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SECRECY VERSUS PATENTS: PROCESS INNOVATIONS AND THE ROLE OF UNCERTAINTY

Secrecy Versus Patents: Process Innovations and the Role of Uncertainty*

Tapan Biswas and Jolian McHardy

Abstract

Whilst firms often prefer secrecy to patents and process innovations particularly lend themselves to secrecy, we establish a rationale for process innovators who patent. Using a simple two-period model, we show that under myopic optimisation, the incentive to patent rather than pursue secrecy increases as the probability that the rival firm attaches to it being low-cost falls and as the proportion of the cost reduction due to the innovation, secured by the rival firm in the period after the patent has expired, falls. However, the gain to the innovating firm from patenting rather than secrecy strictly increases if the cost reduction due to the innovation is sufficiently small that the high-cost firm could profitably bluff that it is low-cost. Finally, allowing the low-cost firm the option of using an output signal in such cases, may make the patent strategy more or less attractive relative to the case of myopic optimisation.

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1 Introduction

Technological innovation is the random outcome of research and development (R&D) efforts taking the form of new production processes (offering production opportunities at lower cost) or new products. R&D is generally expensive and incentives to undertake such expenditures depend, amongst other things, upon the ability of agents to appropriate the rewards from their investment. Patenting is one way of protecting the rewards from R&D investment since it allows the inventor an effective monopoly, excluding others from making, selling or using the innovation for a specified period of time. However, although taking out a patent on a product or process innovation prevents rivals from legally copying the innovation it does not necessarily prevent some degree of imitation which may be legal. This is important because one condition of the patent being awarded is that the innovation be disclosed. So whilst the patent may protect against copying, the act of patenting may release important information that could be exploited by rivals in imitating 'around' the patent.[1] Patenting can also be expensive to take out and enforce. Hence in the face of these costs alongside the prospect of disclosure some agents prefer secrecy as a strategy for appropriating the rewards of R&D.

Since the seminal work of Nordhaus (1969), numerous studies have started from the assumption that innovators will always patent. Interestingly, empirical evidence on the patent /secrecy question has consistently found manufacturing firms to have higher average ratings for secrecy rather than patenting as a method of appropriation (examples using US, Australian and European data, respectively, include Rausch, 1995; McLennan, 1995; Arundel, 2001). Indeed, this has generally been true for both process and product innovations.[2] Arundel (2001, Figure 1, pp. 615) for instance, reports that, of a survey of R&D-intensive firms, 11.2% gave their highest rating to patents as a method of appropriation for product innovations, whilst the figure for process innovations was 7.3%.[3] The relevant figures for secrecy were 16.9% and 19.8% respectively.

There is a small but growing body of literature devoted to the theoretical consideration of innovation protection that does not explicitly or otherwise assume patenting as the only option. The earliest major contribution here is due to Horstmann *et al.* (1985). In their model, a successful innovator gains important private information about the profits available to a rival should they imitate or copy the innovation. However, the innovator's choice over whether or not to patent the innovation, is influenced by the fact that taking out a patent may itself signal some of this private information to the

[1]The breadth of a patent describes how far away from the protected innovation an imitation must go (in product space for a product innovation, or in inability to match the full cost reduction in a process innovation) in order not to be considered a copy and hence infringe the patent. An interesting literature has developed on this issue, including the issue of optimal breadth, see for instance Denicolò (1996). However, in order to focus on the impact of strategic output interaction under cost uncertainty on the incentives to patent in this paper, we assume away imitation.

[2]One notable exception is the case of Japan (Cohen *et al.*, 1998), where manufacturing firms were reported to have had a higher rating for patenting in the case of product but, again, not process innovations.

[3]The survey included 2849 firms from across Belgium, Denmark, Germany, Ireland, Luxembourg, the Netherlands and Norway.

rival firm whilst at the same time offering only limited coverage against imitation. The central prediction of this model is an equilibrium in which the propensity to patent may lie between zero and one. Anton and Yao (2004) also analyse the patenting decision with asymmetric information and incomplete patent coverage. However, in this case the innovator chooses how much knowledge to disclose alongside the decision to patent which has a signalling property to the rival firm. Amongst their main findings are that, whilst small innovations are not imitated, secrecy rather than patenting is preferred for the protection of large innovations when property rights are weak. Denicolò and Franzoni (2004), in a model of sequential innovation, conclude that generally patenting is preferable to secrecy from a social welfare perspective.

The evidence that secrecy often appears to provide a better option in terms of protection than patents raises questions about why firms engage in costly patenting. Kultti *et al.* (2007) suggest a theoretical answer to this puzzle under which secrecy is only profitable if the innovator knows they are the sole innovator, that is to say, rival firms are not pursuing secrecy having already made the same discovery. The equilibrium result is that innovators choose to patent.

In this paper we pursue a related question. Like Kultti *et al.* (2007) we seek to explain the incentive to patent, but focus on an argument specific to process innovations. We recognise that whilst many factors influence an agent's decision over whether to take a patent or pursue secrecy, there is an important distinction to be made between the cases of product and process innovations in the patent/secrecy choice. In the case of a new product, from the moment it is placed on the market there will necessarily be a good deal of information available about it. Indeed rivals may well be able to discover the new product's deepest secrets through purchasing the product and reverse-engineering. Contrast this with the case of process innovation where it is not always possible to determine the production technology from the final product, and hence in the absence of information disclosure under a patent, there may be very little information available about the process innovation. This would tend to suggest that the balance of risks in the secrecy/patent decision is very different in the cases of product and process innovations: it is much easier to pursue secrecy if the innovation is hidden. If, as Kultti *et al.* (2007) note in their preamble, the ratings given to patents as a means of appropriation appear surprisingly high for innovations in general, then the above argument tends to make the case even more strongly for process innovations.

This paper offers one possible explanation for why agents might pursue patenting over secrecy in the case of a process innovation. For simplicity, and to eliminate other factors which might drive the decision to patent, we assume that, in the absence of a patent, there is complete secrecy (the rival firm cannot copy or imitate the innovation) and the rival firm does not discover the innovation through its own R&D.[4] Like Kultti *et al.* (2007), our argument is based upon asymmetric information and uncertainty. However, whilst in the former case, uncertainty arises in relation to whether a rival firm has simultaneously discovered an innovation and is maintaining secrecy, in this paper

[4]The latter effect is central to the argument for patenting put forward by Kultti *et al.* (2007).

the uncertainty relates to whether or not, in the eyes of a rival firm, the firm that has claimed to have reduced its cost through a process innovation is bluffing or not.

Our model begins with a firm that has achieved a cost-reducing process innovation. The firm announces that it has reduced its cost in the hope that a rival firm will believe it and the market will move to an equilibrium favourable to the innovating firm, reflecting its cost advantage. However, we assume that unless the innovator discloses the innovation (i.e. takes a patent) then the innovation is hidden and there is no risk of imitation. Secrecy would therefore appear to be an attractive option to pursue. However, secrecy may have a disadvantage in this context, since under asymmetric information the local firm knows that the multinational firm may have an incentive to announce a successful cost-reducing innovation even if it has not been successful in reducing its cost. If the innovating firm is not able to convince the rival that it has reduced its cost then its profit, the ability to appropriate the rewards from the innovation, may suffer. In this setting, disclosure through patenting may be seen as a strategy to resolve the asymmetric information and uncertainty.[5]

In the next Section we introduce our simple two-period model. Section 3 considers the circumstances affecting the patenting/secrecy question for the firm who has been successful in reducing its cost. The model is solved under the assumption of myopic (expected) profit maximisation. However, if the innovating firm's cost reduction is sufficiently small then this myopic picture may not represent a realistic outcome as it would be possible for a high-cost firm to bluff that it has reduced its cost. In Section 4 we show how, for sufficiently small innovations, the bluff possibility for a high-cost firm increases the incentive for an innovating firm to take a patent. We then consider how the innovating firm might use output signalling to address the bluff issue and show that this may make the patent option more or less attractive to the innovating firm relative to the situation under myopic (expected) profit maximisation. Section 5 is a conclusion.

