \alpha - \beta x - \theta x \quad (49)$$

$$c_f = \alpha - x - \beta \theta x \quad (50)$$

The cost of inducing a probability of success θ is $\lambda\theta^2$. The subsidy now goes to covering part of this cost.

The profit functions become

$$pr_d = (p - c_d)y_d - (1 - \theta t_c)\lambda\theta^2 \quad (51)$$

$$pr_f = (p - c_f)y_f \quad (52)$$

And the welfare function becomes

$$w = cs + pr_d - \theta t_c \lambda \theta^2 \quad (53)$$

Firms choose output in the last stage. This yields (we only write expected output)

$$y_d = \frac{1}{3}(A - \alpha - x + 2\beta x + 2x\theta - \beta x\theta) \quad (54)$$

$$y_f = \frac{1}{3}(A - \alpha - x(-2 + \beta + \theta - 2\beta\theta)) \quad (55)$$

In the second stage, the domestic firm chooses θ to maximize joint profits. This yields

$$\theta = \frac{1}{54t_c\lambda} \left(-10x^2 + 16\beta x^2 - 10\beta^2 x^2 + 18\lambda - 18t_u\lambda - \sqrt{(-108t_c(2Ax + 2A\beta x - 2\alpha x - 2\beta\alpha x - 8x^2 + 20\beta x^2 - 8\beta^2 x^2)\lambda)} \right) + (10x^2 - 16\beta x^2 + 10\beta^2 x^2 - 18\lambda + 18t_u\lambda)^2 \quad (56)$$

β	θ	t_c	W	pr_d
0	0.101932	1	200237	99383.2
0.1	0.115637	1	200512	99595.2
0.2	0.130201	1	200785	99803.7
0.3	0.145826	1	201055	100008
0.4	0.162807	1	201321	100208
0.5	0.181603	1	201583	100404
0.6	0.194178	0.937067	201839	100591
0.7	0.189908	0.734352	202094	100776
0.8	0.185624	0.512132	202349	100961
0.9	0.181327	0.268191	202604	101148
1	0	0	202672	101336

Table 6.1: Optimal θ with t_c only

In the first stage, the government chooses t_c . We fix all the parameters of the model to be able to obtain the optimal subsidy ($A = 1000, \alpha = 50, \lambda = 3000, x = 5$). We then calculate the optimal subsidy for any given level of β . Substituting this optimal subsidy into the

R&D and output solutions, Table 6.1 illustrates the optimal subsidy, the choice of θ by the domestic firm, and total welfare as a function of spillovers.

The optimal conditional subsidy declines (slightly) with spillovers. It is equal to 100% for $\beta \leq 0.5$ and declines for higher values of β , to reach 0 when $\beta=1$. The reason for this negative relationship is the same as above: higher spillovers increase the benefits to the foreign firm at the expense of the domestic firm.

As for θ , it first increases then decreases with spillovers. It first increases with spillovers because firms are cooperating in R&D, and higher spillovers increase the joint benefits from success. It then declines with spillovers because the decline of the subsidy becomes so strong as to increase the net cost of θ significantly.

Domestic profits always increase with spillovers, in spite of the decline in the subsidy and the probability of success for high values of spillovers. This is compensated by the benefit the domestic firm obtains from the R&D of the foreign firm, a benefit which increases with spillovers. Finally, total welfare increases with spillovers.

6.2 Endogenous probability of success with unconditional subsidies

In this section, we will compare conditional subsidies with unconditional subsidies. Assume that the model is as in the last section, except that now the government can use only unconditional subsidies. The model becomes

$$\begin{aligned}p &= A - y_d - y_f \\c_d &= \alpha - \beta x - \theta x \\c_f &= \alpha - x - \beta \theta x \\pr_d &= (p - c_d)y_d - (1 - t_u)\lambda\theta^2 \\pr_f &= (p - c_f)y_f \\CS &= (A - p)(y_d + y_f)/4 \\W &= cs + pr_d - t_u\lambda\theta^2\end{aligned}\tag{57}$$

The game is solved using the same method as in the previous sections.

