2004s-02

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Série Scientifique
Scientific Series

Montréal
Janvier 2004

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Centre interuniversitaire de recherche en analyse des organisations

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ISSN 1198-8177

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Résumé / *Abstract*

Le papier propose un modèle où les firmes investissent dans la protection de leurs innovations afin de réduire les externalités de recherche reçues par leurs concurrents, en plus d'investir dans la R&D permettant de réduire leurs coûts de production. Le résultat principal est qu'une augmentation des externalités technologiques augmente l'investissement en protection, ce qui implique que la protection légale et stratégique sont des substituts. Un niveau plus élevé de différenciation des produits est associé avec davantage d'innovation et moins de protection. Une augmentation dans la taille du marché, une réduction des coûts de la protection, ou une réduction des coûts de la recherche, induisent une augmentation de la protection. Les externalités de recherche augmentent la réduction des coûts lorsque le niveau de différenciation des produits est élevé, et ont un effet en forme de U inversé lorsque le niveau de différentiation est faible. La concurrence en quantités génère des niveaux plus élevés de R&D, de protection et de réduction des coûts.

Mots clés : protection des innovations, innovation, technologie, externalités de recherche, R&D, appropriation des innovations.

This paper proposes a model where firms invest in secrecy to limit technological spillovers accruing to their competitors, in addition to investing in cost-reducing R&D. The main result of the paper is that increases in spillovers increase secrecy, suggesting that legal and strategic protection are substitutes. Higher product differentiation is associated with higher levels of innovation and lower levels of secrecy. An increase in the size of the market, a reduction in the cost of secrecy, or a reduction in the cost of R&D, all lead to an increase in secrecy. As for the effect of spillovers on effective cost reduction, it is positive when products are sufficiently differentiated, and has an inverted-U shape with low product differentiation. Compared to price competition, quantity competition yields higher levels of R&D, secrecy and effective cost reduction.

Keywords: *secrecy, protection, innovation, technology, spillovers, R&D, appropriability*

Codes JEL : L13, O31, O32, O34

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1. Introduction

Investments in research and development are a major source of competitive advantage in modern industrial organization. One major characteristic of discovery and innovation is the imperfect control over technology diffusion: technology leaks out to competitors through employees, scientists, suppliers, customers, trade, patent disclosure, etc. Technology exchange and sharing is both valued and apprehended by firms. On the one hand, technology exchange is behind the formation of many cooperative research agreements.[1] On the other hand, information exchange is not always positively viewed, and firms may prefer to limit the diffusion of their technology for competitive reasons. Technological spillovers, both intra and inter-industry, are widespread and significant, and can dampen the incentives for innovation considerably. In that context one can expect firms to try to limit those spillovers by reducing technological flows to their competitors.

The theoretical literature on R&D investments and spillovers is blooming. The issues of R&D spending, R&D spillovers, R&D cooperation, and public policy towards R&D have been dealt with extensively. In particular, the effect of spillovers on firms' incentives to invest in R&D has been covered by a number of papers. In most of this literature spillovers are taken as given by firms, and studies have typically focused on how firms react to knowledge spillovers.

The present paper contributes to the literature on strategic R&D investment by analysing the interaction between investments in innovation and investments in secrecy. I will model the behaviour of two firms which compete by setting output/prices. Firms will be able to invest in cost-reducing Research and Development. However, there are knowledge spillovers which imply that a firm can benefit from the technology invented by its competitor. This benefit is not, as has been assumed until now in the literature, exogenous, rather, it is determined by firms' efforts to protect their innovations. The "effective spillover rate" depends on both an exogenous spillover level and an endogenous investment in secrecy. In a three-stage game, firms decide first on R&D, then on investments in secrecy, and finally compete in output/prices.

1.For instance, the European cooperative research programs Esprit and Race require participating firms to share information. Branstetter and Sakakibara (1998) report that access to complementary knowledge of other consortium members is the most highly cited motive behind participation in research consortia by Japanese R&D managers. Mariti and Smiley (1983) studied 70 cooperative agreements between European firms which took place in 1980, and found that one way flows of information were behind 41% of agreements, while information sharing (two-ways flows of information) were behind 29% of agreements. Cassiman and Veugelers (2002), from the study of a sample of firms from the Belgian manufacturing industry, find that spillovers received by a firm tend to be higher when the firm engages in cooperative R&D, which is consistent with improved information sharing between cooperating firms.

The main results of the paper are as follows. First, increases in spillovers increase secrecy, suggesting that legal and strategic protection are substitutes. Firms compensate for increased leakages, or for weaker legal protection, by using alternative secrecy mechanisms. In determining the optimal level of legal protection, the relative costs of these two types of protection need to be considered. This is contrary to the results of Cassiman et al. (2002) who find that legal and strategic protection are complements, but is in conformity with the results of Takalo (1998). Moreover, protection acts as a substitute for legal protection of the firm's own innovation as well as for legal protection of the competitor's innovation: a deterioration of intellectual property rights (an increase in the spillovers given or received) results in an increase in investments in secrecy by both firms. This result is robust to the type of product market competition (Cournot vs. Bertrand), the sequence of the game (simultaneous vs. sequential decisions), and product differentiation.

Second, the (privately) optimal investment in secrecy is affected by demand, R&D costs, and protection costs. Namely, an increase in demand, a decline in the cost of R&D, or a decline in the cost of protection all lead to an increase in secrecy investments.

Third, the order of decision-making has no significant impact on the levels of secrecy, R&D, and effective cost reduction, or on the comparative statics of the model. However, these variables are significantly affected by the type of product market competition. Quantity competition yields considerably higher levels of innovation, investments in secrecy, and effective cost reduction than price competition. The higher investments in R&D under quantity competition more than compensate for the higher levels of secrecy, resulting in higher effective cost reduction.

In parallel, spillovers increase and then decrease effective cost reduction when product differentiation is low. On the other hand, effective cost reduction increases uniformly with spillovers when products are sufficiently differentiated. Because product differentiation softens competition between firms, it induces them to invest less in secrecy and to increase secrecy less steeply with spillovers, resulting in a positive effect on effective cost reduction, both in terms of levels and of the impact of spillovers on effective cost reduction.

A few papers have dealt with the attempts to influence spillovers through information sharing or through imitation. By investing in learning and improving their absorptive capabilities (Cohen and Levinthal, 1989; Adams, 2000), firms can increase the effective information they receive from other agents. Atallah (2003) endogenizes spillovers in a Research Joint Venture, along with membership and innovation, in a context where sharing information voluntarily is associated with increased outgoing spillovers (because of government requirements, or because of the spread of information outside the firm). Eger et al. (1992) develop a model where firms can choose between innovation and imitation and they derive the equilibrium proportion of each strategy.[2]

A small number of papers have dealt explicitly with the control of firms over their outgoing spillovers, and that literature provides a mixed answer to the main questions addressed here. Gersbach and Schmutzler (2003) model the attempt to reduce outgoing spillovers through the retention of R&D employees, and the increase in incoming spillovers through the attraction of the competitors' R&D employees. They find that the incentives to acquire and prevent spillovers are stronger under price competition than under quantity competition. In Severinov (2001) firms regulate spillovers by the means of the incentive schemes they offer to their employees. He studies the link between product market competition and information exchange. Takalo (1998) develops a model where a firm chooses between patenting and secrecy to protect its innovation, concluding that there is substitutability between the two policies. An increase in patent breadth discourages the resort to secrecy, while an increase in patent life encourages secrecy when spillovers are high. The latter occurs because a longer patent life increases the incentives for imitation.