2 A Simple Model

In this section we develop a simple two-period model to allow us to explore the patent/secrecy question focussing on the central issues of interest.

Assumption 1. *The game has two players: firms 1 and 2.*

Assumption 2. *The firms produce a homogenous good with inverse demand function, $p = a - bx$, where p is the market price, $x = \sum_i x_i$ $(i = 1, 2)$ is the total quantity produced and sold in the market and x_i is the output of firm i.*

We are now going to allow for the possibility that one of the firms (Firm 2) has been successful in reducing its constant marginal cost due to a process innovation.

Definition 1. Let firm i be denoted F_i^* (F_i) if it *has* (*has not*) been successful in reducing its constant marginal cost.

[5]Contrast this with the usual role that disclosure is assumed to play as a *deterrent* to patenting (e.g., Scotchmer and Green, 1990; Cohen *et al.*, 1998).

Assumption 3. *(i) F_i has constant marginal cost $c_i = c \in (0, a)$ $(i = 1, 2)$. (ii) F_i^* has constant marginal cost $c^* = c - \delta$ where $\delta \in (0, c)$.*

The following assumptions set out the structure of the game.

Assumption 4. [6] *(i) The game has two periods, $t = 1, 2$. (ii) In each period the two firms compete in a simultaneous quantity-setting game with firms acting as independent (expected) profit maximisers. (iii) The game is solved by backward induction. (iv) The discount rate is r.*

Remark 1. It follows straightforwardly from Assumption 4 that, given the firms are (expected) profit maximisers in a finitely repeated game with period two as the terminal period, there is no signalling benefit from deviation from the myopic maximisation of profit in the final period of the game.

Assumption 5. *The game begins when firm 2: (i) achieves a cost-reducing process innovation; (ii) announces that it is F_2^* and (iii) decides between taking a patent or pursuing secrecy.*

Assumption 6. *Under the patent strategy: (i) firm 2 incurs an immediate cost $P > 0$; (ii) firm 2's low-cost status becomes common knowledge; (iii) the patent lasts for period 1 offering firm 2 complete protection from imitation and copying during this time; (iv) in period 2 the patent runs out and firm 1 adopts a version of the low-cost technology yielding a proportion $\gamma \in (0, 1]$ of the innovating firm's cost reduction δ and there is full information.*

Assumption 6 places some important restrictions on the model, that are, nevertheless, necessary in order to preserve tractability and transparency. The main restriction is that the patent length, period one, coincides with the time available for the low-cost firm to meaningfully establish that it is low-cost under secrecy if it is to achieve a second-period information generated separating equilibrium. Hence, the time for which the patenting firm sees it's cost advantage eroded following the end of the patent (the second period) is the same as the time the low-cost firm under secrecy gets to enjoy the gains if it is successful in achieving an information generated separating equilibrium. Indeed, within this framework it is shown later that secrecy would always be more profitable to F_2^* if firm 1 were able to fully reproduce the cost saving δ (i.e. $\gamma = 1$) in the second period under patenting: the one (first) period gain from certainty under patenting carries a lower profit than the one (second) period loss due to firm 2 gaining low-cost equality to the extent that a profitable patent would require a very high discount rate. Introducing the parameter γ allows us to overcome this otherwise restrictive characteristic of our simple framework. We rule out $\gamma = 0$ though as this would immediately rule out any benefit from secrecy other than avoiding the cost of the patent.

[6]We have chosen the Cournot model with asymmetric information as the backbone of our analysis. Bonanno and Haworth (1998) compare the relative suitability of the Cournot and Bertrand models for analysing the behaviour of patenting by firms. They concluded that the Cournot model is a better model for analysing process patenting whereas the Bertrand model is more suitable for the analysis of product patenting.

Assumption 7. [7] *Under secrecy firm 1: (i) attaches probability λ_t in period t ($t = 1, 2$) to the event that firm 2 has reduced its cost; (ii) $\lambda_1 \in (0, 1)$, hence under secrecy, uncertainty always prevails in period 1; (iii) firm 1 updates the probability to $\lambda_2 = 0$ ($\lambda_2 = 1$) in period 2 only if it is convinced by the observed outcome in period 1 that firm 2 is F_2 (F_2^*); (iv) otherwise firm 1 leaves λ unchanged: $\lambda_2 = \lambda_1$; (v) λ_t is common knowledge for firms making period t decisions.*

For the time being we introduce an assumption which dramatically simplifies the analysis but which we will progressively relax throughout the paper.

Assumption 8. [8] *All firms are myopic (expected) profit maximisers in period 1 and this is common knowledge.*

Given Assumptions 1-8, we can now distinguish between four equilibria which represent possible outcomes in period 1, 2 or both.

Definition 2. Let: (i) **E(0)** represent the full information symmetric high-cost equilibrium; (ii) **E(1)** represent the (myopic) equilibrium under cost uncertainty where firm 2 is high-cost; (iii) **E(2)** represent the (myopic) equilibrium under cost uncertainty where firm 2 is low-cost; (iv) **E(3)** represent the full information asymmetric cost $(c_1, c_2) = (c, c^*)$ equilibrium; (v) **E(4)** represent the full information asymmetric cost equilibrium under which firm 1 achieves a proportion γ of the cost reduction δ achieved by F_2^*: $(c_1, c_2) = (c - \delta\gamma, c^*)$.

For convenience, we begin with equilibria **E(1)** and **E(2)**.

Lemma 1. *In the case of cost uncertainty with Assumption 8, (i) the equilibrium output combinations must be represented by either $(x_1(1), x_2(1))$ or $(x_1(2), x_2(2))$, where,*

$$x_1(1) = x_1(2) = \frac{(a-c)}{3b} - \frac{\lambda\delta}{3b}, \tag{1a}$$

$$x_2(1) = \frac{(a-c)}{3b} + \frac{\lambda\delta}{6b}, \tag{1b}$$

$$x_2(2) = \frac{(a-c+2\delta)}{3b} - \frac{(1-\lambda)\delta}{6b}. \tag{1c}$$

and, (ii) the associated per period profit levels for each of the firms under under **E(1)** and **E(2)** are then:

$$\pi_1(1) = \frac{(2a-2c+\delta\lambda)(a-c-\delta\lambda)}{18b}, \quad \pi_2(1) = \frac{(2a-2c+\delta\lambda)^2}{36b}, \tag{2a}$$

$$\pi_1(2) = \frac{(2a-2c+\delta(\lambda-3))(a-c-\delta\lambda)}{18b}, \quad \pi_2^*(2) = \frac{(2a-2c+\delta(\lambda+3))^2}{36b}, \tag{2b}$$

[7] The common knowledge assumption on λ is a simplification that allows us to focus on the main information asymmetry here - firm 2's cost, whilst preserving tractability.

[8] Following from Remark 1, the following assumption needs only address period 1 behaviour.