The expected outputs

$$y_d = \frac{1}{3}(A - \alpha - x + 2\beta x + 2x\theta - \beta x\theta)\tag{58}$$

$$y_f = \frac{1}{3}(A - \alpha + 2x - \beta x - x\theta + 2\beta x\theta)\tag{59}$$

Then the domestic firm chooses θ to maximize joint profits. This yields

$$\theta = \frac{x(-A(1+\beta) + (1+\beta)\alpha + 2(2-5\beta+2\beta^2)x)}{(5-8\beta+5\beta^2)x^2 + 9(-1+t_u)\lambda} \quad (60)$$

The government chooses t_u to maximize expected welfare.

$$t_u = \frac{-((-1+\beta)(1375+625\beta^3-275\beta-125\beta^2(15+\alpha)) + A(275-500\beta+125\beta^2-18\lambda)-135\lambda)+18\alpha\lambda + 5\beta(-225+100\alpha+27\lambda))}{(3(2A(-5+\beta)+35\beta^2-2\beta(55+\alpha)+5(7+2\alpha))\lambda)} \quad (61)$$

β	θ	t_u	W	pr_d
0	0.44	0.6	200610	99921
0.1	0.43	0.55	200851	100050
0.2	0.42	0.5	201092	100181
0.3	0.415	0.45	201335	100315
0.4	0.406	0.392	201578	100452
0.5	0.398	0.334	201821	100592
0.6	0.389	0.273	202065	100735
0.7	0.38	0.209	202310	100881
0.8	0.372	0.143	202556	101030
0.9	0.363	0.073	202802	101181
1	0.354	0	203048	101336

Table 6.2: Optimal θ with t_u only

Table 6.2 illustrates the choice of θ by the firm and the choice of t_u by the government, as well as domestic profits and total welfare. Again, it is found that t_u declines with spillovers. The explanation is the same as above. Moreover, θ declines with spillovers, because of the decline of t_u , and in spite of the fact that spillovers should contribute to

increasing θ , because of the presence of R&D cooperation. Finally, domestic profits and total welfare increase with spillovers.

It is useful to compare the optimal subsidy and the choice of θ between this model and the previous one. As tables 6.1 and 6.2 illustrate, t_u is always lower than t_c . This is because the firm gets t_u with certainty; the conditionality of the provision of t_c forces the government to set it at a higher level.

Paradoxically, θ is higher when only t_u is offered than when only t_c is offered. Even though t_c is higher, and even though it is conditional on success, the presence of uncertainty with respect to the provision of the subsidy reduces the incentives for innovation efforts. Because the maximum total subsidy is 100%, there are limits to what a conditional subsidy alone can do. In this setting, it would be necessary to set the conditional subsidy at a rate much greater than 100% of the cost of innovation to induce a larger probability of success than under t_u only, which is unrealistic.

Because θ is higher under t_u only, domestic profits and total welfare are also higher under that scenario.

Chapter 7: Conclusions and Discussions

In this thesis, five different models dealing with the subsidization of cooperative R&D have been considered. Some of the models have been compared in terms of subsidies, R&D, welfare, and choice of innovation levels and probabilities.

A common finding is that the optimal subsidy declines with spillovers. This is true whether there is R&D uncertainty or not, whether the firm chooses the level of innovation or the probability of innovation, and whether the subsidy is conditional, unconditional or both. As explained above, this is due to the fact that the increase in spillovers increases the benefits to the foreign firm at the expense of the domestic firm, which is undesirable from the point of view of the domestic government. Hence the domestic government chooses to subsidize domestic R&D at a lower rate.

Domestic R&D increases with spillovers in the absence of the subsidy, because there is R&D cooperation. With the subsidy present, however, domestic R&D declines with spillovers, because the subsidy declines with spillovers. The subsidy always increases domestic R&D.

Foreign R&D increases with spillovers, because there is R&D cooperation, and because domestic R&D declines with spillovers.