Perhaps the closest work to the current paper is Cassiman et al. (2002), who study secrecy in a context where a leading firm invests in basic research (which increases incoming spillovers), in applied research, as well as in secrecy (which reduces outgoing spillovers). The leader faces a fringe that imitates it, but that does not innovate. They find that a larger size, which is modelled in their case through a larger innovation and protection budget, leads to higher investments in protection. However, contrarily to our results, they find that enhanced legal protection increases investments in secrecy. As will be discussed, their result is due to the absence of strategic interaction, since only the leading firm innovates. Whereas, the relationship between legal and strategic protection obtained here is a negative one, due to the account of strategic interaction between firms regarding innovation and secrecy.

2.Other studies having endogenized R&D spillovers include d'Aspremont et al. (2000), Katsoulacos and Ulph (1998a, 1998b), Poyago-Theotoky (1999), and Kamien and Zang (2000).

Section 2 provides some background about the empirical evidence on secrecy and the different mechanisms used to achieve it. The model is presented and solved in section 3. The comparative statics are analyzed in section 4. Section 5 presents the results under Bertrand competition, and incorporates the effects of product differentiation. Section 6 discusses some of the implications of the analysis, and section 7 concludes.

2. Background

In high-tech industries firms walk a fine line between transparency, diffusion and knowledge exchange on the one hand, and secrecy, protection and exclusive in-house development on the other hand. As Fujiwara (2000:8.1) notes: "It is very difficult to manage confidential information. While giving it too much can cause breach of confidence, giving it too little affects workflow." Secrecy is socially harmful when compared with two related activities: innovation and imitation. Those three types of activities require resources and efforts. Innovation is costly, but those costs are compensated by the benefits from the innovation. Similarly, imitation requires resources, but those resources are compensated by the benefits of imitation. However, the resources devoted to secrecy raise the costs of other firms by reducing knowledge flows to those firms, and hence reduce social welfare in two ways: resources wasted, and increased production costs for competitors. The inputs and outputs of investments in secrecy are socially wasteful. This suggests that one important benefit of Research Joint Ventures is that they reduce secrecy within the research consortium.[3] The only benefit of secrecy is in terms of the ex ante incentives for innovation. Cohen and Walsh (2000) reach a similar conclusion through their study of the U.S. manufacturing sector: "of all the appropriability strategies ... secrecy robustly diminishes intraindustry R&D spillovers and has the weakest positive incentive effect on R&D intensity, suggesting that, of all the ways that firms can protect their profits due to invention, secrecy imposes the greatest social welfare [losses]" (p. 20).

Empirically, secrecy is an important appropriability mechanism. Secrecy is particularly prevalent in the semiconductor industry (Samuelson and Scotchmer, 2002). Cohen and Walsh (2000), using the Carnegie Mellon Survey for the U.S. manufacturing sector, find that secrecy significantly dampens R&D information flows. Based on the same survey, Cohen (2000) notes a

3.See footnote 1.

considerable increase in the importance of secrecy as an appropriability mechanism between 1983 and 1994. The diversity in secrecy practices can be found within the same industry. In his study of the Japanese computer industry, Fujiwara (2000:8.1) notes that "Some companies share information very openly and others are closed like secret society". McMillan et al. (1995) contend that scientists give more weight to openness and publications than engineers, and hence we should expect firms with a larger proportion of Ph.D. graduates -either in top management or in research personnel- to have a lower degree of secrecy.

In addition, asymmetries between firms may induce asymmetric behaviour toward secrecy even within the same industry. Agency problems may be more acute in some firms, in which case they may prefer lower diffusion rates. If a firm's R&D is more sensitive to diffusion than other firms, this firm may end up giving less technology than the average firm does. Technology can be a strategic factor for some firms, but a mere cost reducing medium for other firms, in which case the latter may be willing to exchange more technology than the former.[4] Larger firms value cost-reduction more, and may prefer more technology exchange than smaller firms.[5] Different efficiencies of the R&D process imply that the cost of producing technology is higher for some firms than for other firms; the firm with a less efficient R&D process can be lead to prefer higher diffusion rates because of the high internal cost of producing technology. Finally, the technological distance between two firms may be asymmetric (in the sense that one firm benefits from the innovations of the other firm more than the converse), in which case firms will have divergent preferences over diffusion.

Although patents are the main legal means of protecting the incentives for innovation, it is commonly asserted that patents are not very effective in protecting innovations, and that firms use other means to maintain their technological edge. Arundel and Kabla (1998) report that in the early 1990s, the majority of innovations in Europe and the U.S. were not patented. Firms are particularly worried about the disclosure requirements associated with patenting. In contrast to this aversion to patenting, economists and jurists have a bias toward patents as opposed to secrecy (Arundel, 2001).

4.For instance, cost reduction is a strategic factor for a low cost/low quality firm, while it is less important for a high quality producer.

5.There is evidence that innovations diffuse faster in industries with few firms and with a small variance of firm size (Davies, 1979).

Arundel (2001), using data from the 1993 European Community Innovation Survey, finds that in all size classes, a higher proportion of firms rate secrecy above patents as protection mechanisms, with a stronger preference by small firms. 17% of firms rated secrecy as the most important appropriability mechanism for product innovations, with a corresponding figure of 20% for process innovations. This puts secrecy as the second most important mechanism overall (after lead-time advantages), well ahead of patents. He also reports similar findings from innovation surveys from the U.S. and Australia. One exception is Japan, where secrecy rates higher for process innovations, but not for product innovations (Cohen et al., 1998).

Firms use different mechanisms as alternatives to legal protection (e.g. patents) to maintain a relative level of secrecy on their discoveries. They can explicitly require buyers or users of its technology to maintain a ceratin degree of confidentiality through non-disclosure agreements.[6] To be effective, such agreements call for enforcement and potential litigation costs. Technology may be critical from the point of view of national security (e.g. the defense industry), and may be classified. Increasing product complexity makes copying the technology more difficult for competitors to imitate. The secrecy or encryption of codes can be reinforced, at a cost. A firm can affect the outgoing spillover rate through the choice of the location of its laboratories, or by controlling the participation of its researchers to scientific conferences (De Fraja, 1990). Bhattacharya et al. (1992) report reluctancy on the part of some firms to send their best researchers to a Research Joint Venture. In the same token, Baumol (1993) finds that in some cases management approves *reluctantly* of informal technology exchange because highly skilled scientists are unwilling to work for firms not allowing them communication within their professional/scientific community. As Hamel et al. (1989) note:

> *A strategic alliance is a constantly evolving bargain whose real terms go beyond the legal agreement or the aims of top management. What information gets traded is determined day to day, often by engineers and operating managers. Successful companies inform employees at all levels about what skills and technologies are off-limits to the partner and monitor what the partner requests and receives. (p.134)*

And further they stress the importance for firms to

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6. The following is an excerpt from a contract model of the International Trade Centre UNCTAD/WTO: “You agree to hold in confidence and not to disclose to third party any part of TECHNICAL INFORMATION furnished directly or indirectly, in writing or otherwise, to you by us, ...” (Juris International, 2003).

develop safeguards against unintended, informal transfers of information. (p.136)[7]

One could argue that instead of “wasting” resources on secrecy, firms should rather invest in newer technologies to get ahead of their competitors, or buy the rival’s information through cross-licensing agreements. Many arguments can be made to justify the view that firms will find it optimal to invest in secrecy, even when one way of overcoming imitation is to invest in new technologies. First, if the rate of imitation is high, the net return on investment in innovation will be low, reducing the incentives for innovation. Therefore the firm is not in a position where it wants to innovate more because it has invested less in secrecy. Second, even though investments in secrecy are “mutually destructive”, they serve a purely negative purpose (raising the rival’s cost), it can also be said that R&D is mutually destructive (destructive competition), as its main purpose is to improve the competitive position of the firm relative to other firm, and to displace older firms, technologies, and products. Third, even in a market where the pace of technological change is high, secrecy can provide the firm with a time lag (even if eventual imitation is inevitable) during which it gets ahead of its competitors. Finally, even if the firm could keep introducing new technologies to always stay ahead of the competition, a minium delay is required between innovations for the firm to obtain a reasonable return on its large investments in R&D, and to amortize the adjustment costs (training, equipment, organizational adjustment) induced by the adoption of the new technology. Secrecy increases the return on innovation until the introduction of the new technology. It can thus be said that secrecy increases the profitability of innovation, rather than being in competition with it. This will be confirmed below, where it will be shown that innovation and secrecy are strategic complements.