Proof. (i) Given uncertainty Firm 1 recognises that Firm 2 may be high-cost or low-cost with respective profit:

$$\pi_2 = (a - bx_1 - bx_2 - c)x_2, \tag{3a}$$

$$\pi_2^* = (a - bx_1 - bx_2 - c + \delta)x_2. \tag{3b}$$

Maximising profit with respect to x_2 under the Cournot assumption yields the reaction functions for F_2 and F_2^*, respectively:

$$x_2 = \frac{(a - c - bx_1)}{2b}, \tag{4a}$$

$$x_2^* = \frac{(a - c + \delta - bx_1)}{2b}. \tag{4b}$$

By Assumption 7, under uncertainty firm 1 attaches a probability $\lambda \in (0, 1)$ to the event that firm 2 has been able to reduce the unit cost. Its expected profit for a given x_1 is therefore,

$$E(\pi_1) = (1 - \lambda)[\{a - b(x_1 + x_2) - c\}x_1] + \lambda[\{a - b(x_1 + x_2^*) - c\}x_1], \tag{5}$$

and since, by Assumption 4, Firm 1 maximizes its expected profit under asymmetric information, it produces $x_1(1) = x_1(2)$. Consequently, Firm 2 produces either $x_2(1)$, in the absence of any technological improvement, or, $x_2(2)$ if it has reduced its cost. (ii) Firm per period profits follow from substitution of Eqs. (1a)-(1c) into Eqs. (3a), (3b) and (5), as appropriate. □

The asymmetric and symmetric cost full-information equilibria now follow as a special case of **E(2)** and **E(1)**, respectively.

Lemma 2. *(i) The asymmetric cost full-information equilibrium, **E(3)**, is given by:*

$$x_1(3) = \frac{(a - c - \delta)}{3b}, \quad \pi_1(3) = \frac{(a - c - \delta)^2}{9b}, \tag{6a}$$

$$x_2(3) = \frac{(a - c + 2\delta)}{3b}, \quad \pi_2^*(3) = \frac{(a - c + 2\delta)^2}{9b}. \tag{6b}$$

*(ii) The symmetric high-cost full information equilibrium, **E(0)**, is given by:*

$$x_i(0) = \frac{(a - c)}{3b}, \quad \pi_i(0) = \frac{(a - c)^2}{9b}, \quad (i = 1, 2); \tag{7}$$

Proof. (i) **E(2)** represents the asymmetric cost equilibrium under uncertainty, hence under certainty with full information and asymmetric cost, **E(3)** is derived from **E(2)** with $\lambda = 1$. (ii) **E(1)** represents the symmetric cost equilibrium under uncertainty, hence under certainty with full information and symmetric cost, **E(0)** is derived from **E(1)** with $\lambda = 0$. □

We now address the remaining full information asymmetric equilibrium in which firm 1 is able to achieve some proportion γ of the cost reduction δ achieved by firm F_2^*.

Lemma 3. *The asymmetric cost full information equilibrium, where firm 1 achieves a cost reduction of $\gamma\delta$ is given by:*

$$x_1(4) = \frac{(a - c - \delta(1 - 2\gamma))}{3b}, \quad \pi_1(4) = \frac{(a - c - \delta(1 - 2\gamma))^2}{9b}, \tag{8a}$$

$$x_2(4) = \frac{(a - c + \delta(2 - \gamma))}{3b}, \quad \pi_2^*(4) = \frac{(a - c + \delta(2 - \gamma))^2}{9b}. \tag{8b}$$

Proof. **E(3)** represents the full information asymmetric equilibrium with cost differential δ. Under **E(4)** the cost differential is $\delta(1-\gamma)$. Replacing c with $c - \gamma\delta$ and replacing δ with $\delta(1-\gamma)$ in **E(3)** yields **E(4)**. □

3 Patenting versus Secrecy

We now seek to determine the rewards to each firm in each stage of the game and begin with the more straightforward case, patenting.

3.1 Patenting

In this section we derive the equilibrium in each period under the scenario in which F_2^* opts to take out a patent. Throughout the paper, we use a '*tilde*' to indicate a variable determined under the patent action.

Lemma 4. *If firm 2 takes out a patent the equilibrium outputs and profits in each period are given by:*[9]

$$\tilde{x}_i^1 = x_i(3), \quad \tilde{x}_i^2 = x_i(4), \quad (i = 1, 2), \tag{9a}$$

$$\tilde{\pi}_i^1 = \pi_i(3), \quad \tilde{\pi}_i^2 = \pi_i(4). \tag{9b}$$

Proof. By Assumption 6, by taking out a patent F_2^* resolves the information asymmetry, hence period 1 and 2 equilibria are given by the full information asymmetric cost **E(3)** and full information symmetric low-cost **E(4)**, respectively. □

Corollary 1. *The discounted flow of profits to firms 1 and 2 under the patenting, where P is the cost of taking out the patent, is given by:*

$$\tilde{\Pi}_1 \equiv \frac{\pi_1(3)}{(1+r)} + \frac{\pi_1(4)}{(1+r)^2} = \frac{(a - c - \delta)^2}{9b(1+r)} + \frac{(a - c - \delta(1 - 2\gamma))^2}{9b(1+r)^2}, \tag{10a}$$

$$\tilde{\Pi}_2^* \equiv \frac{\pi_2^*(3)}{(1+r)} + \frac{\pi_2^*(4)}{(1+r)^2} = \frac{(a - c + 2\delta)^2}{9b(1+r)} + \frac{(a - c + \delta(2 - \gamma))^2}{9b(1+r)^2} - P. \tag{10b}$$

[9] Superscripts here denote the period of the game the outcome applies to.

3.2 Secrecy

First, we establish the following results which apply generally under secrecy.

Lemma 5. *F_2 always has an incentive to create uncertainty by announcing it is F_2^*.*

Proof. From Eqs. (2a) and (7), the per period profit to F_2 from $\mathbf{E(1)}$ is strictly greater than (equal to) that from $\mathbf{E(0)}$ if λ is strictly positive (equal to zero), since $\pi_2(1) \geq \pi_2(0)$ if $\delta\lambda(4a - 4c + \delta\lambda) \geq 0$ and $a - c > 0$ by Assumption 3. □

Lemma 6. *Under secrecy **E(1)** can only be a one period equilibrium.*

Proof. Clearly, if firm 2 chooses $x_2^1 = x_2(1)$ then it signals to firm 1 that it is high-cost and in the second period $\lambda_2 = 0$. Alternatively, if uncertainty prevails in the second period, (i.e., $x_2^1 \neq x_2(1)$) then F_2 maximises profit for the one remaining period with $x_2^2 = x_2(1)$. □

Under the Patenting option, no deviation from myopic maximisation is possible since the Patent resolves the asymmetric information. However, under secrecy it is not always reasonable to assume myopic behaviour. In order to progress towards illustrating the trade-off between secrecy and patenting, we begin under the simplification of the framework (which we later progressively relax) represented by Assumption 8. Essentially, this assumption ensures that although F_2 will announce that it is F_2^* it will not follow this up with an attempt to bluff it is F_2^* in period 1 and also F_2^*. Equally, F_2^* will not attempt to deviate from its myopic maximisation in period 1 in order to signal it is low-cost.

Lemma 7. *Under secrecy and Assumption 8, F_1 always plays:*

$$x_1^1 = x_1(1). \tag{11}$$

Proof. By Assumption 7, under secrecy in period 1 by Assumption 7, $\lambda_1 \in (0, 1)$, and by Assumption 8, firm 1 is a myopic maximiser. Hence F_1 makes its choice under uncertainty and it's expected profit maximising choice of output is as derived in Lemma 1. □

This turns out to be an important simplification which allows the rest of the one period equilibria to be determined straightforwardly.

