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Abstract

This paper studies R&D investment decisions of a firm facing the threat of new technology entry and subject to technical uncertainty. We distinguish four scenarios: inevitable entry, entry deterrence, entry blockade, and non-credible entry threat. The entry threat stimulates the incumbent to innovate in case entry prevention is possible, but discourages R&D if entry is inevitable. In the case of entry deterrence the incumbent successfully prevents entry by innovating. Greater technical uncertainty stimulates starting R&D and can result in implementation of more expensive research projects. The welfare analysis shows that the relation between welfare and entry cost and between welfare and uncertainty is non-monotonic.

JEL Code: C72, D21, O31.

Keywords: investment under uncertainty, real options, R&D, competition.

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1 Introduction

In this paper we approach the issue of interaction between innovation and cost-efficient entry which in the first place results in a more competitive environment for various incumbent firms. Those firms, which previously enjoyed relative safety inside their markets, now face the possibility of entry by often more efficient competitors. Establishing production of Japanese car manufacturers in the US is one (among many others) example of such an entry. In the 1970s Japanese companies entered the US with a new "lean" auto assembling technology, which had advantages over the mass production assembling lines used by US companies (Van Biesebroek (2003)).

The aim of this paper is to provide analytical results regarding incentives for R&D investments of firms dealing with an entrant that produces with a more modern technology. To do so we design a framework as simple as possible while still containing the specific aspects of strategic R&D: uncertainty, time to complete, competition, and entry threat. Next, we discuss these aspects in this order. Then the Introduction proceeds with a presentation of our main results, a summary of our welfare analyses, and an overview of the paper's contents, respectively.

Two important features of R&D investments are that an R&D project takes time to complete and that the outcome of R&D is uncertain. In the existing literature the factor of technical uncertainty is mainly represented by assuming a random date of new technology or innovation arrival (such as Poisson arrival in Kamien and Schwartz (1971), Loury (1979), Dasgupta and Stiglitz (1980), Weeds (2002), and Doraszelski (2003)). The technical uncertainty in our model is being modeled by a random outcome about the costs of R&D. Following Dixit and Pindyck (1994, pp. 345-356), we assume that the firm does not know beforehand how much time, effort, and resources it will need to complete an R&D project. The arrival of a new technology can only be achieved by completing the research project with an uncertain cost. The technical uncertainty in our case influences firm's total R&D cost, rather than the probability of new technology arrival. A typical characteristic of such technical uncertainty is that it cannot be resolved by waiting. Therefore, one of the reasons that the firm starts carrying out the R&D is to learn about the total cost of research.

Investment cost uncertainty is modeled in a different way, compared to Kort (1998) or Schwartz and Moon (2000). Instead of using stochastic Wiener process formulations, we introduce a simple two-stage R&D process, which has an uncertain outcome of the first stage. This enables us to obtain analytical results for a framework containing both technical uncertainty and competition. As in Moscarini and Smith (2001), in our model first-stage R&D decreases uncertainty about future payoffs by revealing the true R&D cost. Unlike the one-decision-maker model of Moscarini and Smith, we study the effect of R&D cost uncertainty on the firm's decision to undertake R&D in a strategic setting, combining the effects of technological uncertainty and competition.

We require that completion of the next stage requires that the previous stage is carried out in full. In many cases the introduction of a new process is done by reequipping or reorganizing the production line (Rosenbloom and Christensen (1998)). To do so, the firm must first develop new tools and machinery with required specifications, followed by building and testing prototypes (with the outcomes of tests being uncertain), and later integrate them into the production process and test the upgraded production line as a whole (the cost of which depends on the outcome of the previous stages).

In our framework it is important that the firm has the possibility to abandon the R&D project midstream, which is a key characteristic of sequential investment (Dixit and Pindyck, (1994)). Like in Kort (1998) and Schwartz and Moon (2000) this opportunity can be worthwhile in case the completion of the R&D process is more difficult or costly than expected. The implication is that this abandonment possibility can make it optimal to start up the R&D project even if its NPV is negative. The paper introduces this feature into the industrial organization literature and shows that it increases the entry deterrence power of R&D.

From our model we conclude that greater R&D cost uncertainty encourages the firm to start undertaking the R&D project in order to resolve it. The fact that greater technical uncertainty stimulates R&D, also holds in decision problems without strategic interactions as shown in Kort (1998) and Schwartz and Moon (2000). The point we want to make here is that this result can influence market behavior of firms. As it is now, many papers are devoted to the topic of R&D without taking the effect of technical uncertainty into account (see, among many others, Symeonidis (2003)). We show in our paper that under increased uncertainty the firm has a large incentive to start up the R&D project, which implies that under increased uncertainty the entry deterrence power of R&D is larger.

In the context of competitive interactions our model is related to that of Kulatilaka and Perotti (1998) but differs in three aspects: (i) in Kulatilaka and Perotti the firm can carry out one investment expenditure in order to reduce unit production costs in the next period, while in our framework the firm needs to go through a two stage investment procedure; (ii) in Kulatilaka and Perotti there is demand uncertainty while we have R&D cost uncertainty, the impact of which can be derived unambiguously; and (iii) we put explicit difference between the incumbent and the entrant by allowing the incumbent to have one time period lead over the entrant, while Kulatilaka and Perotti use the Stackelberg setting to distinguish the leader and the follower.

A similar approach, oriented at analyzing Cournot and Stackelberg competition, was employed in Smit and Trigeorgis (1998). In our model Stackelberg competition is less suitable, because there is no commitment of the incumbent to its investment decision. Therefore, the time-lead introduction is a more realistic way to distinguish the players. In real life there are many opportunities for the incumbent firm to anticipate entry and be able to prepare its reaction. For example, the study of Thomas (1999) provides empirical evidence for the incumbent's preemptive actions under the threat of entry. Additional to entry prevention, we consider cases where the incumbent finds it optimal to exit the market.

It has been shown in the existing literature (Dasgupta and Stiglitz (1980), Gilbert and Newbery (1982), and Reinganum (1983)) that an incumbent firm can preempt competition by innovating before the entrant does (and subsequently patenting the innovation). In our model we consider process innovation and assume that the potential entrant already possesses a newer and more cost-efficient production technology. As more than one technology can lead to the same improvement in the production process, nothing can prevent the incumbent from developing a new technology, which is equivalent (production-cost-wise) to that of the entrant.

The firm can use R&D as an entry deterrence (or blockade) instrument when entry is preventable due to a sufficiently high entry cost. By obtaining a new technology the firm can prevent the previously more efficient entrant from entering the market. In this situation the market remains to be a monopoly, but due to the entry threat it is a different monopoly: the monopolist now produces with the new technology, which would not have been the case without the entry threat. Note that this kind of potential competition is not measurable by traditional concentration indices.