3. The model

There are two identical firms selling an homogeneous product. The linear inverse demand is given by $p=A-y_1-y_2$, where y_i denotes the output of firm i. The game has three stages. In the first

7.Hamel et al. (1989:138) find that in many Western firms, “*[i]n their excitement and pride over technical achievements, engineering staffs sometimes shared information that top management considered sensitive*”. This was less likely to happen from Japanese engineers. Loyalty to the profession (Western personnel) leads to more information revelation than loyalty to the firm (Japanese personnel).

stage each firm invests in R&D, which is subject to leakages. In the second stage, each firm adopts a level of secrecy.[8] In the final stage firms compete in quantities as Cournot oligopolists.[9]

The constant marginal cost of firm i is given by

$$c_i = \alpha - x_i - \beta(1-\lambda_j)x_j, \qquad \textbf{(1)}$$

where $\alpha>0$ denotes an exogenous initial marginal cost level, $x_1,x_2>0$ represent R&D outputs[10] of firms 1 and 2, respectively, $\beta\in[0,1]$ is the exogenous involuntary spillover rate, and $\lambda_j\in[0,1]$ is the level of secrecy chosen by firm j. If firm j chooses maximal secrecy, the last term vanishes, and firm i receives no spillovers. If firm j chooses not to invest in secrecy at all, firm i benefits fully from the exogenous spillover rate β. By increasing λ_j, firm j reduces the extent to which firm i benefits from x_j, for any given level of spillover β (of course, when $\beta=0$ there is no gain from investing in secrecy).

The profit of firm i is

$$\pi_i = (p-c_i)y_i - \gamma_x x_i^2 - \gamma_\lambda \lambda_i^2, \qquad \textbf{(2)}$$

where γ_x and γ_λ are parameters representing the (convex) costs of R&D and secrecy, respectively. Note that R&D costs and secrecy costs are additively separable. Given the sequential decision-making process adopted here, it is natural to assume that the two costs are additively separable. Innovation expenditures are first incurred. Then, the firm engages in different activities to protect that innovation. Perhaps in a model where decisions are simultaneous, there would be more scope for interaction between the two types of costs. But even then, such an interaction is unlikely to change any of the results obtained here. And as explained above, simultaneous decisions do not change any of our results. In the presence of such an interaction, the presence of economies

8.There are contexts where firms may value disclosure of their technology to competitors: complementarities in R&D, joint research, standard setting, etc. Here, however, we focus the analysis on a situation where a firm always loses from technology leakages. To counter those spillovers, each firm may invest in secrecy, which reduces the spillovers accruing to its competitor. Secrecy is one way of "raising rivals' costs" à la Salop and Scheffman (1983). Contrary to other models in this literature, where the firm can affect mainly its own cost (through investment in R&D and/or imitation), here it is also possible to affect the competitor's cost.

9.The model has been re-run using only two stages, with simultaneous choices of R&D and secrecy. This modification does not alter any of the results of the model, and even the levels of R&D and secrecy are identical between the two models.

10.Notice that we are adopting the d'Aspremont and Jacquemin (1988) framework where spillovers take place at the level of R&D outputs. This is in contrast to the model of Amir (2000) and Kamien et al. (1992), where spillovers take place at the level of R&D inputs. While the two latter model have certain desirable properties over the model with output spillovers, it was impossible to solve the model using the input spillovers framework: no closed form solution exists, and even numerical simulations are not of much assistance. It would seem that the incentives for secrecy are so great under input spillovers that the model always yields a corner solution where firms choose $\lambda=1$ irrespective of the cost of secrecy (as long as it is positive).

(diseconomies) of scale between secrecy and innovation would increase (decrease) investments in both. However, the effect would be mainly on the levels, not on the direction of the comparative statics, which are the main focus of the paper.[11]

Although firms ultimately care about the effective spillover rate $\beta(1-\lambda)$, there is an important difference between spillovers and secrecy: the firm takes spillovers as given, whereas it can effect its investment in secrecy. Hence, when choosing R&D, the firm does it for a given level of β, but takes into account the impact of its choice of R&D on its own optimal secrecy level, and on the secrecy behavior of its competitor.

In the third stage each firm chooses its output. It is straightforward to verify that the solution to that stage is

$$y_1(\boldsymbol{x},\lambda) = (1/3)\ [A-\alpha+x_1(2-\beta(1-\lambda_1))-x_2(1-2\beta(1-\lambda_2))], \qquad \textbf{(3)}$$

with an analogous expression for y_2, where $\lambda \equiv (\lambda_1,\lambda_2)$ and $\boldsymbol{x} \equiv (x_1,x_2)$.

We now turn to the second stage of the game, the choice of secrecy levels. In principle it is possible to find parameter values for which firms choose corner solutions for secrecy: it may be optimal not to invest in secrecy at all (λ_i=0), or to induce complete secrecy (λ_i=1). We rule out these corner solutions, for two reasons. First, they introduce a discontinuity in the solution for λ, which makes the analysis more difficult. Second, they lack realism; on the one hand, firms generally have an incentive to make at least some effort to reduce undesirable leakages to competitors; on the other hand, even if a firm wanted to induce complete secrecy, this is difficult to achieve, as some information will leak out through employees, suppliers, distributors, etc.

Substituting $y_1(\boldsymbol{x},\lambda)$ and $y_2(\boldsymbol{x},\lambda)$ into the profit functions and letting each firm choose its level of secrecy to maximize its profits yields the following program for firm 1:

$$\max_{\lambda_1} \qquad \pi_1(\boldsymbol{x},\lambda) = [p(y_1(\boldsymbol{x},\lambda),y_2(\boldsymbol{x},\lambda))-c_1(\boldsymbol{x},\lambda)]\ y_1(\boldsymbol{x},\lambda) - \gamma_x x_1^2 - \gamma_\lambda \lambda_1^2,$$

with a similar program for firm 2. Focusing on interior solutions, the optimal level of secrecy for firm 1 is given by

11.Additive separability of the two types of costs is better suited to sequential than to simultaneous decisions.

$$\lambda_1(\mathbf{x}) = \frac{\beta x_1[-\beta^2 x_2^2(\alpha - x_1\beta - x_2) + A(\beta^2 x_2^2 - 3\gamma_\lambda) + 3\gamma_\lambda(\alpha - x_1(2-\beta) + x_2(1-2\beta)]}{3(\beta^2 x_2^2 - 9\gamma_\lambda)\gamma_\lambda + x_1^2(\beta^4 x_2^2 + 3\beta^2\gamma_\lambda)}, \quad \textbf{(4)}$$

with an analogous expression for firm 2. The second-order condition for the secrecy stage is $\beta^2 x_i^2 - 9\gamma_\lambda < 0$.