Lemma 8. *Under secrecy and Assumption 8, the equilibrium output configurations in each period are, (i) in the case that firm 2 is high-cost:*

$$(x_1^1, x_2^1) = (x_1(1), x_2(1)), \quad (x_1^2, x_2^2) = (x_1(0) = x_2(0)), \tag{12}$$

and, (ii) in the case that firm 2 is low-cost:

$$(x_1^1, x_2^1) = (x_1(2), x_2(2)), \quad (x_1^2, x_2^2) = (x_1(3), x_2(3)). \tag{13}$$

Proof. (i) Given uncertainty in period 1, $x_1^1 = x_1(1) = x_1(2)$ by Lemma 1. Under Assumption 8, $x_2^1 = x_2(1)$ and $x_2^1 = x_2(2)$ by Lemma 7, hence neither firm attempts to deviate from myopic profit maximisation in order to bluff or signal to influence the period 2 outcome. However, by Lemma 6, $x_2^1 = x_2(1)$ results in $\lambda_2 = 0$ and hence the high-cost symmetric full information equilibrium, $\mathbf{E(0)}$, is obtained in period 2. (ii) By the same reasoning $x_2^1 = x_2(2)$ leads to $\lambda_2 = 1$ and the second period equilibrium is $\mathbf{E(3)}$. □

Corollary 2. *Under myopic (expected) profit maximisation, the discounted flow of profits in the case of (i) firm 2 being high-cost, are:*

$$\Pi_1^M \equiv \frac{\pi_1(1)}{(1+r)} + \frac{\pi_1(0)}{(1+r)^2} = \frac{(2a-2c+\delta\lambda)(a-c-\delta\lambda)}{18b(1+r)} + \frac{(a-c)^2}{9b(1+r)^2}, \tag{14a}$$

$$\Pi_2^M \equiv \frac{\pi_2^*(1)}{(1+r)} + \frac{\pi_2^*(0)}{(1+r)^2} = \frac{(2a-2c+\delta\lambda)^2}{36b(1+r)} + \frac{(a-c)^2}{9b(1+r)^2}, \tag{14b}$$

(ii) firm 2 being low-cost, are:

$$\Pi_1^M \equiv \frac{\pi_1(2)}{(1+r)} + \frac{\pi_1(3)}{(1+r)^2} = \frac{(2a-2c+\delta(\lambda-3))(a-c-\delta\lambda)}{18b(1+r)} + \frac{(a-c-\delta)^2}{9b(1+r)^2}, \tag{15a}$$

$$\Pi_2^{*M} \equiv \frac{\pi_2^*(2)}{(1+r)} + \frac{\pi_2^*(3)}{(1+r)^2} = \frac{(2a-2c+\delta(\lambda+3))^2}{36b(1+r)} + \frac{(a-c+2\delta)^2}{9b(1+r)^2}. \tag{15b}$$

Of course this begs the question: under what circumstances with myopic profit maximisation will F_2^* opt for a patent even though it can resolve the asymmetry under secrecy through its myopic profit maximising behaviour in period 1?

Corollary 3. *F_2^* opts for a patent rather than secrecy under myopic profit maximisation, Assumption 8, if:*

$$\Omega^M \equiv \tilde{\Pi}_2^* - \Pi_2^{*M} \equiv \frac{[\pi_2^*(3)-\pi_2^*(2)]}{(1+r)} + \frac{\{\pi_2^*(4)-\pi_2^*(3)\}}{(1+r)^2} - P > 0 \tag{16}$$

Proposition 1. *(i) $[.] > 0$ and $\{.\} < 0$.*
(ii) Ω^M is decreasing in P, γ and λ_1.
(iii) $\partial\Omega^M/\partial\delta$ is (negative) monotonic in γ and λ.
(iv) $\partial\Omega^M/\partial\delta = 0$ at $(\gamma,\lambda) = (0,1)$ and at other points following the trade-off contour $d\lambda/d\gamma = -2(a-c+2(2-\gamma))/[(1+r)(a-c+\delta(3+\lambda))]$.
(v) $\partial\Omega^M/\partial\delta > (<)0$ for points below (above) the contour in (iv) in the (γ,λ) plane.

Proof. (i) The term [.] represents the gain in profit to F_2^* in period 1 though patenting and {.} represents the gain in period 2. Note, [.] is strictly positive given $\lambda_1 \in (0,1)$, since $\lim_{\lambda_1\to 1}[.] = 0$, $\lim_{\lambda_1\to 0}[.] = 4(a-c+2\delta)^2 - (a-c+1.5\delta)^2) > 0$ and [.] is negative monotonic in λ_1 since $\partial[.]/\partial\lambda_1 = -2\delta(\lambda_1+3) < 0$. Also, note that {.} is strictly negative, given by Assumption 3, δ is strictly positive. (ii) $\partial\Omega^M/\partial P = -1 < 0$; $\partial\Omega^M/\partial\lambda_1 = -\delta[4(a-c)-\delta(6+2\lambda)]/(36b(1+r)) < 0$; $\partial\Omega^M/\partial\gamma = -\delta[(a-c)-\delta(\gamma-2)]/(4b(1+r)^2) < 0$. (iii) First:

$$\frac{\partial\Omega^M}{\partial\delta} = \frac{2\,[4(2a-2c+4\delta)-(3+\lambda)(2a-2c+(3+\lambda)\delta)]}{36b(1+r)} + \frac{8\,\{(2-\gamma)(a-c+(2-\gamma)\delta)-2(a-c+2\delta)\}}{36b(1+r)^2}$$

Hence, $\partial^2\Omega^M/(\partial\delta\partial\gamma) = 2(a-c+2(2-\gamma))/(9b(1+r)^2) < 0$ and $\partial^2\Omega^M/(\partial\delta\partial\lambda) = (a-c+2\delta(3+\lambda)/(9b(1+r)) < 0$. (iv) Substituting $(\gamma,\lambda) = (0,1)$ into $\partial\Omega^M/\partial\delta$

reduces both [.] and {.} to zero. Taking the total differential of $\partial\Omega^M/\partial\delta = 0$ yields $d\lambda/d\gamma = -2(a - c + 2(2 - \gamma))/[(1 + r)(a - c + \delta(3 + \lambda))]$. (v) The sign of $\partial\Omega^M/\partial\delta$ above (below) the contour in (iv) follow from the negative monotonicity of $\partial\Omega^M/\partial\delta$ with respect to λ and γ. □

Hence, we have shown using a very simple framework that the low-cost firm may resort to taking out a patent, even if there is no risk of the innovation being copied or imitated, due to the desire to restore full information to appropriate the gains from its cost reduction. This is made more attractive as an option the lower the cost of the patent, the lower the probability F_1 places on firm 2 being low-cost, and the lower the degree to which F_1 is able to match the cost reduction at the end of the patent period, the smaller the incentive to patent. The role of δ is less transparent. Since an increase in δ increases profit for F_2^* under each of the relevant equilibria, what matters is the relative size of the increase in profit in each case, which is more problematic to study. However, an increase in δ will tend to increase the incentive to patent if λ (γ) is relatively large (small). We now consider how relaxing the assumption of myopic first-period profit maximisation a little can affect the result.

4 Bluffing and Signalling

In this Section we consider to what extent the balance between patenting and secrecy is altered by the relaxation of the assumption of universal myopic (expected) profit maximisation in favour of the high- (low-) cost firm being able to deviate from its short term maximisation of profit in order to try to bluff (signal) that it is low-cost.

4.1 Bluffing

We begin by setting out a new condition of the game, relaxing Assumption 8, as follows.

Assumption 9. *In period 1, F_1 and F_2^* are myopic (expected) profit maximisers, but F_1 believes that F_2 will attempt to bluff that it is F_2^* in order to profit in the second period, if this is strictly profitable to F_2, and this is common knowledge.*

Essentially, this assumption allows us to model the possibility of F_2 bluffing whilst not over complicating the analysis by allowing F_2^* to undertake a first-period output signal. The restriction of the bluff scenario to the case of a strict gain in profit to F_2 from the bluff over myopic profit maximisation in Assumption 9 is purely for convenience, but does not materially affect the nature of the results.

First, it is necessary to introduce a new outcome under **E(2)** and a new equilibrium that is specifically related to the second period following a successful bluff. First:

Lemma 9. *Under Assumption 9 $\pi_2(2)$ is the profit to F_2 if it plays $x_2(2)$ and hence attempts to bluff that it is F_2^*:*

$$\pi_2(2) = \frac{(2a - 2c + \delta(\lambda + 3))(2a - 2c + \delta(\lambda - 3))}{36b}. \tag{17}$$

Proof. Eq. (17) follows from substitution of Eqs. (1a) and (1c) in Eq. (3a). □

Definition 3. Let **E(5)** represent the equilibrium in which F_2 has convinced F_1 that it is low-cost.