From our study we conclude that the threat of entry stimulates R&D in case of preventable entry. However, in case of inevitable entry we find that R&D is discouraged. The reason is that the resulting profit increase is diminished by the reduction in the incumbent's market share. Moreover the innovating incumbent replaces its old profits by the profits obtained with the new technology. Consequently, the new technology profit gain of the entrant is higher, because it just equals the new technology profits. In the literature this is known as the "replacement effect" first identified by Arrow (1962).

The welfare analysis shows that the relation between welfare and entry cost can be non-monotonic. This implies that beforehand it is not clear whether it is better for welfare to facilitate entry or to put up an entry barrier. Symeonidis (2003) has shown that Cournot competition can provide higher welfare values than the Bertrand setting given strong knowledge spillovers and product differentiation. In our model the social desirability of competition depends on the degree of entry preventing innovation and the current entry cost. Hence, by means of decreasing or increasing tariffs and licenses, the regulator can influence the entry cost in the right way, so that social welfare can be increased.

Mankiw and Whinston (1986) state that in a homogeneous product market entry can be socially undesirable because entrants deteriorate the incumbents' market share (business stealing). In our model we observe that cost-efficient entry is socially undesirable only when the positive effect of bringing a more cost-efficient technology to the market and increasing competition is outweighed by the sum of several negative effects: business stealing, entry cost, and the R&D investment cost that the incumbent has to incur when it chooses for the active entry reaction strategy.

The paper is organized as follows. The model is presented in Section 2. Section 3 contains the welfare analysis in the proposed setting. We discuss the model's robustness in Section 4. Finally, conclusions and topics for further research are presented in Section 5.

2 The Model

The model is based on the following setup. Consider an Incumbent firm, which produces at a unit cost K. Then there is a potential Entrant that has a better technology in a sense that it allows him to produce with a smaller unit cost, which for simplicity is put to zero. The cost of entry is given by f.

To incorporate the fact that an R&D project takes time to complete and is subject to technical uncertainty, we consider a two-step R&D process with an uncertain outcome of the first step. After the second step is completed, the Incumbent is able to produce more efficiently from this moment onwards. In particular, it is assumed that the new technology developed by the Incumbent is equivalent to that of the Entrant, whose unit cost equals zero instead of K.

At time zero the Incumbent has an opportunity to make an initial irreversible R&D investment βI, where it is assumed that $0 < \beta < 1$. The outcome of this investment is stochastic. After having carried out the initial R&D investment, at time one the Incumbent needs to invest $(1 - \beta)I - h$ with probability $\frac{1}{2}$ in order to achieve the breakthrough, and with the same probability it needs to invest $(1 - \beta)I + h$ to achieve the same breakthrough. This can be interpreted in a sense that a bad outcome means that the firm needs to use more time, effort, or materials to complete the R&D project. The extra cost that must be incurred in this case, compared to that of the good outcome, is $2h$. The total "planned" cost of R&D is equal to I, the first-stage share of this cost is βI, and the parameter determining the second-stage investment cost's volatility is h. All these parameters are known beforehand, and, to keep second-stage investment cost possible, only scenarios are considered where $0 \leq h \leq (1-\beta)I$.[1]

In the literature, R&D project uncertainty was mainly modeled using a Poisson arrival process (for example Dasgupta and Stiglitz (1980) and Weeds (2002)). The drawbacks of this approach are that the current success probability is independent of investments in the past and that it is not possible to analyze the effect of increased uncertainty while keeping the mean constant. Our approach to technical uncertainty allows us to capture the uncertainty resolving nature of research and development and use the analytical advantages of a mean preserving spread.

To make the model more realistic we assume that the Incumbent has a time lead over the Entrant. The Incumbent anticipates the entry and has one time period advantage in developing the response to this threat. We assume that the Incumbent, while being a monopolist and producing with unit cost K, makes the R&D investment decision about starting the research at time $t = 0$. Based on the outcome of the first-stage R&D investment, at time $t = 1$ the Incumbent decides about completing the R&D project, while it still produces with unit cost K. The Entrant makes its entry decision at time $t = 1$.

We assume perfect information in the sense that the Entrant has perfect knowledge concerning the Incumbent's decision whether to complete its R&D project or not. If the Incumbent develops a new technology (implying that the

[1] The advantage of this formulation is that mean preserving spreads can be considered.

unit production cost drops from K to zero), it will start producing with it from time $t = 2$. If the Entrant decides to enter, it incurs the entry cost f and it will also start its production with zero unit cost from time $t = 2$. Therefore, the final market structure will be realized from time $t = 2$ onwards. The game's structure is presented in Figure 1.

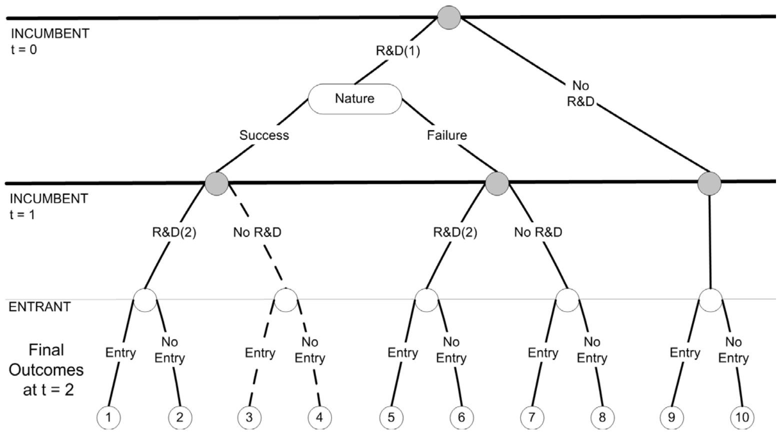

Figure 1: The game of R&D investment under the threat of entry.

3 Equilibrium

This section presents the equilibrium of the game developed in the previous section. First, the optimal output is determined for different scenarios. Then we proceed by presenting the different entry regimes and the optimal Incumbent behavior within these regimes. This is followed by analyzing the effects of uncertainty on Incumbent behavior. Finally, two sections on, respectively, entry accommodation and entry deterrence are presented.

3.1 Optimal Outputs in Duopoly. Non-Drastic vs. Drastic Innovation.

Consider Cournot competition in a market with two firms. The normalized inverse market demand function is $P(Q) = 1 - Q$, where $Q = q_{inc(umbent)} + q_{ent(rant)}$. For the moment we assume that the Entrant decides to enter, which results in a duopolistic market structure. As the Entrant already produces with a new technology, its unit cost is $K_{ent} = 0$. There are two different market structures that can emerge. One is symmetric competition with R&D completed by the Incumbent, which has the same production cost $K_{inc} = 0$ as the Entrant. The other is the case of asymmetric competition in which the Incumbent has $K_{inc} = K$ and the Entrant has zero production cost.