We now turn to the first stage of the game. The problem of firm 1 is

$$\max_{x_1} \quad \pi_1(\boldsymbol{x}) = [p(y_1(\boldsymbol{x},\lambda(\boldsymbol{x})),y_2(\boldsymbol{x},\lambda(\boldsymbol{x})))-c_1(\boldsymbol{x},\lambda(\boldsymbol{x}))]\, y_1(\boldsymbol{x},\lambda(\boldsymbol{x})) - \gamma_x x_1^2 - \gamma_\lambda \lambda_1(\boldsymbol{x})^2.$$

In a symmetric equilibrium $x_1=x_2=x$ and $\lambda_1=\lambda_2=\lambda$. Focusing on this symmetric equilibrium, the chosen investment in R&D is the root of the following complex polynomial:

$$\begin{aligned}
&243\, \gamma_\lambda^4(A-\alpha)(2-\beta) + x\, [A^2\beta^2-2A\alpha\beta^2+\alpha^2\beta^2+18\gamma_\lambda+9\beta\gamma_\lambda-9\beta^2\gamma_\lambda-81\gamma_x\gamma_\lambda]\, 27\gamma_\lambda \\
&+ x^2\, [(A-\alpha)(2-\beta)\, \beta]\, 27\beta^2\gamma_\lambda^3 + x^3\, [2A^2\beta^2-4A\alpha\beta^2+2\alpha^2\beta^2+3\gamma_\lambda-3\beta\gamma_\lambda-6\beta^2\gamma_\lambda]\, 9\beta^2\gamma_\lambda^2 \\
&+ x^4\, [(A-\alpha)(10+13\beta)]\, 3\beta^4\gamma_\lambda^2 + x^5\, [-A^2\beta^2+2A\alpha\beta^2-\alpha^2\beta^2+12\gamma_\lambda+33\beta\gamma_\lambda+21\beta^2\gamma_\lambda+162\gamma_x\gamma_\lambda]\, \beta^4\gamma_\lambda \\
&- x^6\, [(A-\alpha)(2+\beta)]\, \beta^6\gamma_\lambda + x^7\, [-1-\beta+24\gamma_x]\, \beta^6\gamma_\lambda + x^9\, [\beta^8\gamma_x] \qquad \textbf{(5)}
\end{aligned}$$

Obviously, no closed solution for x can be found from this expression. For that reason, the results will be analyzed using numerical simulations. By substituting numerical values for the parameters A, α, β, γ_x and γ_λ into this polynomial, we obtain the equilibrium values of x and, through the function $\lambda(x)$ given by (4), of λ. By varying those parameters, we obtain the comparative statics of the model.

Note that λ_1 and λ_2 are strategic substitutes:

$$\partial^2\pi_1/\partial\lambda_1\lambda_2 = -4\beta^2 x_1^2 x_2^2/9 < 0; \qquad \textbf{(6)}$$

an increase in secrecy by firm 2 raises c_1, reducing the marginal value of raising the rival's cost for firm 1 (given that $\partial^2\pi_1/\partial c_1\partial c_2 < 0$), reducing secrecy by firm 1. This is a major difference with the relationship between firms' research efforts. It is well known that research efforts are strategic substitutes (complements) when spillovers are low (high). But secrecy efforts, which determine those very spillovers, are always strategic substitutes. On the other hand, innovation and secrecy are strategic complements:

$$\partial^2\pi_1/\partial\lambda_1\partial x_1 = (2\beta/9)[A-\alpha+2x_1(2-\beta+\beta\lambda_1)-x_2(1-2\beta+2\beta\lambda_2)] > 0 \qquad \textbf{(7)}$$

for all positive output. The increase in innovation reduces costs, increasing the value of secrecy. Similarly, the increase in innovation makes secrecy more valuable, since the technology to be protected is now more important or more significant.

4. Comparative statics

In this section we analyze how changes in spillovers, demand, secrecy costs and R&D costs affect investments in secrecy and innovation, and the net impact on effective cost reduction (Q). We adopt the following numerical parametrization of the model: A=1000, α=50, β=0.1, γ_x=60, γ_λ=600. This is the "basic" configuration. Comparative statics will be derived by varying one parameter while holding the others fixed. Robustness checks have been performed, and none of the results that follow is sensitive to the numerical values used for demand, production costs, secrecy costs or R&D costs.

For the analysis that follows it will be useful to examine how the value of raising the rival's cost through secrecy varies with own cost and with the competitor's cost. Under Cournot competition with linear demand and constant marginal costs, the value of raising the rival's cost decreases with own cost and increases with the rival's cost. The value of secrecy decreases with own cost because $\partial^2\pi_1/\partial c_1 c_2<0$: a lower c_1 increases the rate at which π_1 increases with c_2. And the value of secrecy increases with the rival's cost because $\partial^2\pi_1/\partial c_2^2>0$: a higher c_2 also increases the rate at which π_1 increases with c_2.

Consider first the effect of spillovers on secrecy, innovation and effective cost reduction.

Proposition 1. *Under Cournot competition with homogeneous products, an increase in spillovers* (β) *increases secrecy and reduces R&D. It first increases, then reduces, effective cost reduction.*

The increase in spillovers can be decomposed into two parts. Consider the effects from the point of view of firm 1. On the one hand, it represents an increase in the spillovers received by firm 1. This reduces firm 1's costs, increasing the value of secrecy, increasing secrecy. An increase in received spillovers reduces the marginal cost of firm 1, which, given that $\partial^2\pi_1/\partial c_1 c_2<0$ (a reduction in c_1 increases the value of raising the rival's cost), makes investment in secrecy more profitable for firm 1. This means that the firm views the legal protection of the innovations of its competitors and its own secrecy as substitutes: a deterioration in the legal protection of the innovation of a competitor raises the value of secrecy to the firm, leading it to increase its strategic protection.

On the other hand, the increase in spillovers represents an increase in information flows from firm 1 to firm 2. Not surprisingly, an increase in the spillover rate received by firm 2 makes secrecy more valuable for firm 1, since a larger portion of its technological stock is now flowing to firm 2. This result can also be understood from the marginal effect of a change in c_2 on the relationship between π_1 and c_2: $\partial^2\pi_1/\partial c_2^2>0$; thus the profits of firm 1 decline at a decreasing rate when c_2 declines. The increase in β, which reduces c_2, increases the rate at which π_1 increases with c_2 (i.e. increases the marginal value of raising the rival's cost), thus increasing secrecy by firm 1. This induces firm 1 to strengthen its secrecy to reduce those flows, i.e. the marginal profitability of secrecy has increased.

Hence both effects of spillovers, those on incoming flows and those on outgoing flows, induce an increase in the optimal level of secrecy. The sum of the two effects represents the net effect of an increase in spillovers on secrecy. The same analysis applies when the problem is viewed from the point of view of firm 2. This means that firms view legal and strategic protection as substitutes: a deterioration of intellectual property rights (an increase in the spillovers given or received) result in an increase in investments in secrecy by both firms.

Consider next the effect of spillovers on R&D. It is well known that noncooperative R&D declines with spillovers. The presence of secrecy does not change this result.

The net effect of spillovers on effective cost reduction depends on the cumulative effect of R&D, secrecy and spillovers. Note that the increase in spillovers, for given levels of secrecy and R&D, has a positive effect on effective cost reduction. In a first phase, the effect of spillovers dominate the effects of secrecy and R&D, increasing effective cost reduction. In the second phase, the effect of the decline of R&D and the increase in secrecy dominate the effect of spillovers, leading to a decrease in effective cost reduction. In that second phase spillovers are particularly harmful, for they reduce innovation, induce firms to invest in wasteful protection, and reduce effective spillovers. Figure 1 illustrates those results.[12]

12.On figures 1 through 6 R&D and effective cost reduction are read off the left axis, while secrecy is read off the right axis.