Lemma 10. *(i)* ***E(5)*** *can only be a second period equilibrium under secrecy. (ii) Under* ***E(5)*** *the outputs and profits of F_1 and F_2 are:*

$$x_1(5) = x_1(3), \quad x_2(5) = \frac{(2a - 2c + \delta)}{6b}, \tag{18a}$$

$$\pi_1(5) = \frac{(2a - 2c + \delta)(a - c - \delta)}{18b}, \quad \pi_2(5) = \frac{(2a - 2c + \delta)^2}{36b}. \tag{18b}$$

Proof. (i) **E(5)** requires $\lambda = 1$ but it follows from Assumption 7 that under secrecy in period 1 $\lambda \in (0, 1)$. (ii) Having convinced firm 1 that it is F_2^*, F_2 knows that F_1 will play $x_1^2 = x_1(3)$. In this knowledge F_2's profit is $\frac{(2a-2c+\delta-3bx_2)x_2}{3}$. Maximising with respect to x_2 yields $x_2 = x_2(5)$. Consequently, given F_2 does not play $x_2 = x_2(3)$, and $\pi_1(5) \neq \pi_1(3)$. □

Lemma 11. *The discounted flow of profit available to F_2 under a successful bluff in which setting $x_2^1 = x_2(2)$ convinces F_1 that it is F_2^* is given by:*

$$\begin{aligned}\Pi_2^B \equiv& \frac{\pi_2(2)}{(1+r)} + \frac{\pi_2(5)}{(1+r)^2} \\ =& \frac{(2a - 2c + \delta(\lambda_1 + 3))(2a - 2c + \delta(\lambda_1 - 3))}{36b(1+r)} + \frac{(2a - 2c + \delta)^2}{36b(1+r)^2}.\end{aligned} \tag{19}$$

Proof. In period 1, the bluff requires F_2 to move from its myopic maximising choice of $x_2(1)$ to adopt $x_2(2)$. The period 1 equilibrium is then given by the output combination $(x_1(2), x_2(2))$. However, since firm 2 is not low-cost its profit is not $\pi_2^*(2)$, but rather $\pi_2(2)$, in Lemma 9. Having convinced F_1 that it is low cost, in period 2 F_2 enjoys $\pi_2(5)$ as given by Eq. (18b). Discounting accordingly and summing yields Eq. (19). □

Proposition 2. *Let Ψ^B be the gain to F_2, under Assumption 9, of pursuing a bluff rather than myopic profit maximisation:*

$$\Psi^B \equiv \Pi_2^B - \Pi_2^M = \frac{\delta(-\delta(8 + 9r) + 4a - 4c)}{36b(1+r)^2}. \tag{20}$$

(i) Ψ^B is strictly concave in δ, (ii) $\Psi^B = 0$, yields:

$$\delta = \left\{0, \delta^B\right\}, \quad \delta^B \equiv \frac{4(a - c)}{8 + 9r} \tag{21}$$

(iii) $\Psi^B > 0$, and F_2 chooses to bluff iff $\delta < \delta^B$.

Proof. (i) Differentiating Ψ^B twice with respect to δ we get, $\partial^2\Psi^B/\partial\delta^2 = -(1/18)(8 + 9r)/((1+r)^2 b) < 0$. (ii) The roots of $\Psi^B = 0$ follow straightforwardly from Eq. (31). (iii) The result follows straightforwardly from noting the strict concavity of Ψ^B in (i) and the roots of $\Psi^B = 0$ in (ii), hence Ψ^B is strictly positive in the interval $\delta \in (0, \delta^B)$, and by Assumption 3, and from Assumption 9, the strict inequality $\Psi^B > 0$ is required for F_2 to bluff. □

Lemma 12. *If $\delta < \delta^B$ then $x_2(2)$ in period one does not yield an information generated separating equilibrium.*

Proof. By Proposition 2, if $\delta < \delta^B$, F_1 knows that F_2 will have an incentive to bluff with $x_2^1 = x_2(2)$ if F_1 treats $x_2^1 = x_2(2)$ as a signal that F_2 is low cost. Hence, by Assumption 7, if $\delta < \delta^B$ and $x_2^1 = x_2(2)$ then $\lambda_2 \in (0,1)$ and the second period equilibrium is represented by **E(1)** under F_2 and **E(2)** under F_2^*. □

Remark 2. It might appear that, given $\pi_2(1) < \pi_2(5)$ and hence F_2 could not profitably undertake the bluff if it fails to resolve uncertainty, F_2^* might be able to convince F_1 that it is low-cost for some range of $\delta < \delta^B$, by playing $x_2^1 = x_2(2)$. However, as long as F_1 is open to taking the signal of $x_2^1 = x_2(2)$ to indicate that firm 2 is low cost, then if $\delta < \delta^B$ there is a danger that F_2 will bluff its way in.

Corollary 4. *Under Assumption 9, with secrecy and $\delta < \delta^B$ then F_2^* is unable to resolve the uncertainty and by myopic profit maximisation earns profit:*

$$\Pi_2^{*B} \equiv \frac{\pi_2^*(2)}{(1+r)} + \frac{\pi_2^*(2)}{(1+r)^2} = \frac{(2a-2c+\delta(\lambda+3))^2}{36b(1+r)} + \frac{(2a-2c+\delta(\lambda+3))^2}{36b(1+r)^2}. \tag{22}$$

Corollary 5. *Given $\delta < \delta^B$, F_2^* opts for a patent rather than secrecy if:*

$$\begin{aligned} \Omega^B &\equiv \tilde{\Pi}_2^* - \Pi_2^{*B} \\ &\equiv \frac{[\pi_2^*(3) - \pi_2^*(2)]}{(1+r)} + \frac{\{\pi_2^*(4) - \pi_2^*(2)\}}{(1+r)^2} > 0 \end{aligned} \tag{23}$$

Proposition 3. *$\Omega^B > \Omega^M$, and the gain to F_2^* from taking a patent relative to secrecy is strictly greater in the scenario where F_2 can bluff than under myopic profit maximisation.*

Proof. Ω^M and Ω^B differ only in respect to the second period reward under secrecy, sharing the same first period uncertainty and same first and second period outcomes under the patent. In the case of Ω^M the second period under secrecy is the full information asymmetric cost equilibrium, whilst uncertainty prevails in the second period in the case of Ω^B. Since $\pi_2^*(3) > \pi_2^*(2)$, the result follows immediately. □

4.2 Signalling

We now take the game a stage further, modifying Assumption 9 as follows.

Assumption 10. *Under $\delta < \delta^B$ and secrecy, F_2^* can attempt to signal that it is low-cost in period 1 and this is common knowledge.*

Analysing the scenario under a signal requires the introduction of a few more equilibria.

Definition 4. Under cost uncertainty where $\delta < \delta^B$ and there exists an information generating separating equilibrium signal which is profitable to F_2^*, let: (i) **E(6)** represent the equilibrium under which firm 2 is low-cost and pursues the output signal; (ii) **E(7)** represent the equilibrium under which firm 2 is high-cost.

Remark 3. Note, **E(6)** and **E(7)** are distinct from **E(5)** and **E(1)**, respectively. This is because, as we will see, the output of F_2^* required to signal that it is low-cost under $\delta < \delta^B$ will be different from $x_2(2)$ and hence firm 1 maximises expected profit over different levels of firm 2 outputs than in **E(5)** and **E(1)**.