The optimal output of the Incumbent if it has not completed the R&D project will be $q_{inc}(K) = \frac{1-2K}{3}$, and the Entrant will produce $q_{ent}(K) = \frac{1+K}{3}$. Their corresponding profits are $\pi_{inc}(K) = \left(\frac{1-2K}{3}\right)^2$ and $\pi_{ent}(K) = \left(\frac{1+K}{3}\right)^2$.

Suppose that it is profitable for the Incumbent to complete the R&D project and obtain the new technology, so that $K_{inc} = 0$. Then, both the Incumbent and the Entrant will be producing with the advanced technology and at zero unit cost. Their optimal output at a given moment in time will be $q_{inc}(0) = q_{ent}(0) = \frac{1}{3}$, which will lead to the profit level $\pi_{inc}(0) = \pi_{ent}(0) = \frac{1}{9}$.

We observe that if the unit production cost K lies between $\frac{1}{2}$ and 1, then $q_{inc}(K)$ is negative. This implies that the asymmetric R&D costs game automatically transforms into a standard monopoly situation with the Entrant pushing the Incumbent out of the market. Here we can distinguish between the cases of **non-drastic** and **drastic** innovation (Tirole, (1988)). The **non-drastic innovation** corresponds to the case of a relatively low $K \in [0, \frac{1}{2})$. If one firm innovates and the other does not, the innovation is not strong enough to drive the not innovating firm out of the market. On the other hand, if we observe **drastic innovation** (bringing a relatively large K to zero), the innovating agent gains so much that it actually forces the other firm to exit.

Table 1 contains the Incumbent's and Entrant's payoffs corresponding to the bottom row outcomes in Figure 1. In this table the subscript "m" of π denotes the monopoly situation. It is easy to understand that, once the R&D project is started and the outcome of the first stage is successful, the firm will always complete the research. Therefore, the game's branches in Figure 1 leading to the outcomes *v(3)* and *v(4)* are "dead". In the discussion below we consider those outcomes as not feasible.

Furthermore, in Table 1 we ignore the Incumbent's monopolistic profits received at times *0* and *1*. These profits equal $\frac{2+r}{1+r}\pi_m(K)$ and are the same for any outcome of this game. Thus, they do not affect the Incumbent's investment decisions.

	Firms' payoffs	
	Non-drastic innovation	**Drastic innovation (if different payoff)**
$v(1)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{inc}(0) - \beta I - \frac{(1-\beta)I-h}{1+r} \\ \frac{1}{r}\pi_{ent}(0) - f \end{cases}$	
$v(2)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{m}(0) - \beta I - \frac{(1-\beta)I-h}{1+r} \\ 0 \end{cases}$	
$v(5)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{inc}(0) - \beta I - \frac{(1-\beta)I+h}{1+r} \\ \frac{1}{r}\pi_{ent}(0) - f \end{cases}$	
$v(6)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{m}(0) - \beta I - \frac{(1-\beta)I+h}{1+r} \\ 0 \end{cases}$	
$v(7)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{inc}(K) - \beta I \\ \frac{1}{r}\pi_{ent}(K) - f \end{cases}$	$\begin{cases} -\beta I \\ \frac{1}{r}\pi_{m}(0) - f \end{cases}$
$v(8)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{m}(K) - \beta I \\ 0 \end{cases}$	
$v(9)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{inc}(K) \\ \frac{1}{r}\pi_{ent}(K) - f \end{cases}$	$\begin{cases} 0 \\ \frac{1}{r}\pi_{m}(0) - f \end{cases}$
$v(10)$	$\begin{cases} \frac{1}{r(1+r)}\pi_{m}(K) \\ 0 \end{cases}$	

Table 1. Payoffs of the duopoly game with a new technology entry threat. The Incumbent's (Entrant's) payoffs are presented in the top (bottom) row.

3.2 Entry Regimes and the Incumbent's Reactions

We determine the equilibria of this game by backward induction starting with the Entrant's decision. The Entrant will enter the market if profits are higher than the entry cost. In the situation where the Incumbent decides to invest in R&D, the Entrant will enter only if $\frac{1}{r}\pi_{ent}(0) - f > 0$. If the Incumbent does not invest in R&D and the innovation is non-drastic, the Entrant will enter if $\frac{1}{r}\pi_{ent}(K) - f > 0$.

In the case of drastic innovation when the Incumbent does not invest in R&D, the Entrant enters only if $\frac{1}{r}\pi_m(0) - f > 0$. Since $\pi_{ent}(K) > \pi_{ent}(0)$ for the case of non-drastic innovation and $\pi_m(0) > \pi_{ent}(0)$ when the innovation is drastic, it holds that the Entrant is always better off when the Incumbent does not innovate.

This allows us to define the intervals of entry cost f that determine three types of entry threat: Inevitable Entry (IE), Entry Prevention (EP), and No Entry Threat (NE), which are depicted in Figure 2:

i) **Inevitable Entry**. This type of entry threat occurs when $f \in [0, f^{EP}]$, where

$$f^{EP}(r) = \frac{1}{r}\pi_{ent}(0).$$

The decision to enter does not depend on the innovation type and the

Entrant will enter the market regardless the actions of the Incumbent.

ii) The **Entry Prevention** situation exists when $f \in (f^{EP}, F^{EP}]$, where

$$F^{EP}(r, K) = \frac{1}{r}\pi_{ent}(K)$$

for non-drastic innovation and

$$F^{EP}(r) = \frac{1}{r}\pi_m(0)$$

for drastic innovation. The Entrant will enter only if the Incumbent does not invest in R&D. This case of entry prevention can be subdivided into the cases of blockaded and deterred entry. We will return to this in Section 2.4.

iii) The **No Entry Threat** case occurs when the entry cost is prohibitively high: $f \in (F^{EP}, \infty)$. It is evident that if f lies in this interval, we obtain a monopoly market structure.

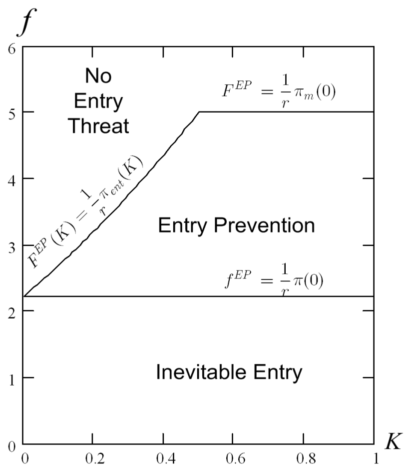

Figure 2: Entry cost regions ($r = 5\%$).

As can be seen in Figure 2, for any value of $K > 0$ and any reasonable value of the discount rate $r << \infty$ there exist values of the entry cost f which give rise to one of the three entry regimes.