[Figure 1]

The effective spillover rate, β(1-λ(β)) is always increasing in β, even though λ'(β)>0: spillovers increase effective spillovers faster than they increase secrecy.

The simultaneous increase in protection expenditures and the decline in R&D result in a ratio of protection to innovation expenditures that is increasing in spillovers. This ratio depends ultimately on the parameters γ_λ and γ_x. Table 1 illustrates the ratio λ^2/x^2 (which is a ratio of outputs), which does not depend on these parameters and gives an idea of the evolution of the relative importance of each expenditure as spillovers increase.

Table 1. Protection output relative to R&D output as a function of spillovers

β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
λ^2/x^2	0.03%	0.12%	0.28%	0.50%	0.78%	1.12%	1.53%	2.00%	2.53%	3.12%

Consider next the impact of a shift in demand and costs.

Proposition 2. *Secrecy increases following:*
-an increase in demand (*A*)*;*
-a decline in the cost of secrecy (γ_λ)*;*
-a decline in the cost of R&D (γ_x)*.*

The most straightforward effect of the increase in demand is to induce firms to increase their investments in secrecy: the marginal benefit from secrecy increases with market size. Demand also affects R&D. The direct effect of demand is to increase the incentives for innovation. However, by increasing secrecy, demand also reduces the effective spillover rate, β(1-λ). Figure 2 illustrates the effect of demand. It can easily be checked that even though both innovation and protection increase with demand, protection increases faster: the ratio λ^2/x^2 increases with demand. Henceforth investments in secrecy should be relatively more important in larger markets, and should see their share increase as the market grows.

[Figure 2]

The increase in secrecy costs has the expected effect of reducing secrecy. However, it also has the unintended effect of increasing innovation. The reduction in secrecy leads to an increase in the spillovers received by each firm, increasing the value of innovation and increasing R&D. This effect dominates the negative effect which arises from weakened appropriability. Naturally, the net effect of increased innovation and reduced protection is to increase effective cost reduction. Figure 3 illustrates those results.

[Figure 3]

The increase in R&D costs, in addition to the direct effect of decreasing innovation, reduces the incentives for firms to invest in secrecy. However, the direct effect on innovation is more important, leading to a reduction in effective cost reduction. Figure 4 illustrates that result.

[Figure 4]

Investments in secrecy move in tandem neither with R&D nor with effective cost reduction: secrecy can move in the same or in the opposite direction of either of these quantities. Hence secrecy cannot be understood as a byproduct of the model (depending solely on the value of cost reduction, for instance), it has to be modeled explicitly.

5. Bertrand competition

The model was solved in the pervious section in the simple case of homogeneous products to get the main intuitions behind the results in a transparent fashion. In this section we test the robustness of the results to the type of product market competition and to product differentiation. As will be explained shortly, the results of the model continue to hold, except for the sensitivity of the relationship between effective cost reduction and spillovers to the level of product differentiation. Assume that everything is as in the above model, except that now the inverse demand functions are given by

$$p_i=A-ey_i-fy_j, \qquad i,j=1,2, \qquad i\neq j. \qquad \textbf{(8)}$$

The parameters e and f capture the degree of substitution between outputs. When f=0, the firms' products are independent, whereas they are perfect substitutes when $e=f$. As usual, $e>f>0$, implying that the price of good i is more sensitive to its own quantity than to the quantity of its substitute. Defining

$$a=\frac{A(e-f)}{e^2-f^2}, \quad g=\frac{e}{e^2-f^2}, \quad h=\frac{f}{e^2-f^2}, \qquad \textbf{(9)}$$

this yields the demand functions

$$y_i = a - gp_1 + hp_2, \qquad i,j=1,2, \qquad i \neq j. \qquad \textbf{(10)}$$

In the last stage each firm chooses its price:

$$p_1 = \frac{a(2g+h) + g[h(\alpha - x_2 - x_1\beta(1-\lambda_1)) + 2g(\alpha - x_1 - x_2\beta(1-\lambda_2))]}{4g^2 - h^2} \qquad \textbf{(11)}$$

with a symmetric expression for firm 2.

The secrecy stage yields:

$$\lambda_1 = \frac{\begin{array}{c} gh^2x_1\beta[(g-h)(g^3x_2^2\beta^2(x_2 - \alpha + x_1\beta) - g^2(x_2 - \alpha + x_1\beta)(hx_2^2\beta^2 - 4\gamma_\lambda) \\ + 2gh(x_1 - x_2)(1-\beta)\gamma_\lambda - h^2(x_1 - \alpha + x_2\beta)\gamma_\lambda) + a(g^3x_2^2\beta^2) - h^2\gamma_\lambda - g^2(hx_2^2\beta^2 + 4\gamma_\lambda))] \end{array}}{\begin{array}{c} 16g^6x_2^2\beta^2\gamma_\lambda + 4gh^4\gamma_\lambda^2 - 2h^5\gamma_\lambda^2 + 2g^2h^3\gamma_\lambda(hx_1^2\beta^2 + 8\gamma_\lambda) + g^3h^2(h^2x_1^2x_2^2\beta^4 - 6hx_1^2\beta^2\gamma_\lambda - 32\gamma_\lambda^2) \\ - 2g^4h(h^2x_1^2x_2^2\beta^4 - 2h(x_1^2 + 2x_2^2)\beta^2\gamma_\lambda + 16\gamma_\lambda^2) + g^5(h^2x_1^2x_2^2\beta^4 - 24hx_2^2\beta^2\gamma_\lambda + 64\gamma_\lambda^2 \end{array}} \qquad \textbf{(12)}$$

with a symmetric investment in secrecy by firm 2. The second-order condition is

$$(ghx\beta)^2(h-g) - (4g^2 - h^2)\gamma_\lambda < 0. \qquad \textbf{(13)}$$

Solving the R&D stage yields a polynomial of the same type as (5) which we do not reproduce here due to its length.

Note that as in the Cournot model, λ_1 and λ_2 are strategic substitutes:

$$\frac{\partial^2 \pi_1}{\partial \lambda_1 \partial \lambda_2} = \frac{\beta^2 x_1 x_2 g h^3 (h-g)}{(-4g^2 + h^2)^2} < 0 \qquad \textbf{(14)}$$

since $g>h$.

We first compare the levels of innovation and secrecy under Cournot and Bertrand competition. It is obvious from figures 1 and 5 that Cournot competition yields higher levels of R&D, and substantially higher levels of secrecy, both in absolute terms and in relation to R&D expenditures. Firms have more market power and make more profits under Cournot, which explains the higher investments. This difference in levels will be important to understand the following results.

[Figure 5]

Given that the comparative statics rely on numerical simulations, we will need to choose numerical values for the degree of substitution. We evaluate the results at the same values of parameters used for the Cournot model, with the additional parameters taking the values e=1, f=0.5.