Lemma 13. *(i) Output for F_1 under **E(6)** and **E(7)** and output and profit for F_2 under **E(7)** are, respectively:*

$$x_1(6) \equiv x_1(7) = \frac{(a-c)(1+\lambda) - 2b\lambda x_2(6)}{b(3+\lambda)}, \tag{24a}$$

$$x_2(7) = \frac{a-c+b\lambda x_2(6)}{b(3+\lambda)}, \tag{24b}$$

$$\pi_2(7) = \frac{(a-c+b\lambda x_2(6))^2}{b(3+\lambda)^2}. \tag{24c}$$

(ii) The discounted flow of profit for F_2 under myopic profit maximisation in the presence of a signal $x_2^*(6)$, is given by:

$$\Pi_2^{SM} = \frac{\pi_2(7)}{1+r} + \frac{\pi_2(0)}{(1+r)^2}. \tag{25}$$

Proof. (i) Firm 1 maximises expected profit in period one under uncertainty, given by Eq. (5), as before attaching probability λ $(1-\lambda)$ to firm 2 being F_2^* (F_2). Under the prospect of F_2^* using the information generated separating equilibrium signal $x_2(6)$, F_2 has reaction function Eq. (4a). Solving simultaneously gives the following expressions for the reaction functions of F_1 (which is the same under **E(6)** and **E(7)**) and F_2 (under **E(7)**) in terms of $x_2(6)$, respectively, Eqs. (24a) and (24b). Period one profit to F_2 is then given by Eq. (24c). (ii) With F_2 having set out to maximise period 1 profit myopically, period 2 is the full information symmetric cost equilibrium **E(0)**. Total profit for F_2 over the two periods with signalling in period 1 is then given by Eq. (25). □

In order to achieve an information separating equilibrium signal, F_2^* needs to ensure that if F_2 were to adopt the signal and successfully convince F_1 that it was low-cost, then the associated profit would be less than under myopic profit maximisation.

Lemma 14. *The information generated separating equilibrium signal for F_2^* under cost uncertainty and $\delta < \delta^B$ is an output strictly greater than the myopic profit maximising level of output for F_2^* under cost uncertainty: $x_2(6) > x_2(2)$.*

Proof. The proof is by contradiction. Suppose $x_2(6) = x_2(2)$. Given, under $\delta < \delta^B$, F_2 gains from playing $x_2(2)$ in period one to bluff that it is low-cost it could also profitably signal using $x_2(6)$. However, $x_2(6)$ is then not an information generating separating equilibrium signal. □

The following Lemmas address the profit gain to firm F_1 from adopting the signal $x_2(6)$, relative to myopic behaviour, in order that we can identify some $x_2(6)$ which will cause this to be a loss-making option for F_1, and hence offer a possible information generated separating equilibrium output for F_2^*.

Lemma 15. *(i) Profit for F_2 under **E(6)**, where F_2 adopts the signalling output $x_2(6)$, is given by:*

$$\pi_2(6) = \frac{[2(a-c) + bx_2(6)(\lambda - 3)]x_2(6)}{3+\lambda}. \tag{26}$$

(ii) The discounted flow of profit for F_2 in the case that it opts for the signal $x_2(6)$ in period 1 is given by:

$$\Pi_2^{SS} = \frac{\pi_2(6)}{1+r} + \frac{\pi_2(5)}{(1+r)^2}. \tag{27}$$

Proof. (i) Given, by Lemma 13, $x_1(6) \equiv x_2(6)$ and F_2 plays $x_2(6)$, industry output is $x_1(6) + x_2(6)$ and the proof follows straightforwardly. (ii) By playing $x_2(6)$ in period 1, the high-cost firm convinces F_1 that it is low-cost, hence the equilibrium in period 2 is **E(5)**. □

Lemma 16. *Let $\Psi(x_2(6)) \equiv \Pi_2^{SS} - \Pi_2^{SM}$ (i.e. the gain to F_2 from adopting the signal $x_2(6)$ to bluff that it is low-cost, relative to myopic profit maximisation in period one). Then, $\Psi(x_2(6))$ is negative monotonic in $x_2(6)$.*

Proof. $\Psi'(x_2(6)) = 6(a-c-3bx_2(6))/[(1+r)(3+\lambda)^2]$, which is negative by noting from Lemma 14 that $x_2(6) > x_2(2)$ and further that $x_2(2) > (a-c)/b$ given $\lambda, \delta > 0$. □

The following Lemma identifies a separating equilibrium output signal for the low-cost firm.

Lemma 17. *The cost-minimising information generated separating equilibrium signal for F_2^* under Assumption 10 is given by:*

$$x_2(6) = \frac{1}{18b(1+r)} \left\{6(a-c)(1+r) + (\lambda+3)\delta^{0.5}(1+r)^{0.5}(4(a-c)+\delta)^{0.5}\right\} \tag{28}$$

Proof. The minimum requirement for an information generated separating equilibrium signal by F_2^* under Assumption 10 is one which, if reproduced by F_2 would result in F_2 earning no more profit than under myopic optimisation, hence $\Pi_2^{SS}(x_2(6)) \leq \Pi_2^{SM}(x_2(6))$. Since, by Lemma 16(ii), Ψ is negative monotonic in $x_2(6)$, the lowest level of $x_2(6)$ to achieve the separating equilibrium is one which yields $\Psi = 0$. This is also the cost-minimising signal for F_2^*. $\Psi = 0$ is quadratic in $x_2(6)$. The solution to the quadratic is given by

$$x_2(6) = \frac{1}{18b(1+r)} \left\{6(a-c)(1+r) \pm (\lambda+3)\delta^{0.5}(1+r)^{0.5}(4(a-c)+\delta)^{0.5}\right\} \tag{29}$$

Notice that the first part of Eq. (29) (the unambiguous part) simplifies to $(a-c)/(3b)$, which is the equilibrium firm output under the full information symmetric high-cost equilibrium $x_i(0)$. Since any feasible signal by F_2^* must be strictly greater than its myopic equilibrium output $x_2(3)$, which in turn is strictly greater than $x_i(0)$, the right hand side of Eq. (29) must add to not diminish the left hand side, hence $x_2(6)$ is given by Eq. (28). □

Corollary 6. *Under Assumption 10 and $\delta < \delta^B$, if F_2^* undertakes the first-period separating equilibrium signal, $x_2(6)$, under secrecy, it earns profit:*

$$\begin{aligned}\pi_2^*(6) =& \frac{1}{324b(1+r)} \\ & (36(a-c)^2 + 108\delta(a-c)(1+r) - \delta(3+\lambda)(3-\lambda)(4(a-c)+\delta) \\ & +6[9\delta + \lambda(2(a-c)+3\delta)]\delta^{0.5}(1+r)^{0.5}(4(a-c)+\delta)^{0.5}).\end{aligned} \tag{30}$$

In our most simplistic model with the restrictive Assumption 8, F_2^* was not able to signal nor was there a possibility of F_2 bluffing. We saw that under these restrictions F_2^* still had an incentive to take out a patent under some circumstances. We then saw that under Assumption 9, in which the high-cost firm was allowed to pursue a bluff but F_2^* was not allowed to pursue a signal, the profit to F_2^* due to secrecy was lower and the incentive to patent higher than under Assumption 8. We now turn our attention to addressing the question as to whether, under Assumption 10, in which F_2^* is able to use the signal $x_2(6)$ to resolve uncertainty, it now has a greater or lesser incentive to pursue a patent than under Assumption 8. We begin by establishing the relationship between period 1 profit to F_2^* under myopic behaviour $x_2(2)$ and non-myopic behaviour $\hat{x}_2(6)$ ($\hat{x}_2(6) \neq x_2(2)$) where, for simplicity $\hat{x}_2(6)$ is not necessarily the signalling output, $x_2(6)$.