To determine the optimal R&D investment strategy of the Incumbent in the given setup, we observe its decisions backwards starting at time $t = 1$. If the first step R&D was *unsuccessful*, it costs $(1 - \beta)I + h$ in the second stage to complete the R&D project. This leads to the following investment gain (the difference between the net present value (NPV) of this investment and the NPV of not making the investment):

$$\Delta^U_{inc,2} = \frac{1}{r}\Delta\pi_{inc} - [(1 - \beta)I + h],$$

where r is the discount rate, the superscript "U" refers to the unsuccessful first stage research, and the subscript "*inc,2*" denotes the second-stage investment decision of the Incumbent. In general, we define the new technology profit gain (or just the profit gain) at a given point in time as

$$\Delta\pi_{inc} = \pi_{inc}(0) - \pi_{inc}(K).$$

When the first step R&D investment was *successful*, it only costs $(1-\beta)I-h$ to develop a new technology. Then the investment gain is

$$\triangle^{S}_{inc,2} = \frac{1}{r}\Delta\pi_{inc} - [(1-\beta)I - h].$$

The Incumbent's decision to start the project is based on two different optimal investment criteria. One is the unconditional investment criterion, which is applied in case it is always optimal to complete the project. This criterion is based on the straightforward net present value of the R&D project. Then the project will only be carried out if

$$\triangle_{inc,NPV} = \frac{\frac{1}{2}\triangle^{S}_{inc,2} + \frac{1}{2}\triangle^{U}_{inc,2}}{1+r} - \beta I > 0.$$

The other criterion is the conditional (or a success-dependent) investment criterion,which is relevant when the R&D project will be finished only if the first stage was successful. In that case the R&D project will be undertaken if

$$\triangle^{S}_{inc,NPV} = \frac{\frac{1}{2}\triangle^{S}_{inc,2}}{1+r} - \beta I > 0.$$

On the basis of this analysis we formulate the proposition, which defines the optimal strategy of the Incumbent under the threat of entry.

Proposition 1 *The Incumbent's optimal R&D investment strategy is:*
i) Start the first stage of the R&D project if the Initial Decision criterion

$$\Delta_{inc,1} = \max(\Delta_{inc,NPV}, \Delta^{S}_{inc,NPV}) > 0$$

is met.
ii) Once the R&D is launched, carry out the second-stage R&D if the first-stage R&D is successful, or if the initial stage fails and $\Delta^{U}_{inc,2} > 0$.

Proof. See Appendix. ∎

Considering the different strategies of the Entrant, the Incumbent must adjust the values of its new technology profit gain $\Delta\pi_{inc}$ accordingly.

If *entry is inevitable*, the Incumbent knows that the Entrant will enter at time $t = 1$. In this situation the Incumbent will calculate its criteria based on

$$\Delta\pi_{inc}(f \leq f^{EP}, K \in [0, \frac{1}{2})) = \pi_{inc}(0) - \pi_{inc}(K)$$

under conditions of non-drastic innovation and

$$\Delta\pi_{inc}(f \leq f^{EP}, K \in [\frac{1}{2}, 1)) = \pi_{inc}(0)$$

if the innovation is drastic.

In the case of *preventable entry* the Incumbent is capable of locking the entrant out of the market by obtaining the new technology. If entry is prevented, the Incumbent keeps the monopoly position. The new technology profit gain of the Incumbent depends on the innovation type. If innovation is non-drastic, the Incumbent determines its criteria based on

$$\Delta\pi_{inc}(f \in (f^{EP}, F^{EP}], K \in [0, \frac{1}{2})) = \pi_m(0) - \pi_{inc}(K).$$

In the case of drastic innovation, the Incumbent risks being pushed out of the market if it does not invest. Therefore it must consider

$$\Delta\pi_{inc}(f \in (f^{EP}, F^{EP}], K \in [\frac{1}{2}, 1)) = \pi_m(0).$$

Finally, the entry threat is *non-credible*, then the Incumbent is a monopolist so that

$$\Delta\pi_{inc}(f > F^{EP}) = \pi_m(0) - \pi_m(K).$$

3.3 Effect of Uncertainty on the Incumbent's R&D Strategy

Using Proposition 1 we can formulate three propositions about the effect of uncertainty on the Incumbent's decisions in different entry regimes.

Proposition 2 *Under conditions of inevitable entry threat,* $f \in [0, f^{EP}]$, *increased uncertainty about the outcome of R&D while keeping the mean fixed:*
i) does not affect the Incumbent's decision to start R&D with innovation levels not greater than

$$K^*_{inc} \equiv \arg_K \left(\Delta^S_{inc,NPV} \Big|_{h = (1-\beta)I} = 0 \right);$$

ii) positively affects the Incumbent's decision to start R&D when it faces a project with negative NPV for $K > K^*_{inc}$*;*
iii) negatively affects the Incumbent's decision to continue the project with positive NPV for $K > K^*_{inc}$*;*

Proof. See Appendix. ■

Proposition 3 *Under conditions of entry prevention, $f \in (f^{EP}, F^{EP}]$, increased uncertainty about the outcome of R&D while keeping the mean fixed:*
i) does not affect the Incumbent's decision to start R&D with innovation levels not greater than

$$K^*_{inc} \equiv \arg_K \left(\Delta^S_{inc,NPV} \Big|_{h = (1-\beta)I} = 0 \right),$$

given that $K^*_{inc} \geq K^{EP}(f)$, where $K^{EP}(f)$ is the inverse of the upper bound $F^{EP} = \frac{1}{r}\pi_{ent}(K)$ for the entry prevention region under non-drastic innovation;
ii) positively affects the Incumbent's decision to start R&D when it faces a project with negative NPV for $K > K^*_{inc}$;
iii) negatively affects the Incumbent's decision to continue the project with positive NPV for $K > K^*_{inc}$.

Proof. Similar to that of Proposition 2, and therefore omitted. ■

Proposition 4 *In the case of non-credible entry threat, $f \in (F^{EP}, \infty)$, increased uncertainty about the outcome of R&D while keeping the mean fixed:*
i) does not affect the firm's decision to start R&D with innovation levels lower than

$$K^*_m = \arg_K \left(\Delta^S_{m,NPV} \Big|_{h = (1-\beta)I} = 0 \right);$$

ii) positively affects the firm's decision to start R&D when it faces a project with negative NPV,
iii) negatively affects the firm's decision to continue the project with positive NPV.

Proof. Similar to that of Proposition 2, and therefore omitted. ■

Here the new finding is that the propositions show that the effect of uncertainty on the decision of an individual firm can be positive or negative depending on the NPV of the underlying project.

In the following analyses we will concentrate our attention on two criteria: i) the initial investment criterion $\Delta_{inc,1}$, and ii) the unsuccessful R&D abandonment criterion $\Delta^U_{inc,2}$. In Figure 3 we plot the zero-value lines of these two criteria and analyze different decision areas. In this figure we distinguish two areas: **unconditional** (with $\Delta_{inc,1} > 0$ and $\Delta^U_{inc,2} > 0$) and **conditional** ($\Delta_{inc,1} > 0$ and $\Delta^U_{inc,2} < 0$) R&D project completion areas. The critical boundary of the initial decision criterion $\Delta_{inc,1} = 0$ is drawn as a thick line and can be called the Initial Decision Frontier. Line $\Delta^U_{inc,2} = 0$ represents the Abandonment Decision Line in a sense that above this line the R&D project will not be completed if the first stage is unsuccessful.