In the presence of the subsidy, domestic profits first decrease, then increase with spillovers. This is due to the decline in the subsidy and in domestic R&D as spillovers increase. However, as spillovers increase further, the domestic firm benefits from the increase in the R&D of the foreign firm, which induces a positive relationship between domestic profits and spillovers. Moreover, the subsidy always increases domestic profits.

As explained in this paper, the foreign firm may benefit or lose from the subsidy, depending on spillovers: it loses with low spillovers, but gains with high spillovers.

Total welfare increases with spillovers, because consumer surplus increases with spillovers, and because domestic profits increase with spillovers when spillovers are high.

Moreover, total welfare increases with spillovers. Even when R&D declines with spillovers, the benefits of diffusion more than compensate, prices and costs are lower and consumer surplus and profits are higher.

From a policy point of view, we conclude that there is a role for R&D subsidization of a domestic firm when it competes with a foreign firm on the domestic and foreign markets, and firms cooperate technologically in the presence of R&D spillovers. The subsidy can help the domestic firm increase its R&D, which benefits consumers and increases domestic profits. The subsidy benefits the domestic industry most when spillovers are low. Moreover, the optimal subsidy should be set at higher levels when spillovers are low, and

at low levels when spillovers are high. This is because, with high spillovers, domestic R&D benefits the foreign firm significantly, and this may hurt the market share of the domestic firm on both domestic and foreign markets. However, the fact that the foreign firm may benefit from the subsidy (especially when spillovers are high) should not be perceived as negative. In fact, it is in these circumstances that the foreign government will have the fewest reasons to complain about the subsidy to the domestic firm.

The paper also considered R&D subsidies that are conditional on the success of the project, in the presence of R&D uncertainty. It was shown how the government can use different combinations of conditional and unconditional R&D subsidies to reach the same outcome. The government can rely on conditional subsidies alone if it wishes; however, for low values of the probability of success, it cannot; it must use also unconditional R&D subsidies to induce the socially optimal level of innovation. In general, the model warns against the use of conditional R&D subsidies alone. For a wide range of degrees of riskiness, conditional subsidies alone may yield suboptimal levels of innovation. This problem can be avoided by combining conditional and unconditional R&D subsidies to achieve the optimal expected subsidy. It was also shown that, even in the presence of uncertainty, the optimal subsidy declines with spillovers.

Surprisingly, it was found that the optimal subsidy declines with the probability of success, meaning that the government should give larger subsidies to riskier R&D projects and lower subsidies to safer R&D projects. The explanation of that result is that, as the

risk of the project increases, the firm invests less in R&D; to counter that effect, the government has to increase the R&D subsidy. This result sheds light on the debate of when R&D subsidies contribute to increasing R&D and when they finance research activities the firm would undertake anyway. The argument that the subsidy should be positively correlated with the social profitability from innovation (size of innovation, market size, probability of success, etc.) overlooks the fact that many of the factors that increase the social value of the innovation also increase its private value to the innovator, increasing the privately optimal investment. Hence, the innovator already accounts for a large number of these factors, and it may be redundant for the government to subsidize R&D projects because they are promising or socially beneficial; the innovator's actions already partly reflect those benefits. Rather, it is when the private value of the innovation is small (due to a small market size, a low probability of success, etc.) that government intervention is most needed.

We also considered the case where the domestic firm can devote resources to increase the probability of success of the R&D project. It was shown that the probability of success first increases, then decreases with spillovers. It first increases with spillovers because firms are cooperating in R&D, and higher spillovers increase the joint benefits from success. It then declines with spillovers because the decline of the subsidy becomes so strong as to increase the net cost of the probability of success significantly.

Moreover, we derived the optimal unconditional subsidy from when the firm chooses the probability of success. It was shown that the optimal unconditional subsidy is higher than

the optimal conditional subsidy. This is because the firm gets the conditional subsidy only with a certain probability; to compensate for that risk, the government has to set the conditional subsidy at a higher level.