Lemma 18. *Let $\Theta \equiv \hat{\pi}_2^*(6) - \pi_2^*(2)$.*

(i) The period one profit for F_2^* under Assumption 10 and the output $\hat{x}_2(6)$ is the same as the period one profit for F_2^* under Assumption 8 and myopic profit maximisation, if:

$$\hat{x}_2(6) = x_2(2)\frac{(3 \pm \lambda)}{(3-\lambda)}; \tag{31}$$

(ii) Θ is strictly concave in $x_2(6)$;
(iii) Θ is strictly positive in the interval:

$$x_2(2) < \hat{x}_2(6) < x_2(2)\frac{(3+\lambda)}{(3-\lambda)}, \tag{32}$$

and strictly negative for:

$$\hat{x}_2(6) < x_2(2)\frac{(3+\lambda)}{(3-\lambda)}. \tag{33}$$

Proof. (i) Note, using Eq. (24a) in $x(6) = x_1(6) + \hat{x}_2(6)$, profit for F_2^* under the signal $\hat{x}_2(6)$, can be expressed as:

$$\hat{\pi}_2^*(6) = \frac{\hat{x}_2(6)\left[\{2(a-c)+\delta(3+\lambda)\} - b(3-\lambda)\hat{x}_2(6)\right]}{(3+\lambda)} \tag{34}$$

Further, noting that in Eq. (34), $\{.\} = 6bx_2(2)$, Θ can be written:

$$\Theta = \frac{[6x_2(2) - (3-\lambda)\hat{x}_2(6)]b\hat{x}_2(6)}{(3+\lambda)} - bx_2(2)^2. \tag{35}$$

Setting Eq. (35) equal to zero and solving for the quadratic in $\hat{x}_2(6)$:

$$\hat{x}_2(6) = \frac{6x_2(2) \pm \{36x_2(2)^2 - 4(3-\lambda)(3+\lambda)x_2(2)^2\}^{0.5}}{2(3-\lambda)}. \tag{36}$$

Recognising that in Eq. (36) $\{.\}$ simplifies to $(2\lambda x_2(2))^2$, completes the proof. (ii) Differentiating θ in Eq. (35) twice with respect to $\hat{x}_2(6)$:

$$\frac{\partial^2 \Theta}{\partial \hat{x}_2(6)^2} = -\frac{2b(3-\lambda)}{(3+\lambda)} < 0. \tag{37}$$

(iii) This follows from the concavity of $\Theta(\hat{x}_2(6))$, since Θ must lie above zero in the open interval between the roots, $\hat{x}_2(6) = x_2(2)$ and $\hat{x}_2(6) = x_2(2)(3+\lambda)/(3-\lambda)$, and vice versa. □

Whilst Lemma 18 establishes the range of $\hat{x}_2(6)$ for which the low-cost firm would prefer to pursue the signal rather than myopic behaviour in period 1 to achieve a separating equilibrium in period 2, we have yet to show that such values of $\hat{x}_2(6)$ actually achieve a separating equilibrium and that such outcomes are viable in the case $\delta < \delta^B$. We now refine this result with the help of the following Definition.

Definition 5. Let $\delta \equiv \rho\delta^B \equiv \rho\frac{4(a-c)}{8+9r}$.

Hence, F_2 will have an incentive to bluff that it is low-cost iff $\rho \leq 1$. Also, for the purpose of exploring cases where $\delta < \delta^B$, and given $\delta > 0$, $\rho \in (0, 1]$.

Proposition 4. *Given $\delta < \delta^B$, F_2^* has a greater (lesser) incentive to pursue a patent rather than secrecy under the signal $x_2(6)$ and Assumption 10 compared with myopic profit maximisation under Assumption 8 if:*

$$\begin{aligned}\Upsilon(\lambda,\rho) &\equiv 3\lambda(1+r) \\ &+ \frac{\rho(3+\lambda)}{8+9r}\left[6\lambda(1+r) - (3-\lambda)\left\{(1+r)^{0.5}\left(\frac{8+9r}{\rho}+1\right)^{0.5} - 3(1+r)\right\}\right] < (>)0.\end{aligned} \tag{38}$$

Proof. First, note that under Assumption 8 myopic profit maximisation by F_2^* in period one achieves the separating equilibrium **E(3)** in period 2. The same period 2 outcome for F_2^* results under Assumption 10 with $\delta < \delta^B$ given F_2^* pursues the signal $x_2(6)$. Hence, in each case the second period rewards to secrecy are identical and the relative profitability of each depends only upon the first period profit. Second, from Lemma 18, we know that the period one profit gain to F_2^* pursuing some $\hat{x}_2(6)$ under Assumption 10 relative to the myopic profit maximisation under Assumption 8, given by Θ, is greater (less) than zero according to $\hat{x}_2(6) < (>) x_2(2)(3+\lambda)/(3-\lambda)$. Third, modifying this inequality by substituting $x_2(2)$ using Eq. (1c), replacing $\hat{x}_2(6)$ with the signal $x_2(6)$ and substituting using Eq. (28) and replacing δ according to Definition 5, following some manipulation, gives Eq. (38). One particular step in the manipulation requires explanation. It is straightforward to show that $x_2(6) > x_2(2)$, requires that:

$$(1+r)^{0.5}\left(\frac{8+9r}{\rho}+1\right)^{0.5} - 3(1+r) > 0. \tag{39}$$

Indeed, given $r > 0$ and $\rho \in (0, 1]$ this inequality always holds. This turns out to be useful for our purposes and hence in Eq. (38), the term [.] has been constructed (by adding and subtracting $3(1 + r)(3 - \lambda)$) so that $\{.\}$ reproduces Eq. (39) and hence $\{.\} > 0$. Hence it is possible to find values of the parameters which satisfy both inequalities. Finally, noting that when Eq. (38) is positive (negative) the signalling scenario under secrecy is more profitable than the myopic (non-signal non-bluff) scenario, making patenting relatively less (more) attractive under the former than the latter, completes the proof. □

We now consider the circumstances under which the signalling scenario for F_2^* is more profitable than the myopic scenario.

Lemma 19. *(i)* $\Upsilon(\lambda, \rho)$ *is positive monotonic and strictly convex in* λ *in the relevant range.*
(ii) $\Upsilon(\lambda, \rho)$ *is strictly convex in* ρ *in the relevant range.*
(iii) $\Upsilon(0, \rho) < 0$*;* $\Upsilon(1, 1) > 0$*;* $\Upsilon(1, 0) < 0$*.*
(iv) $\Upsilon_\rho(\lambda, 0) < 0; \Upsilon_\rho(\lambda, 1) > 0$*.*

Proof. (i) Differentiating Eq. (38) w.r.t. λ:

$$\Upsilon_\lambda(\lambda, \rho) = 3(1 + r) + \frac{2\rho}{8 + 9r}\left[3(1 + r)(3 + 2\lambda) + \lambda\{.\}\right] > 0, \tag{40}$$

which is positive since $\{.\} > 0$ from Proposition 4. Differentiating again w.r.t. λ we get:

$$\Upsilon_{\lambda\lambda}(\lambda, \rho) = \frac{2\rho}{8 + 9r}\left[6(1 + r)\{.\}\right] > 0. \tag{41}$$

(ii) Differentiating $\Upsilon(\lambda, \rho)$ twice w.r.t. ρ, we have:

$$\Upsilon_{\rho\rho}(\lambda, \rho) = (3+\lambda)(3-\lambda)(1+r)^{0.5}\left(\frac{8 + 9r}{\rho} + 1\right)^{-0.5}\left[1 + \left(\frac{(8 + 9r)\rho}{4}\right)\left(\frac{8 + 9r}{\rho} + 1\right)^{-1}\right] > 0. \tag{42}$$