Proposition 3. *Under Bertrand competition with sufficiently high product differentiation, an increase in spillovers increases secrecy and effective cost reduction, and reduces R&D.*

Figure 5 shows the effects of spillovers. The impact on secrecy and R&D is the same as in the Cournot model. The intuition is also the same. The major difference between the two models lies in the impact of spillovers on effective cost reduction, and also in the relative levels of effective cost reduction. Whereas effective cost reduction increases and then decreases with spillovers under Cournot competition, it increases uniformly with spillovers under Bertrand competition. The decline of effective cost reduction for high spillovers under quantity competition is due to the decline in R&D and the increase in the relatively high level of secrecy. While the constant increase in effective cost reduction with spillovers under price competition is due to the lower level of secrecy under Bertrand, which implies that the effect of the increased spillover rate dominates the effects of both the decline in R&D and the increase in secrecy.[13]

However, these results were obtained under different levels of product differentiation. Remember that products were assumed to be homogeneous in section 4, while here they are differentiated. To distangle the effects of product market competition from those of product differentiation, we solve the model described in this section by assuming that firms compete in quantities rather than in prices. Figure 6 illustrates R&D, secrecy and effective cost reduction in this case. As usual, R&D declines with spillovers. Moreover, secrecy increases with spillovers, so that the substitutability between legal and strategic protection extends also to the Cournot model with product differentiation. However, effective cost reduction increases uniformly with spillovers. This is conform to the results of the Bertrand model with product differentiation, but in contrast to the results of the Cournot model with homogeneous products. Therefore, what drives the inverted-U shaped relationship between Q and spillovers in section 4 is the low degree (or absence) of product differentiation, rather than quantity competition per se.

[Figure 6]

13.The results for demand, secrecy costs and R&D costs being the same as under the Cournot case, we do not reproduce them here.

Proposition 4. *Under either Cournot or Bertrand competition, effective cost reduction declines with spillovers for high spillovers when product differentiation is sufficiently low. On the other hand, effective cost reduction always increases with spillovers when product differentiation is sufficiently high.*

This result can be understood from figure 7, which illustrates the impact of product differentiation on secrecy in the Cournot model (this figure is drawn for β=0.5). As f declines, i.e. as product differentiation increases, secrecy decreases. This is intuitive: as competition is softened between firms, they care less about technological leakages to their competitor. This can also be seen by comparing the levels of secrecy between figures 1 (where products are homogeneous) and 6 (where products are differentiated): the level of secrecy is uniformly lower with product differentiation. As secrecy is reduced due to product differentiation, this eliminates the decline of effective cost reduction observed with high spillovers in the absence of product differentiation. Also, secrecy increases more steeply with spillovers in the absence of product differentiation.

[Figure 7]

Proposition 5. *An increase in product differentiation reduces secrecy.*

Moreover, the Cournot model yields uniformly higher levels of effective cost reduction than the Bertrand model. This is illustrated in figure 8 (this figure is drawn for e=1 and f=0.5). In spite of the higher secrecy under Cournot, and hence the lower effective spillover rate, the higher level of innovation is sufficient to result in higher effective cost reduction.

[Figure 8]

Qiu (1997) shows that the comparison of R&D expenditures between the Cournot and Bertrand models depends on R&D productivity, spillovers and substitutability/complementarity between products. Symeonidis (2003) shows that the comparison of welfare, profits and consumer surplus between the two models depends on spillovers and product differentiation. In our model, the comparison of R&D, secrecy, and effective cost reduction between the Cournot and Bertrand markets is insensitive to spillovers, R&D productivity, and product differentiation.

Basically, the model suggests two types of configurations, depending on the level of product differentiation. On the one hand, there is a configuration with low product differentiation, low levels of R&D, high levels of secrecy (due to intense competition between firms), low levels of effective spillovers, and a decline of effective cost reduction with spillovers for high levels of spillovers. On the other hand, we find a configuration with high product differentiation, high levels of R&D (the value of cost reduction is higher), low levels of secrecy (because product differentiation softens competition between firms), high levels of effective spillovers, and a uniformly positive relationship between spillovers and effective cost reduction. Product differentiation has a much more important impact on the results than the distinction between Cournot and Bertrand competition.

6. Discussion

The substitutability between legal and strategic protection suggests that there is a trade-off between the two, or an optimal mix of the two. Strategic protection has two advantages over legal protection. First, legal protection is (almost) uniform across firms, industries, and technologies (within a given legislation). As the optimal length and breadth of legal protection varies with the characteristics of the technology being protected and with the market structure in which the firm operates, the uniform legal protection will inevitably be too short/narrow in some cases and too long/broad in other cases. Strategic protection has the advantage that the firm tailors its secrecy policy to the specific technology being protected and to its own competitive environment.

The second advantage of strategic protection over legal protection is that the firm may have private information about its incentives to innovate, about the nature of the technology, and about how much protection it really requires. In contrast to legal protection, the secrecy decision is decentralized; the government need not worry about the private information of the firm, for the latter is the residual claimant of the costs and benefits of protection. Nonetheless, these two arguments must be qualified in the numerous instances where what can be achieved through legal protection cannot be achieved through secrecy, and where the costs of strategic protection are higher than the costs of legal protection. Moreover, the lower level of uncertainty associated with legal protection may provide higher incentives for innovation.

From a policy point of view, governments can have some leverage on R&D investments and R&D cooperation, but it is much harder to affect or punish investments in secrecy by firms, because of obvious incentives issues, but more importantly because of the unobservability of secrecy. The scope for government intervention to improve upon the market is much more limited with secrecy than with innovation or imitation. However the picture is different when seen in an inter-jurisdictional perspective. In the present paper investments in secrecy were made by firms, but the insights of the model extend to interactions between countries. The race between countries to dominate a given market are characterized by a mixture of technological transfer and technological protectionism. Governments may have a larger scope of investing in secrecy (at the national innovation policy level) than do firms.

The substitution/complementarity relationship between legal and strategic protection is crucial to understand the net effect of legal protection on diffusion. If legal and strategic protection are complements, as Cassiman et al. (2002) find, then legal protection, while increasing the incentives for innovation, reduces diffusion in three distinct ways: by reducing spillovers from the innovating firm, by increasing strategic protection by the innovating firm, and by increasing strategic protection by the innovator's competitor(s). In that case the diffusion effects of legal protection are likely to be very strong, eliminating a good part of the positive effect on the incentives to innovate.

If, however, legal and strategic protection are substitutes, then, in addition to the positive effect on the incentives to innovate (and in spite of the negative initial effect on diffusion), legal protection has two indirect positive effects on diffusion: it reduces investments in secrecy by the innovating firm, and it reduces investment in secrecy by the innovator's competitor. In this context, the elimination of wasteful investments in protection can become a justification for intellectual property protection.

Hence whether the initially negative diffusion effects of legal protection are exacerbated or compensated for by strategic protection, is completely determined by the substitution/ complementarity relationship between legal and strategic protection. In the present paper we find that a strong substitutability relationship prevails. Whether this result holds in more general settings is an issue of crucial importance to the understanding of the diffusion of innovations.

The effect of spillovers on secrecy, or the relationship between legal and strategic protection, constitutes one major difference between this model and Cassiman et al. (2002). Whereas we find that legal protection and strategic protection are substitutes, Cassiman et al. find them to be complements. In their model, there is no strategic interaction, because only the leader invests in innovation and protection, while the competitive fringe simply imitates the leader. In the absence of strategic interaction, the strengthening of legal protection in the Cassiman et al. model reinforces the value of protection, increasing investments in secrecy. This complementarity result means, paradoxically, that as appropriability weakens, the firm invests less in protection, which is not very convincing. Whereas, when we account for strategic interaction, we obtain the more logical result that when legal protection is deficient, the firm compensates by increasing its investment in secrecy, implying that firms view legal and strategic protection as substitutes. The positive effect of a strong legal protection for innovations on the incentives to innovate is well known. The paper points to an additional positive effect of strong legal protection: insofar as legal and strategic protection are substitutes, a stronger legal protection reduces wasteful investments in strategic protection.