It was also shown that, comparing these two schemes, the unconditional subsidy induces a higher level of innovation, a higher level of domestic profits, and a higher level of total welfare than the conditional subsidy alone. This is because the conditional subsidy puts too much risk on the domestic firm; in addition, part of the benefits of innovation goes to the foreign firm. Therefore, the domestic firm has to bear all the risks of innovation and of getting the subsidy or not; and then it must share the benefits with the foreign firm; this reduces its incentives for innovation under the conditional subsidy alone.

Therefore, the government may prefer to use only unconditional subsidies or a combination of conditional and unconditional subsidies, in the presence of international technological cooperation. A conditional subsidy alone may not be optimal and may be a risky policy.

In all five models, there is a major asymmetry between the objectives of the government and the objectives of the firm. The government cares only about domestic welfare; hence, whenever the subsidy penalizes the domestic firm and benefits the foreign firm, the government reduces the subsidy, whereas the domestic firm, because it is cooperating in R&D with the foreign firm, may respond positively to a change that benefits the foreign firm, as long as it increases total profits.

The limitations of the current work on conditional R&D subsidies should be seen as avenues for future research. The success or failure of an R&D project is not always easy to establish, even ex post; the project may be multidimensional and may succeed on some dimensions but fail on other dimensions; even in unidimensional cases, success may be a continuous rather than a discrete variable. Moreover, some projects may succeed technologically, but fail commercially. Firms may have private information about the true quality, and hence the probability of success, of their R&D projects.

References

- [1]. Atallah, Gamal, 2003, 'Information Sharing and the Stability of Cooperation, in Research Joint Ventures,' *Economics of Innovation and New Technology*, 12(6): 531-554
- [2]. Atallah, Gamal, 2004, 'The Allocation of Resources to Cooperative and Noncooperative R&D,' *Australia Economic Papers*.
- [3]. Brod, A., and Shivakumar, R., 1997, 'R&D Cooperation and the Joint Exploitation of R&D,' *The Canadian Journal of Economics*, 30(3):673-84.
- [4]. Caballero-Sanz, F., Moner-Colonques, R., and Sempere-Monerris, J.J., 1998, 'Market Structure and R&D Joint Ventures: The Case of Product Innovations,' *European Journal of Law and Economics*, 5:51-66.
- [5]. Cabral, L.M.B., 2000, 'R&D Cooperation and Product Market Competition,' *International Journal of Industrial Organization*, 18:1033-47.
- [6]. Church, J., and Ware, R., 1999, 'Industrial Organization – a Strategic Approach,' *McGraw-Hill*.
- [7]. D'Aspremont, C., and Jacquemin, A., 1988, 'Cooperative and Noncooperative R&D in Duopoly with Spillovers,' *American Economic Review*, 78(5):1133-37.
- [8]. DE Bondt, R., 1996, 'Spillovers and Innovative Activities,' *International Journal of Industrial Organization*, 15:1-28.
- [9]. Delbono, F., and Denicolo, V., 1990, 'R&D investment in a Symmetric and Homogeneous Oligopoly: Bertrand vs. Cournot,' *International Journal of Industrial Organization*, 8:297-314.

- [10]. Fölster, S., 1991, 'The Art of Encouraging Invention: A New Approach to Government Innovation Policy,' *The Industrial Institute for Economic and Social Research, Stockholm*.
- [11]. Fudenberg, D., and Tirole, J., 1991, 'Game Theory,' *The MIT Press, Cambridge, Mass.*
- [12]. Hagedoorn, J., Link, A.N., and Vonortas, N.S., 2000, 'Research Partnerships,' *Research Policy*, 29:567-86.
- [13]. Kamien, M.I., and Zang, I., 1993, 'Competing Research Joint Ventures,' *Journal of Economics and Management Strategy*, 2(1):23-40.
- [14]. Levin, R.C., and Reiss, P.C., 1988, 'Cost-Reducing and Demand-Creating R&D with Spillovers,' *The Rand Journal of Economics*, 19(4): 538-56.
- [15]. Kesteloot, K., and Veugelers, R., 1997, 'R&D Cooperation between Asymmetric Partners, Competition, Cooperation, Research and Development: The Economics of Research Joint Ventures (J.A. Poyago-Theotoky, cd.),' London: *Macmillan*, 97-125.
- [16]. Lambertini, L., 2004, 'Process R&D in Monopoly under Demand Uncertainty,' working paper 507.
- [17]. Long, N.V., and Soubeyran A., 1997, 'Greater Cost Dispersion Improves Oligopoly Profit: Asymmetric Contributions to Joint Ventures,' *The Japanese Economic Review*, 48:2166-175.
- [18]. Matsumura, T., 2003, 'Strategic R&D Investment with Uncertainty', *Economics Bulletin*, 12(1):1-7.