In Propositions 2-4 result i) refers to the case where $K \in [0, K^*_{inc}]$. In Figure 3 it is shown that irrespective of the uncertainty level, the firm does not start R&D. The reason is that the current unit production cost K is already low enough. Result ii) of Propositions 2-4 refers to the scenario where K is

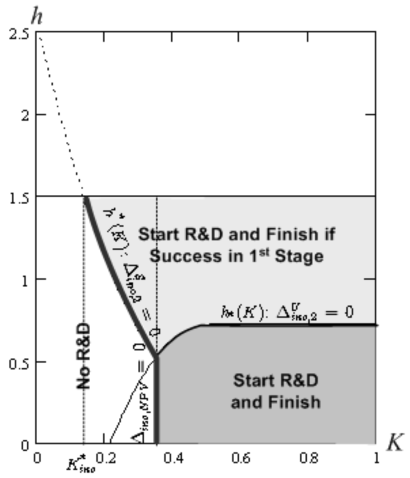

Figure 3: Incumbent's R&D investment decisions $\beta = 25\%$, $r = 5\%$, $f = 1$, $I = 2$.

larger than K^*_{inc} but so small that $\Delta_{inc,NPV} < 0$. In Figure 3 we see that it is optimal for the firm to undertake the first-stage of the R&D project only when uncertainty is sufficiently large. The reason here is that the project is completed only when the first stage is successful and in such a case the profitability increases with h. Result iii) of Propositions 2-4 refers to the case where K is large (corresponding to the right-hand side relative to the line $\Delta^S_{inc,NPV} = 0$ in Figure 3). We conclude that the firm always starts investing in R&D, and will always complete the project if uncertainty is small. In case uncertainty is large, it becomes too expensive to complete the project if the first-stage outcome is unsuccessful.

The effect of technical uncertainty in this model is different from the influence of market uncertainty, which is a more traditional type of uncertainty studied in the real options literature (such as Dixit and Pindyck (1994), Kulatilaka and Perotti (1998)). The overview of empirical studies on investment under uncertainty done by Carruth *et al.* (2000) concludes that increased market uncertainty raises the value of the option to delay the investment, and thus leads to lower investment levels.

Technical uncertainty cannot be resolved without engaging in research, and thus the delay option has no value. Due to the asymmetric nature of the R&D option in this model, increased uncertainty gives a greater value to the case of successful implementation of the first-stage R&D, while downward risk is limited, which was also observed by Lint and Pennings (1998). Consequently, instead that uncertainty delays investment, which is a standard real option result, here it holds that uncertainty stimulates starting up innovative projects. The reason for the latter result is that R&D investments belong to the category of exploratory investments in a sense that this investment reveals information. In our model the first-stage R&D investment resolves cost uncertainty, and the value of this extra information is not contained in the NPV of the project.

3.4 Entry Accommodation under Inevitable Entry

The entry accommodation strategy occurs in case of inevitable entry, thus when the entry cost is relatively low: $f \in [0, f^{EP}]$. In this case the Incumbent can carry out R&D and thus react actively (active accommodation (AA)), or be passive (passive accommodation (PA)) and stay with the current technology. If innovation is drastic, the Incumbent must consider the shut-down (SD) option instead of passive accommodation, because the firm with the inferior technology must leave the market. In this way entry serves as a "creative destruction" agent for the economy (Aghion and Howitt (1992)).

The decision-making areas of the incumbent in such a situation are given in Figure 4.

From Proposition 2 it follows that higher uncertainty about the outcome of the first-stage R&D stimulates the firm to choose a more aggressive entry reaction strategy. For example, under low uncertainty the firm's optimal strategy is always passive accommodation, but if uncertainty is high enough, the firm will choose active accommodation in case first-stage R&D is successful, as illustrated in Figure 4 for values of K between, approximately, 0.2 and 0.4.

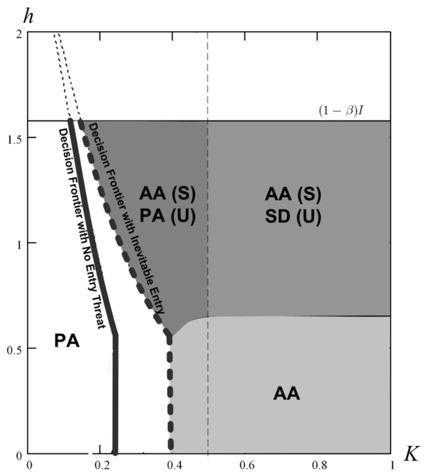

Figure 4: Active vs. passive entry accomodation. $\beta = 25\%$, $r = 5\%$, $f = 1$, $I = 2$.

The Incumbent makes its strategic decision about undertaking R&D driven by two main incentives. One is the willingness to obtain a better technology and more revenue (realized through bringing production cost K to zero). And the other is to strengthen its competitive position in the face of the entry threat by equalizing its own technology with that of the entrant.

Now let us compare the Incumbent's incentives to innovate under the inevitable threat of entry and when no such threat exists.

Proposition 5 *Under conditions of inevitable entry, i.e.* $f \in [0, f^{EP}]$, *every R&D project being profitable for the Incumbent is also profitable for the monopolist facing no such threat. The opposite does not hold.*

Proof. See the Online Appendix. ■

Proposition 5 allows us to conclude that in the case of inevitable entry, the strategic effect, in fact, is negative. Inevitable entry narrows the scope of R&D projects being profitable for the incumbent and in this way becomes an impediment for innovation incentives. This is due to the fact that the deterioration of the Incumbent's market share resulting from inevitable entry reduces the profitability of the innovation (see also Gilbert and Newbery (1982)).

3.5 Entry Blockade and Entry Deterrence under Entry Prevention

If an opportunity for entry prevention exists, the incumbent has a different set of strategies to choose from. The entry prevention case occurs when $f \in (f^{EP}, F^{EP}]$. The possible strategies are: passive accommodation, entry blockade (BL), entry deterrence (DET), and shut down (SD). Entry blockade occurs when the Incumbent performs R&D and effectively blocks entry, but would have also carried out R&D if there was no entry threat at all. Entry deterrence implies that the threat of entry creates an incentive for the Incumbent to carry out R&D in a situation where, if not threatened, the monopolist would not have carried out the R&D. If innovation is non-drastic, the passive accommodation strategy can be an option. In order to analyze the entry blockade and the entry deterrence strategies, let us consider the behavior of the Incumbent under the threat of entry in comparison to the behavior of the monopolist (illustrated in Figure 5).