7. Conclusions

In this paper it was shown how accounting for investments in secrecy by firms to reduce outgoing spillovers affects the incentives for, and the diffusion of, innovations. Increases in spillovers increase secrecy, suggesting that legal and strategic protection are substitutes. Stronger patent protection may have the unintended consequence of reducing wasteful investments in secrecy. This is contrary to the results of Cassiman et al. (2002) who find that legal and strategic protection are complements, but is in conformity with the results of Takalo (1998). Moreover, protection acts as a substitute for legal protection of the firm's own innovation as well as for legal protection of the competitor's innovation: a deterioration of intellectual property rights (an increase in the spillovers given or received) results in an increase in investments in secrecy by both firms. Product differentiation increases innovation and reduces secrecy, resulting in a strong positive effect on effective cost reduction. Effective cost reduction increases uniformly with spillovers when products are highly differentiated, while it first increases and then decreases with them for low levels of product differentiation.

Important interactions between secrecy, innovation and imitation remain to be explored. Innovation and imitation reduce the firm's costs, thereby increasing the value of secrecy directly. Moreover, innovation and imitation by a competitor reduce that competitor's costs, reducing the value of secrecy to the firm. A richer model would address the interactions between innovation, imitation and secrecy. The predictions of the model can be used to assess differences in secrecy practices between industries and between countries. Market size, legal protection, and R&D productivity, in addition to the efficacy of secrecy (which varies greatly form one industry to another) should help in explaining those different practices. A model with explicitly asymmetric firms would go one step further in that direction. Finally, Arundel (2001) argues that secrecy and patenting are not mutually exclusive. A firm could rely on secrecy in the earlier development stages, and rely on patenting while the invention is on the market. A richer dynamic would model would account for this complementary use of the two protection mechanisms.

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Figure 1. Effect of spillovers

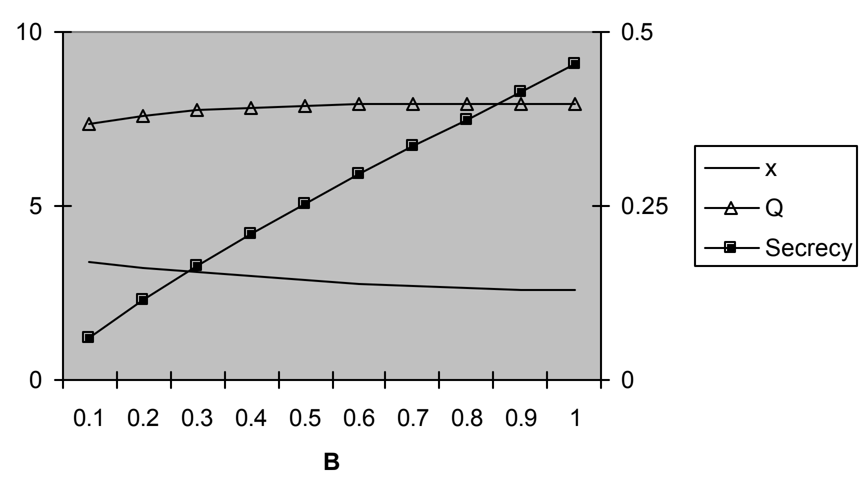


Figure 2. Effect of demand

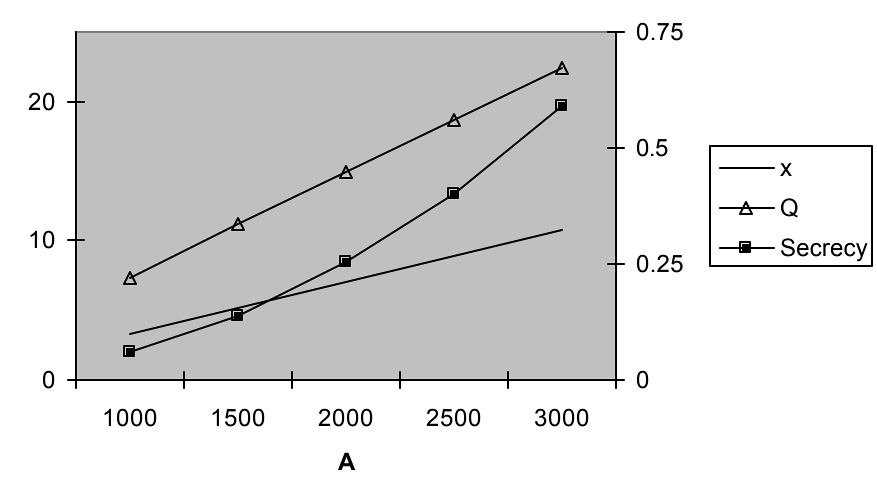


Figure 3. Effect of the cost of secrecy

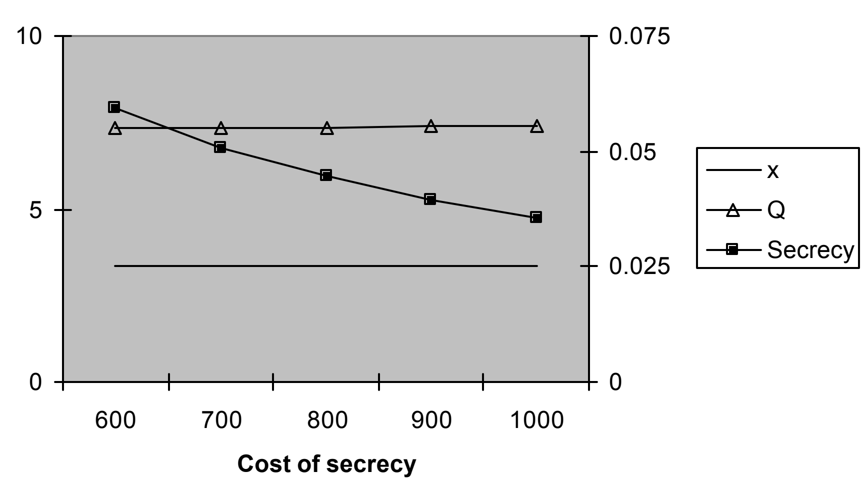
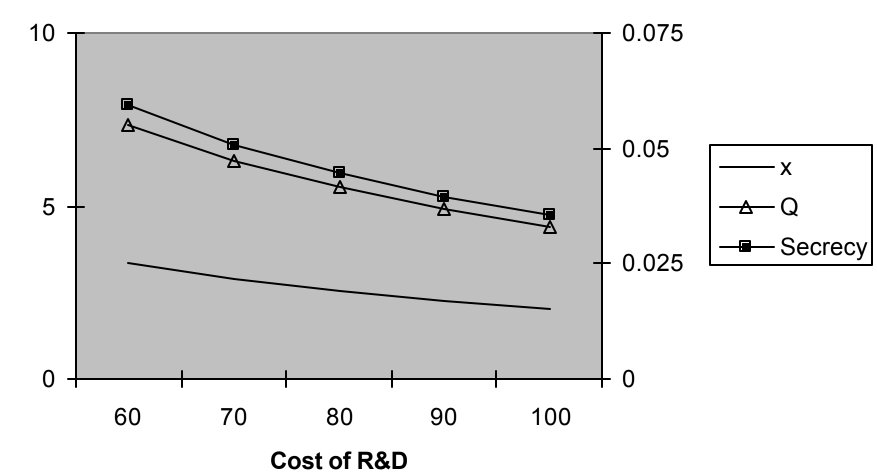