- [19]. Motta, M., 1996, 'Research Joint Ventures in an International Economy,' *Ricerche Economiche*, 50:293-315.
- [20]. Motta, M., 1992, 'Cooperative R&D and Vertical Product Differentiation,' *International Journal of Industrial Organization*, 10:643-61.
- [21]. Muller, T. and Schnitzer, M., 2003, 'Technology Transfer and Spillovers in International Joint Ventures,' *CEPR Discussion Papers*.
- [22]. Miyagiwa, K., and Yuka, O., 2002, 'Uncertainty, Spillovers, and Cooperative R&D,' *International Journal of Industrial Organization*, 20(6):855-76.
- [23]. Oz Shy, 'Industrial Organization: Theory and Applications,' Ch. 6, 7, and 9.
- [24]. Petit, M.L., and Tolwinski, B., 1999, 'R&D Cooperation or Competition?,' *European Economic Review*, 43:185-208.
- [25]. Petrakis, E., and Poyago-Theotoky, J., 2002, 'R&D Subsidies Versus R&D Cooperation in a Duopoly with Spillovers and Pollution,' *Blackwell Publishing Ltd*.
- [26]. Poyago-Theotoky, J., 1996, 'R&D Competition with Asymmetric Firms,' *Scottish Journal of Political Economy*, 43(3):334-42.
- [27]. Poyago-Theotoky, J., 1995, 'Equilibrium and Optimal Size of a Research Joint Venture in an Oligopoly with Spillovers,' *Journal of Industrial Economics*, 43:209-25.
- [28]. Poyago-Theotoky, J., 1998, 'R&D Competition in a Mixed Duopoly under Uncertainty and Easy Imitation,' *Journal of Comparative Economics*, 26(3):415-28.
- [29]. Qiu, L. and Tao, Z., 1998, 'Policy on International R&D Cooperation Subsidy or Tax?,' *European Economic Review*, 42: 1727-1750.

- [30]. Rosen, R.J., 1991, 'Research and Development with Asymmetric Firm Sizes,' *The RAND Journal of Economics*, 22(3):411-29.
- [31]. Rosenkranz, S., 2003, 'Simultaneous Choice of Process and Product Innovation When Consumers Have a Preference for Product Variety,' *Journal of Economic Behavior & Organization*, 50:183-201.
- [32]. Saggi, P., and Lin, K., 2002, 'Product Differentiation, Process R&D, and the Nature of Market Competition,' *European Economic Review*, 46:201-11.
- [33]. Spencer, B., and Brander, J., 1983, 'International R&D Rivalry and Industrial Strategy,' *Review of Economic Studies*, L:707-722.
- [34]. Tanayama, T., Toivanen, O., and Takalo, T., 2004, 'Selection or Self-Rejection?,' *RICAFE Working Paper*, No. 014.
- [35]. Steurs, G., 1995, 'Inter-Industry R&D Spillovers: What Difference Do They Make?,' *International Journal of Industrial Organization*, 13:249-76.
- [36]. Varian. H., *Intermediate Microeconomics: A Modern Approach*; Fifth Edition, 1999.

Appendix 1

In the following parts, we assume that a , b and r are equal to α , β and γ , which appear in the previous equations in terms of simplification.