Proposition 6 *If the opportunity for entry prevention exists, i.e.* $f \in (f^{EP}, F^{EP}]$, *then it will be profitable for the Incumbent to carry out any R&D project, which is profitable for the monopolist facing no threat of entry. The opposite does not hold.*

Proof. See the Online Appendix. ■

This proposition implies that the entry threat stimulates the Incumbent to undertake the R&D project. For a given arrangement of the underlying parameters it is possible to plot different optimal entry reaction strategies of the Incumbent depending on the degree of innovation K and the level of uncertainty h (see Figure 5). The relative "size" of the entry deterrence area can serve as a measure for the strategic effect of R&D investment. Kulatilaka and Perotti (1998) demonstrate that the strategic effect of R&D investment increases the

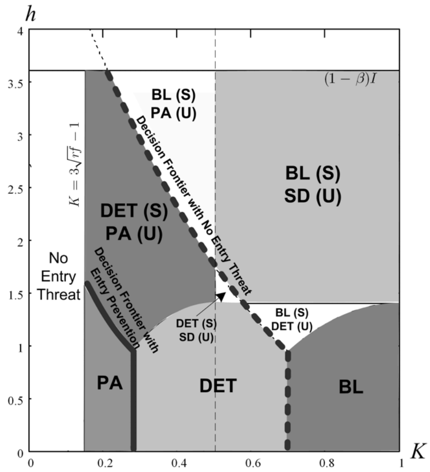

Figure 5: Entry prevention strategies $\beta = 25\%$, $r = 5\%$, $f = 3$, $I = 4.5$.

value of the investor's expansion option, thus inducing a more aggressive investment behavior. In Weeds (2002) it is stated that competition decreases the value of the option to delay. In our model the strategic effect is not straightforward.

Two parameters in the model, K and f, determine the strength of the strategic effect of R&D investment. The degree of innovation required for entry prevention determines the power of the strategic effect, and the value of the entry cost determines its entry prevention capability. If entry is inevitable, the strategic effect has a negative influence on the incumbent's R&D decisions, because investing in R&D does not result in a dramatic change of its competitive position. If the entry cost is high enough to allow for entry prevention, the strategic effect provides additional benefits from investing in the new technology for the Incumbent. Here Arrow's replacement effect (Arrow (1962)) could be identified in the sense that an incumbent under entry threat replaces "less profit" than a monopolist without entry threat. This result relates to Gilbert and Newbery (1982) and Dasgupta and Stiglitz (1980), but in those papers it was obtained from the frameworks where innovations could be patented, while here the entrant already possesses the new technology.

If the Incumbent invests in R&D when entry is preventable, the monopoly is preserved. But the monopoly resulting from entry prevention is different from the one without entry threat. In the situation where $\Delta_{inc,1} > 0 > \Delta_{m,1}$, the pure monopolist without potential competition stays with the same old technology, while the Incumbent facing the entry threat undertakes the R&D in order to preserve its monopoly position. Therefore, potential competition has a positive effect on innovating activities.

4 Welfare Analysis

In this section we consider welfare implications. In our model welfare is affected via several different channels: competition, the cost and type of innovation, and the uncertainty about the outcome of R&D.

Denoting producer and consumer surplus by $PS(\cdot)$ and $CS(\cdot)$ respectively, welfare $W(\cdot)$ can be defined as::

$$W(\cdot) = PS(\cdot) + CS(\cdot),$$

so that

$$W(\cdot) = \frac{1}{r(1+r)}\pi_{inc}(\cdot) + \frac{1}{r(1+r)}\pi_{ent}(\cdot) - C(\cdot, f, I) + CS(\cdot),$$

where

$$CS(\cdot) \equiv \frac{(q_{inc}(\cdot) + q_{ent}(\cdot))^2}{2r(1+r)},$$

and $C(\cdot, f, I)$ are the costs related to the R&D investment and entry in each particular case.

The way uncertainty influences the Incumbent's strategies and welfare is not straightforward. Let us examine Figure 3 once again. An increase in uncertainty in this figure is represented by an increase in the value of h. In the region of "No R&D" uncertainty does not influence the expected welfare because R&D will not be started under any circumstances. On the other hand, technical uncertainty has also no effect on expected welfare if the R&D is started and finished regardless of the outcome of the first-stage. This result comes from the fact that increasing h is embedded in a mean preserving spread.

Uncertainty does affect expected welfare only if the Incumbent exercises the option to abandon the project if the outcome of the first stage is unfavorable. In Figure 3 this happens in the region "Start R&D and finish if success in the 1st stage", which can be subdivided into two subregions: one corresponds to the area where $\Delta_{inc,NPV} < 0$ and $\Delta^S_{inc,NPV} > 0$ and the other has $\Delta_{inc,NPV} > 0$ and $\Delta^U_{inc,2} < 0$. Here it holds that the Incumbent will abandon the project if the preliminary R&D stage is not successful, regardless the size of h, so that any negative outcome is as "bad" as the other. But if the first stage succeeds, an increase in h will mean that the Incumbent will have to invest less in order to complete the project. This implies that the direct effect of increasing uncertainty is positive.

Finally we need to consider cases where increased uncertainty causes a switch of the Incumbent's strategy. For example, increasing uncertainty can make the Incumbent to consider entry deterrence instead of passive accommodation, or conditional entry blockade instead of unconditional entry blockade.

The effect of an uncertainty-induced strategy switch on welfare consists of four components: (a) the entry cost paid or not paid by the Entrant depending on the Incumbent's entry prevention strategy; (b) the change in the Incumbent's R&D investment cost due to starting or abandoning R&D; (c) the change in consumer surplus due to entry or entry prevention; (d) the change in firms' profits due to entry or entry prevention.

We can summarize this discussion in the following proposition.

Proposition 7 *Increased uncertainty about the outcome of R&D while keeping the mean fixed:*
i) does not affect expected welfare, if $\Delta_{inc,NPV} > 0$ *and* $\Delta^U_{inc,2} > 0$*, or if* $\Delta^S_{inc,NPV} < 0$*;*
ii) positively affects expected welfare, if $\Delta_{inc,NPV} < 0$ *and* $\Delta^S_{inc,NPV} > 0$*, or if* $\Delta_{inc,NPV} > 0$ *and* $\Delta^U_{inc,2} < 0$*;*
iii) affects expected welfare positively or negatively depending on changes in four components which relate to (a) entry cost, (b) Incumbent's R&D investment, (c) consumer surplus, and (d) firms' profits, if the sign of $\Delta^S_{inc,NPV}$ *and/or* $\Delta^U_{inc,2}$ *changes due to the increase of* h*.*

Due to the existence of the four components mentioned in statement iii) of Proposition 7, a detailed analysis of the effect of uncertainty on welfare when strategy switch takes place, requires a case-by-case consideration. To illustrate, we present the case which deals with strategy switches under conditions of drastic innovation ($K \in [1/2, 1)$) and preventable entry ($f \in (f^{EP}, F^{EP}]$).