Figure 4. Effect of the cost of R&D



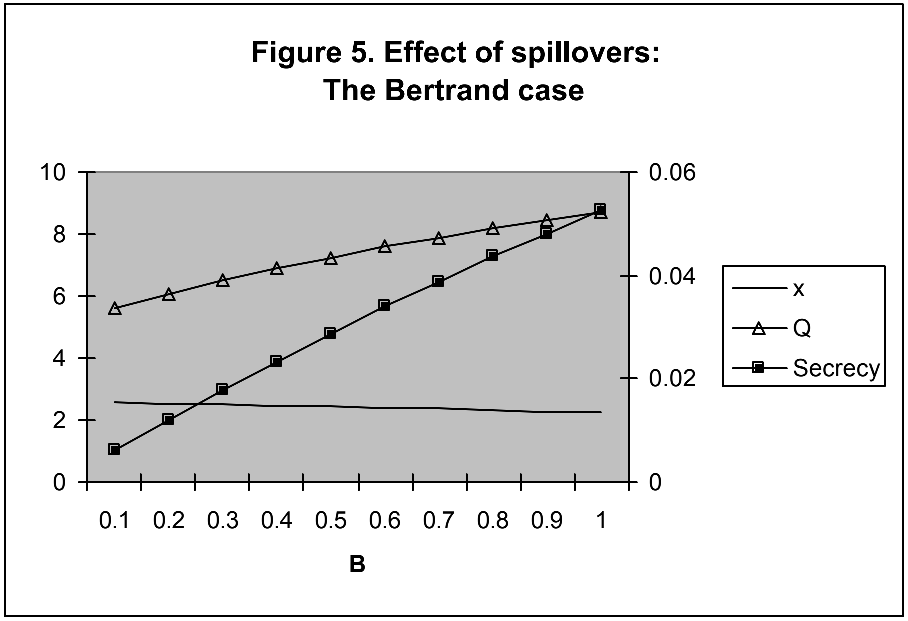


Figure 5. Effect of spillovers: The Bertrand case

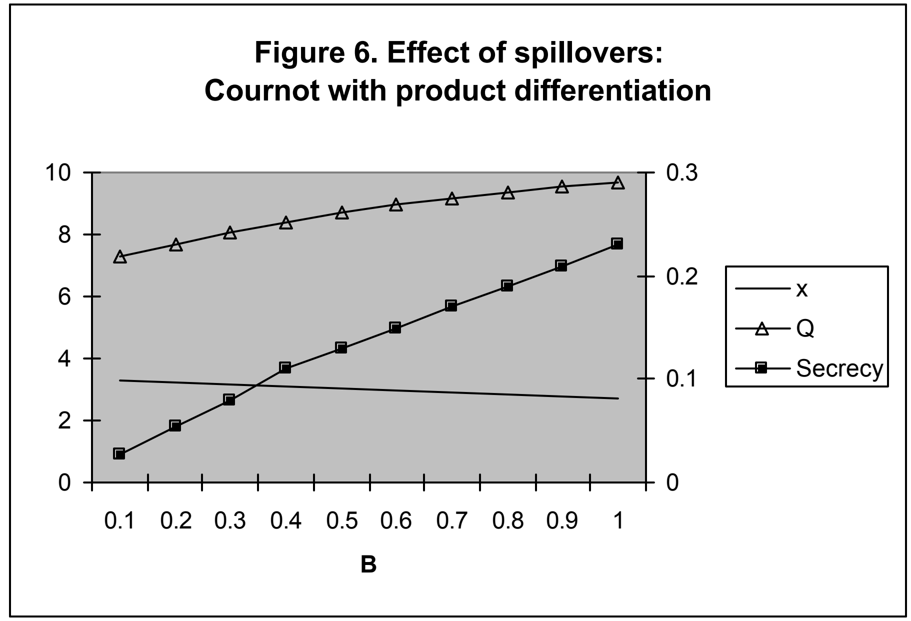


Figure 6. Effect of spillovers: Cournot with product differentiation

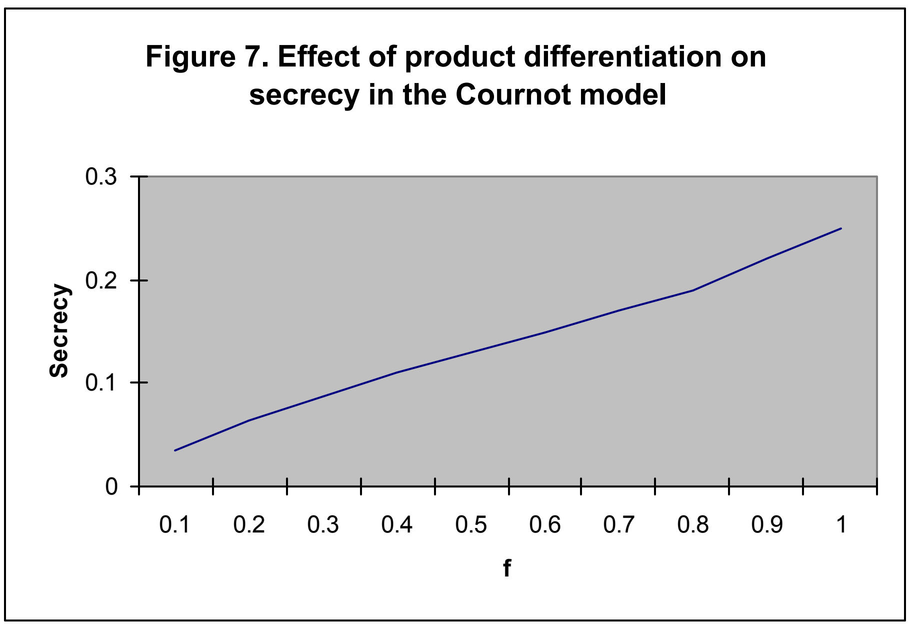


Figure 7. Effect of product differentiation on secrecy in the Cournot model

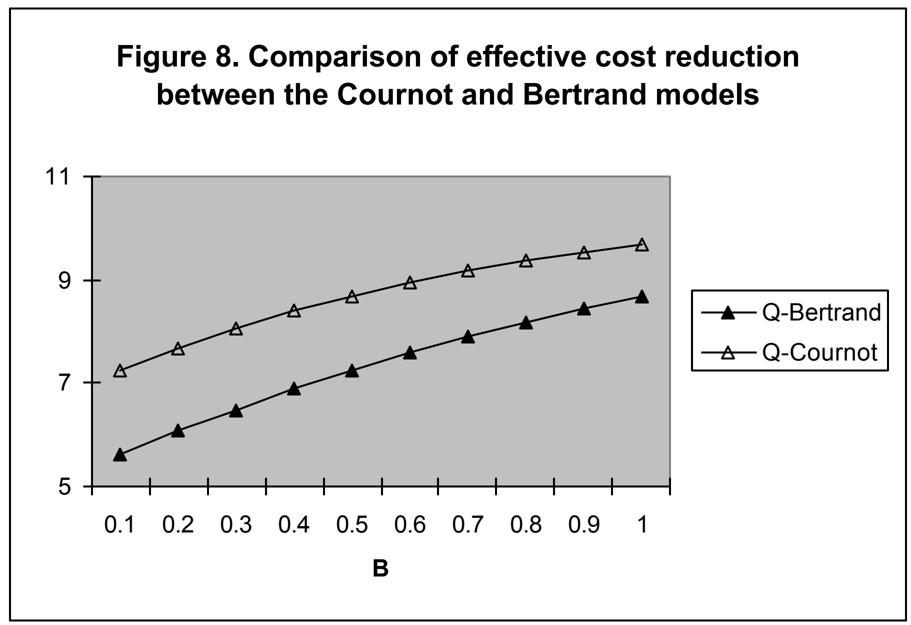


Figure 8. Comparison of effective cost reduction between the Cournot and Bertrand models