Solutions to the cooperative case with R&D subsidy

$t =$

$$\frac{2*(5*b^5-25*b^4+26*b^3+22*r*b^3+14*b^2-66*b^2*r+90*r*b-27*r^2*b-31*b+11-38*r+27*r^2)/(13*b^5-47*b^4+46*b^3-27*r*b^3-9*b^2*r+22*b^2-18*r^2*b+135*r*b-59*b+25-99*r+90*r^2)}$$

$xd_s =$

$$\frac{(13*b^5-47*b^4+46*b^3-27*r*b^3-9*b^2*r+22*b^2-18*r^2*b+135*r*b-59*b+25-99*r+90*r^2)*(a-A)/(13*b^6-34*b^5-94*r*b^4-b^4+68*b^3+224*r*b^3-348*b^2*r-37*b^2+405*r^2*b^2+416*r*b-702*r^2*b-34*b+513*r^2+25-324*r^3-214*r)}$$

$xf_s =$

$$\frac{(-13*b^5*A+13*b^5*a-47*b^4*a+47*b^4*A-17*b^3*a*r+46*b^3*a+17*r*A*b^3-46*b^3*A-22*A*b^2+22*a*b^2+39*r*A*b^2-39*a*b^2*r-59*a*b+36*r^2*a*b-117*r*A*b-36*r^2*A*b+117*r*a*b+59*A*b-25*A+77*r*A+25*a-77*r*a+36*a*r^2-36*A*r^2)/(13*b^6-34*b^5-94*r*b^4-b^4+68*b^3+224*r*b^3-348*b^2*r-37*b^2+405*r^2*b^2+416*r*b-702*r^2*b-34*b+513*r^2+25-324*r^3-214*r)}$$

yd_s =

$$\begin{aligned} & r*(-106*a*b-105*a*b^2*r+156*a*b^2+204*r*a*b-123*r*a+108*a*r^2+29*b^4*a- \\ & 110*b^3*a+106*A*b-156*A*b^2+110*b^3*A-204*r*A*b+105*r*A*b^2- \\ & 29*b^4*A+123*r*A-31*A+31*a-108*A*r^2)/(13*b^6-34*b^5-94*r*b^4- \\ & b^4+68*b^3+224*r*b^3-348*b^2*r-37*b^2+405*r^2*b^2+416*r*b-702*r^2*b- \\ & 34*b+513*r^2+25-324*r^3-214*r) \end{aligned}$$

yf_s =

$$\begin{aligned} & r*(-146*a*b-159*a*b^2*r+144*a*b^2+312*r*a*b-177*r*a+108*a*r^2+19*b^4*a- \\ & 70*b^3*a+146*A*b-144*A*b^2+70*b^3*A-312*r*A*b+159*r*A*b^2- \\ & 19*b^4*A+177*r*A-53*A+53*a-108*A*r^2)/(13*b^6-34*b^5-94*r*b^4- \\ & b^4+68*b^3+224*r*b^3-348*b^2*r-37*b^2+405*r^2*b^2+416*r*b-702*r^2*b- \\ & 34*b+513*r^2+25-324*r^3-214*r) \end{aligned}$$

p_s =

$$\begin{aligned} & -(-13*b^4*A+8*b^3*A+48*a*b^2*r+33*r*A*b^2+30*A*b^2+30*r*A*b-16*A*b- \\ & 84*r*a*b-108*A*r^2+84*r*a+105*r*A-25*A-216*a*r^2)/(13*b^4-8*b^3-30*b^2- \\ & 81*b^2*r+54*r*b+16*b+25+324*r^2-189*r) \end{aligned}$$

prd_s =

$$\begin{aligned} & -3*r*(1172*r*A*a-12096*r^3*a*b*A-602*a^2*b^6*r+2205*a^2*b^4*r^2- \\ & 2102*a^2*b^2*r+6642*a^2*b^2*r^2+4104*a^2*b^3*r+160*a*b^2*A- \end{aligned}$$