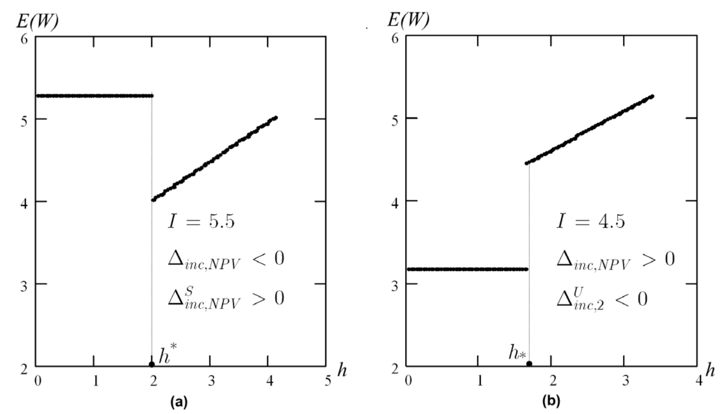

Figure 6: The effect of uncertainty on expected welfare under entry prevention and drastic innovation ($f = \frac{1}{9r}$, $\beta = 0.25$, $r = 0.05$). h^* and h_* have the same meaning as in Figure 3.

Let us first examine the strategy switch which takes place when $\Delta_{inc,NPV} < 0$ and $\Delta^S_{inc,NPV}$ becomes positive. This happens when h becomes greater than h^* (see Figure 3). For values of h below h^* the Incumbent will not start the R&D project and the expected welfare is $E(W) = W(9)$ ("9" corresponds to outcome 9 in the bottom row of Figure 1, i.e. the Incumbent shuts down and the Entrant enters). When h passes the threshold, the expected welfare becomes

$E(W) = \frac{1}{2}W(2)+\frac{1}{2}W(7)$ (either the Incumbent innovates and prevents entry, or the Incumbent will abandon R&D, shut down and allow the Entrant to enter). We calculate $E(\Delta W) = \frac{1}{2}(W(2) + W(7)) - W(9)$ to see how this uncertainty-induced change in strategies affects welfare. A negative value of $E(\Delta W)$ will indicate a drop in the expected welfare. We evaluate this change at h^*, which results in

$$E(\Delta W(h^*)) = \frac{1}{2}\left(f - \frac{1}{4r(1+r)}\right).$$

If the Incumbent decides to start the R&D project, it upgrades its strategy in a sense that it becomes possible that entry will be prevented and paying the entry cost will be avoided.

In a similar manner we treat the change in welfare when $\Delta_{inc,NPV} > 0$ and $\Delta^U_{inc,2}$ changing its sign from positive to negative. This occurs when h increases beyond h_* (see Figure 3). For $h < h_*$ the Incumbent will finish the R&D project regardless the outcome of the first stage and the expected welfare is $E(W) = \frac{1}{2}W(2) + \frac{1}{2}W(6)$ (entry is prevented by finishing R&D with either higher or lower cost). Under higher uncertainty completion of the R&D project becomes conditional on the first stage being successful. This implies that expected welfare equals $E(W) = \frac{1}{2}W(2) + \frac{1}{2}W(7)$, and

$$E(\Delta W(h_*)) = \frac{1}{2}\left(-f + \frac{1}{4r(1+r)}\right).$$

We conclude that the welfare effect of the strategy downgrade in case $\Delta_{inc,NPV} > 0$ and $\Delta^U_{inc,2}$ becoming negative is equal but opposite in sign to the effect of the strategy upgrade in case of $\Delta_{inc,NPV} < 0$ and $\Delta^S_{inc,NPV}$ becoming positive (see Figure 6).

The question whether the strategy change results in a decrease or increase of expected welfare depends on the relative size of the entry cost. Existence of a preventable entry scenario under drastic innovation requires that $f \in (\frac{1}{9r}, \frac{1}{4r}]$. Let us calculate the value of $E(\Delta W(h^*))$ at the boundaries of this interval. We get

$$E(\Delta W(h^*, f = \frac{1}{9r})) = \frac{4r-5}{72r(1+r)} < 0, \text{ for } r < \frac{4}{5}$$

and

$$E(\Delta W(h^*, f = \frac{1}{4r})) = \frac{r}{8r(1+r)} > 0.$$

Figure 6 presents the effect of uncertainty on welfare for two particular parameter constellations. The jump is caused by the strategy change. For low values of h uncertainty has no effect because either the R&D project will always be completed (Figure 6a) or will not be started (Figure 6b). For large values of h uncertainty has a positive effect on welfare because R&D is only completed if the first stage is successful, and in that case the second-stage investment expenditure decreases with h. The fact that the second stage investment expenditure goes up with h in case of a negative outcome of the first-stage R&D

investment has no effect because then the project will be abandoned anyway. From this figure can be concluded that the effect of uncertainty of welfare is not monotonic.

If we analyze the components of the effect of uncertainty on welfare, it becomes clear that there is no change in the expected consumer surplus or the firms' profits associated with the Incumbent's choice to start R&D: in either case the market will have one firm producing with the new technology. If the Incumbent succeeds, it continues to be a monopolist, and, otherwise, the Entrant enters and becomes the only firm in the market. The price of preserving monopoly for the Incumbent is the R&D cost, while for the Entrant the price of monopoly equals the entry cost. Hence, when the entry cost is low compared to the R&D investment, it is better for welfare to have entry rather than to have the Incumbent to be engaged in a relatively more costly R&D. Subsequently, when the entry cost is relatively high, developing the new technology by the Incumbent is better than obtaining it with a costly entry.

Here we extend the discussion of Mankiw and Whinston (1986) regarding social efficiency of free entry. They state that free entry results in an excessive number of entrants in the market which dilute producer's surplus by business stealing. In our case entry has both positive and negative effects on welfare. On the one hand, the entrant brings a more cost-efficient production technology to the market. On the other hand, entry requires an entry cost to be paid. It also deteriorates the Incumbent's market share, and in case the Incumbent decides to deter entry by performing R&D there are investment costs as well.

Next we analyze the relationship between the market entry cost and the social benefit of new technology entry vs. the Incumbent's innovation and monopoly vs. duopoly. We formulate two propositions concerning this issue. First, we analyze the situation when the Incumbent actually develops the new technology (illustrated in Figure 7).

Proposition 8 *When it is optimal for the Incumbent to unconditionally invest in R&D ($\Delta_{inc,NPV} > 0$), there exists a value $f^* < f^{EP}$ such that for any $f^* < f < f^{EP}$ entry is optimal, but not socially desirable, while for any $f \leq f^*$ entry is both optimal and socially desirable.*

Proof. See the Online Appendix. ■

The social planner, therefore, will have an incentive to decrease (if it is possible) the entry cost to the level, where the symmetric innovating duopoly becomes socially preferable, or increase it to the level which makes entry not feasible, resulting in a more socially desirable monopoly. Then the question arises whether it is better to increase or to decrease the entry cost. In Figure 7 it is obvious that a lower entry cost is better than a higher one, because decreasing f in the region below f^* will increase the welfare continuously above the level corresponding to prevented or non-feasible entry. The real limitation is the capability of the social planner to manipulate the entry cost. Therefore, if the regulator can not bring the entry cost down to a satisfactory level, it can be desirable to increase the entry barrier (in the form of a tariff or a license fee) to prevent entry and achieve a higher welfare level.