(iii) First, substituting $\lambda = 0$ into Eq. (38):

$$\Upsilon(0, \rho) = 3\frac{3\rho}{8 + 9r}[3\{.\}] < 0, \tag{43}$$

since, $\rho \in (0, 1]$ and $\{.\} > 0$. Second, substituting $\lambda = 1$ into Eq. (38):

$$\Upsilon(1, \rho) = 3(1 + r) + \frac{4\rho}{8 + 9r}[6(1 + r) - 2\{.\}], \tag{44}$$

which doesn't have a unique sign. However, at the extreme $\rho = 1$, Eq. (44) becomes:

$$\Upsilon(1, 1) = 3(1 + r) + \frac{24(1 + r)}{8 + 9r} > 0, \tag{45}$$

since $\{.\} = 0$. At the other extreme, $\rho = 0$, we have $\Upsilon(1, 0) = 3(1 + r) > 0$. Finally, substituting $\rho = 0$ into Eq. (38) we get $\Upsilon(\lambda, 0) = 3\lambda(1 + r) > 0$ since $\lambda \in (0, 1)$. substituting $\rho = 1$ into Eq. (38):

$$\Upsilon(\lambda, 1) = 3\lambda(1 + r) + \frac{6(1 + r)\lambda(3 + \lambda)}{8 + 9r} > 0, \tag{46}$$

since $\{.\} = 0$. (iv) First, differentiating Eq. (38) w.r.t. ρ:

$$\Upsilon_\rho(\lambda, \rho) = \left(\frac{3 + \lambda}{8 + 9r}\right) \tag{47}$$
$$\left[6\lambda(1 + r) - (3 - \lambda)\left\{\frac{(1 + r)^{0.5}}{2}(8 + 9r + 2\rho)((8 + 9r)\rho + \rho^2)^{-0.5} - 3(1 + r)\right\}\right].$$

Substituting $\rho = 1$ in Eq. (47), $[.]$ reduces to:

$$\left[3(1 + r)(3 + \lambda) - \frac{(3 - \lambda)(10 + 9r)}{6}\right] > 0 \tag{48}$$

which is strictly positive given $\lambda \in (0, 1)$. Finally, substituting $\rho = 1$ in Eq. (47), $\{.\}$, can be written as:

$$\left\{\frac{(1 + r)^{0.5}}{2}\left[\frac{(8 + 9r)}{((8 + 9r)\rho + \rho^2)^{0.5}} + \frac{2}{\left(\frac{(8+9r)}{\rho} + 1\right)^{0.5}}\right] - 3(1 + r)\right\}. \tag{49}$$

As $\rho \to 0$, the right-hand term in $[.] \to 0$ but the left-hand term in $[.] \to \infty$, hence $\Upsilon_\rho(\lambda, \rho) \to -\infty$. □

Proposition 5. *Given $\delta < \delta^B$, (i) patenting becomes relatively more attractive for F_2^* pursuing the signal $x_2(6)$ under Assumption 10 than under myopic behaviour under Assumption 8 as λ falls.*
(ii) patenting becomes relatively more (less) attractive for F_2^* pursuing the signal $x_2(6)$ under Assumption 10 than under myopic behaviour under Assumption 8 as ρ increases if ρ is sufficiently large (small).
(iii) If λ is sufficiently small then the incentive to pursue patenting is always greater for F_2^* pursuing the signal $x_2(6)$ under Assumption 10 than under myopic behaviour under Assumption 8.
(iv) If λ and γ are sufficiently close to 1, then the incentive to pursue patenting is always lesser for F_2^* pursuing the signal $x_2(6)$ under Assumption 10 than under myopic behaviour under Assumption 8.

Proof. (i) This result follows directly from Lemma 19(i). (ii) This result is a consequence of the strict u-shaped convexity of Υ in ρ following from Lemma 19 (ii) and (iv). The strict inequality of the terms in Lemma 19 (iv) when evaluated at the extremes $\rho = 0$ and $\rho = 1$ ensure that there exists an open interval of $\rho \in (0, 1)$ such that $\Upsilon_\rho(\lambda, \rho)$, has the same sign as at $\rho = 0$ and $\rho = 1$, respectively. (iii) Since $\Upsilon(0, \rho) < 0$ in Lemma 19 (iv) is a strict inequality, there exists an open interval of $\lambda \in (0, t)$, where $t < 1$, such that the entire u-shaped $\Upsilon(0, \rho)$, for $\rho \in (0, 1)$ lies below 0. (iv) Since $\Upsilon(1, 1) > 0$ in Lemma 19 (iv) is a strict inequality, there exists an open interval of $\lambda \in (f, 1)$, and $\rho \in (g, 1)$ where $f, g < 1$, such that $\Upsilon(\lambda, \rho)$, lies above 0. □

5 Conclusions

In this paper we have employed a simple 2-period duopoly model to demonstrate that even if a firm can costlessly maintain complete secrecy with regards to a process innovation (there is no threat of an unpatented innovation being discovered or copied) there may still exist an incentive to patent the innovation so as to resolve information asymmetries. We consider the relative incentives to pursue patenting rather than secrecy under three different sets of assumptions. First, we assume that all firms behave as myopic profit maximisers. Second, we assume that if it is profitable for a high-cost firm to bluff that it is low-cost then it will do so and this is common knowledge. Third, we let the low-cost firm have the option of signalling to convince the rival firm that it has reduced its cost and is not a high-cost firm bluffing.

We show that under myopic optimisation, the incentive to patent rather than pursue secrecy increases as the probability that the rival firm attaches to it being low-cost falls and as the proportion of the cost reduction due to the innovation, secured by the rival firm in the period after the patent has expired, falls. However, the gain to the innovating firm from taking out a patent rather than pursuing secrecy strictly increases if the cost reduction due to the innovation is sufficiently small that the high-cost firm could profitably bluff that it is low-cost. Finally, allowing the low-cost firm the option of using an output signal, may make the patent strategy more or less attractive relative to the case of myopic optimisation.

Hence we have demonstrated that for some parameterisations of our model, there exists an incentive for the low-cost firm to pursue a patent rather than secrecy under myopic behaviour and that whilst the range of parameters satisfying this outcome will be larger if a high-cost firm could profitably bluff that it is low-cost, the range may increase or decrease by allowing the low-cost firm to pursue an output signal.

References

ANTON, J. J. and YAO, D. A. (2004). Little patents and big secrets: Managing intellectual property. *RAND Journal of Economics*, **35** (1), 1–22.

ARUNDEL, A. (2001). The relative effectiveness of patents and secrecy for appropriation. *Research Policy*, **30** (4), 611–624.

BONANNO, G. and HAWORTH, B. (1998). Intensity of competition and the choice between product and process innovation. *International Journal of Industrial Organization*, **16**, 495–510.

COHEN, W., NELSON, R. and WALSH, J. (1998). Appropriability conditions and why firms patent and why they do not in the american manufacturing sector. Mimeo, Carnegie Mellon University, Pittsburgh.

DENICOLÒ, V. (1996). Patent races and optimal patent breadth and length. *Journal of Industrial Economics*, **44** (3), 249–65.

— and FRANZONI, L. A. (2004). Patents, secrets, and the first-inventor defense. *Journal of Economics & Management Strategy*, **13** (3), 517–538.

HORSTMANN, I., MACDONALD, G. M. and SLIVINSKI, A. (1985). Patents as information transfer mechanisms: To patent or (maybe) not to patent. *Journal of Political Economy*, **93** (5), 837–58.

KULTTI, K., TUOMAS, T. and TOIKKA, J. (2007). Secrecy versus patenting. *RAND Journal of Economics*, **38** (1), 22–42.

MCLENNAN, W. (1995). *Innovation in Australian Manufacturing 1994*. Catalogue no. 8116.0, Australia Bureau of Statistics, Canberra.

NORDHAUS, W. D. (1969). *Invention, Growth, and Welfare: A Theoretical Treatment of Technological Change*. Cambridge, Mass.: MIT Press.

RAUSCH, L. (1995). Estimates from the manufacturers innovation survey pilot. Mimeo, National Science Foundation, Washington, DC.

SCOTCHMER, S. and GREEN, J. (1990). Novelty and disclosure in patent law. *RAND Journal of Economics*, **21** (1), 131–146.