$$\begin{aligned}
&5436*a^2*b*r^2+2524*a^2*b^5*r-5940*a^2*b^3*r^2+112*a*b^6*A+80*a*b^3*A- \\
&196*a*b^4*A+1148*a^2*b*r-4486*a^2*b^4*r-2102*A^2*b^2*r+4104*A^2*b^3*r- \\
&5436*A^2*b*r^2- \\
&5940*A^2*b^3*r^2+2524*A^2*b^5*r+1148*A^2*b*r+6642*A^2*b^2*r^2- \\
&4486*A^2*b^4*r+2205*A^2*b^4*r^2-602*A^2*b^6*r-26*A*b^8*a- \\
&64*A*b^5*a+16*a^2*b-80*a^2*b^2-56*a^2*b^6-8*a^2*b^7- \\
&40*a^2*b^3+98*a^2*b^4+16*A^2*b-80*A^2*b^2-56*A^2*b^6-8*A^2*b^7- \\
&40*A^2*b^3+98*A^2*b^4+13*A^2*b^8+32*A^2*b^5+13*a^2*b^8+32*a^2*b^5- \\
&586*r*A^2-6048*r^3*A^2+3105*r^2*A^2-586*r*a^2- \\
&6048*r^3*a^2+3105*r^2*a^2- \\
&50*A*a+25*A^2+25*a^2+16*a*b^7*A+4204*a*b^2*r*A- \\
&8208*a*b^3*r*A+10872*a*b*A*r^2+11880*a*b^3*r^2*A-5048*a*b^5*r*A- \\
&2296*a*b*r*A-13284*a*b^2*r^2*A+8972*a*b^4*r*A+12096*r^3*A*a- \\
&3456*r^3*A^2*b^2-6210*r^2*A*a-3456*r^3*a^2*b^2- \\
&32*a*b*A+6912*r^3*A*a*b^2+1204*A*b^6*r*a- \\
&4410*A*b^4*r^2*a+6048*r^3*A^2*b- \\
&7776*a*r^4*A+3888*a^2*r^4+6048*r^3*a^2*b+3888*A^2*r^4)/(13*b^4-8*b^3- \\
&30*b^2-81*b^2*r+54*r*b+16*b+25+324*r^2-189*r)/(13*b^6-34*b^5-94*r*b^4- \\
&b^4+68*b^3+224*r*b^3-348*b^2*r-37*b^2+405*r^2*b^2+416*r*b-702*r^2*b- \\
&34*b+513*r^2+25-324*r^3-214*r)
\end{aligned}$$

prf_s =

$$\begin{aligned}
& -r*(12068*r*A*a-82944*r^3*a*b*A-634*a^2*b^6*r+6633*a^2*b^4*r^2- \\
& 15846*a^2*b^2*r+44334*a^2*b^2*r^2+5464*a^2*b^3*r-1112*a*b^2*A- \\
& 47664*a^2*b*r^2+1092*a^2*b^5*r-20880*a^2*b^3*r^2-2936*a*b^6*A- \\
& 5032*a*b^3*A+5636*a*b^4*A+16644*a^2*b*r-942*a^2*b^4*r- \\
& 15846*A^2*b^2*r+5464*A^2*b^3*r-47664*A^2*b*r^2- \\
& 20880*A^2*b^3*r^2+1092*A^2*b^5*r+16644*A^2*b*r+44334*A^2*b^2*r^2- \\
& 942*A^2*b^4*r+6633*A^2*b^4*r^2-634*A^2*b^6*r-338*A*b^8*a-136*A*b^5*a- \\
& 1700*a^2*b+556*a^2*b^2+1468*a^2*b^6-884*a^2*b^7+2516*a^2*b^3- \\
& 2818*a^2*b^4-1700*A^2*b+556*A^2*b^2+1468*A^2*b^6- \\
& 884*A^2*b^7+2516*A^2*b^3- \\
& 2818*A^2*b^4+169*A^2*b^8+68*A^2*b^5+169*a^2*b^8+68*a^2*b^5- \\
& 6034*r*A^2-27864*r^3*A^2+20457*r^2*A^2-6034*r*a^2- \\
& 27864*r^3*a^2+20457*r^2*a^2- \\
& 1250*A*a+625*A^2+625*a^2+1768*a*b^7*A+31692*a*b^2*r*A- \\
& 10928*a*b^3*r*A+95328*a*b*A*r^2+41760*a*b^3*r^2*A-2184*a*b^5*r*A- \\
& 33288*a*b*r*A-88668*a*b^2*r^2*A+1884*a*b^4*r*A+55728*r^3*A*a- \\
& 23976*r^3*A^2*b^2-40914*r^2*A*a- \\
& 23976*r^3*a^2*b^2+3400*a*b*A+47952*r^3*A*a*b^2+1268*A*b^6*r*a- \\
& 13266*A*b^4*r^2*a+41472*r^3*A^2*b- \\
& 23328*a*r^4*A+11664*a^2*r^4+41472*r^3*a^2*b+11664*A^2*r^4)/(13*b^4- \\
& 8*b^3-30*b^2-81*b^2*r+54*r*b+16*b+25+324*r^2-189*r)/(13*b^6-34*b^5- \\
& 94*r*b^4-b^4+68*b^3+224*r*b^3-348*b^2*r-37*b^2+405*r^2*b^2+416*r*b- \\
& 702*r^2*b-34*b+513*r^2+25-324*r^3-214*r)
\end{aligned}$$

cs_s =

$$36*r^2*(4*a*b^2-4*A*b^2+7*A*b-7*a*b+7*a+18*r*A-18*r*a-7*A)^2/(13*b^4-8*b^3-30*b^2-81*b^2*r+54*r*b+16*b+25+324*r^2-189*r)^2$$

w_s =

$$\begin{aligned} & -r*(186*r*A*a-69*a^2*b^2*r-212*a*b^2*A+120*a*b^3*A- \\ & 26*a*b^4*A+162*a^2*b*r-69*A^2*b^2*r+162*A^2*b*r-84*a^2*b+106*a^2*b^2- \\ & 60*a^2*b^3+13*a^2*b^4-84*A^2*b+106*A^2*b^2-60*A^2*b^3+13*A^2*b^4- \\ & 93*r*A^2+72*r^2*A^2-93*r*a^2+72*r^2*a^2- \\ & 50*A*a+25*A^2+25*a^2+138*a*b^2*r*A-324*a*b*r*A- \\ & 144*r^2*A*a+168*a*b*A)/(13*b^6-34*b^5-94*b^4*r- \\ & b^4+224*r*b^3+68*b^3+405*r^2*b^2-37*b^2-348*b^2*r-702*r^2*b+416*r*b- \\ & 34*b+513*r^2-214*r+25-324*r^3) \end{aligned}$$

Appendix 2

In the following part, we assume that a , b and r are equal to α , β and γ , which appear in the previous equations in terms of simplification.

Solutions to the cooperative case without R&D subsidy

$$xd_c = (-A*b+a*b+a-A)/(b^2+2*b-9*r+1)$$

$$xf_c = (-A*b+a*b+a-A)/(b^2+2*b-9*r+1)$$

$$yd_c = 3*r*(-A+a)/(b^2+2*b-9*r+1)$$

$$yf_c = 3*r*(-A+a)/(b^2+2*b-9*r+1)$$

$$p_c = -(-A*b^2-2*A*b+3*r*A-A+6*r*a)/(b^2+2*b-9*r+1)$$

$$prd_c = -r*(A^2-2*A*a+a^2)/(b^2+2*b-9*r+1)$$

$$prf_c = -r*(A^2-2*A*a+a^2)/(b^2+2*b-9*r+1)$$

$$cs_c = 9*r^2*(-A+a)^2/(b^2+2*b-9*r+1)^2$$

w_c =

$$\frac{-r(-18rA^2 + 36rAa - 18ra^2 + A^2b^2 - 2ab^2A - 4abA + 2A^2b + a^2b^2 + 2a^2b + a^2 - 2Aa + A^2)}{(b^2 + 2b - 9r + 1)^2}$$