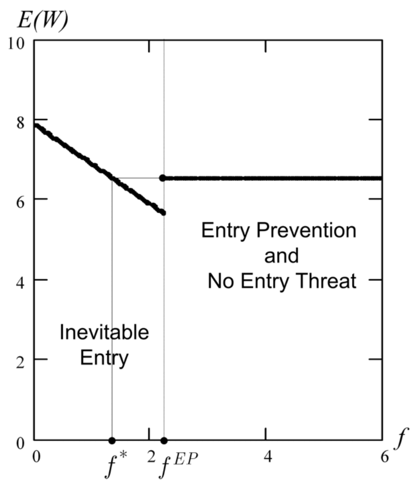

Figure 7: Welfare and entry cost, $I = 1$, $h = 0.4$, $r = 0.05$, $\beta = 0.2$, $K = 0.3$.

Secondly, if the Incumbent decides not to invest in R&D, the next proposition describes the desirability of inviting the new technology with the Entrant.

Proposition 9 *If it is optimal for the Incumbent not to innovate unconditionally ($\Delta^S_{inc,NPV} < 0$), then:*
i) under conditions of non-drastic innovation ($0 \leq K < \frac{1}{2}$), there exists a value f^* such that for any $f^* < f < F^{EP}$ and $K < \frac{1}{3}$ entry is optimal but not socially desirable while for any $f \leq f^*$ entry is both optimal and socially desirable;
ii) if $\frac{1}{3} \leq K < \frac{1}{2}$ (non-drastic innovation) or $\frac{1}{2} \leq K < 1$ (drastic innovation), entry is both optimal and socially desirable for any $f < F^{EP}$.

Proof. See the Online Appendix. ■

Both propositions imply that an increase in entry cost negatively affects welfare when entry takes place. It results in a situation where it may not be socially desirable anymore to have the Entrant enter the market even though entry is optimal for the Entrant itself. Such a case occurs for any level of innovation if the Incumbent invests in R&D, and only for a relatively small non-drastic innovation if the Incumbent decides to stay with the old technology. On the other hand, if this scenario occurs with drastic innovation, entry will effectively result in making the Incumbent shut down, giving us an example of entry-driven creative destruction (Aghion and Howitt (1992)), which can have a positive effect on welfare.

5 Robustness

Admittedly, the model is very special and by now it is not obvious to what extent the results are robust. This section checks robustness by considering Bertrand competition, imperfect information and a different order of moves, respectively.

So far we considered the case of Cournot competition where two firms compete in quantities. Now we investigate the problem of R&D investment with new technology entry threat in the Bertrand competition setting. Bertrand competition results either in a monopoly or a symmetric duopoly market structure. In a duopoly with unit cost K of the Incumbent, the Entrant sets its price at $K - \varepsilon$, so that the Incumbent is pushed out of the market. This implies that there are three possible Bertrand competition outcomes: monopoly of the Incumbent, monopoly of the Entrant, and symmetric new technology duopoly.

However, a symmetric new technology duopoly occurs only in the case of a coordination failure. If the Entrant decides to enter and the Incumbent decides to invest in new technology, they both incur sunk costs. Price competition results in both firms charging price equal to marginal cost, which is zero with new production technology. Hence, sunk costs are not compensated so that both firms end up with negative results. The monopolistic outcomes of Bertrand competition are equivalent to the outcomes of the Cournot competition case with entry prevention and drastic innovation.

Another way to change our model is to consider a different information set. Let us assume that the Entrant cannot observe the Incumbent's R&D investment decisions and the outcome of the first stage. But it is rational to assume that, because the Entrant already obtained the new technology, it knows what is required to carry out the R&D project and what kind of uncertainty is involved there. Hence, the Entrant knows with certainty whether or not the Incumbent will start R&D and whether or not its completion is conditional on success in the first stage. Such a modification does not influence the results of the model if the Incumbent faces an R&D project with positive NPV or if the Incumbent decides not to start it at all. But if the Incumbent undertakes R&D which will only be finished if the first-stage research is successful, then the Entrant must consider both possibilities of abandoning and completing the project by the Incumbent. Thus, asymmetric information makes the Entrant to (under)overestimate its own expected payoff in case the first-stage research of the Incumbent is (un)successful, which could change the entry regime areas (see Figure 8).

Another kind of strategic interactions arise if we change the order of moves of Incumbent and Entrant. Assume that the Entrant makes its decision first and then the Incumbent reacts by investing or not investing in R&D. Deciding over its strategy, the Entrant has the same knowledge about its competitor as in the asymmetric information case: it is possible to infer the Incumbent's decision to launch the R&D project but at the time of taking the entry decision the Entrant does not know the outcome of the first-stage R&D investment.

In case the Entrant decides to enter, the Incumbent's strategy set consists

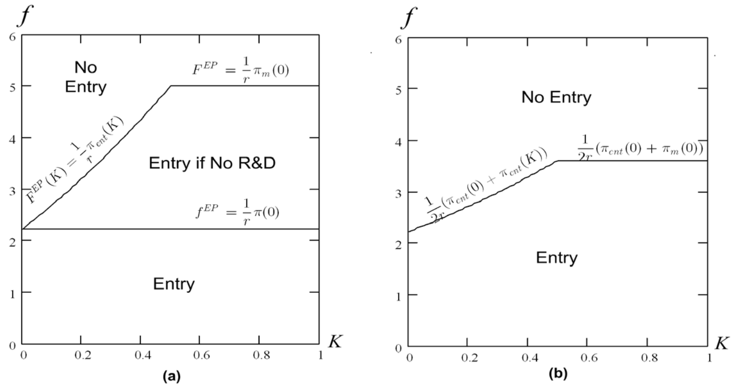

Figure 8: Entry cost regions under (a) full information, and (b) asymmetric information ($r = 5\%$, $I = 4.5$, $K = 0.2$, $h = 2$)

only of accommodation strategies which are the same as in the case of inevitable entry in Figure 4. If there is no entry, the Incumbent behaves as a monopolist. Hence, by moving first the Entrant influences decisions of the Incumbent. Note that in this case the Incumbent cannot employ its R&D strategy to block or deter entry.

6 Conclusions

Decisions of an incumbent firm having the possibility of carrying out an R&D project while facing the threat of new technology entry are determined by a combination of several factors: i) the degree of innovation, which determines the level of production cost reduction; ii) the uncertainty about R&D costs; iii) strategic decisions of the entrant; and iv) the size of the entry cost representing the barrier to entry.

We conclude that greater technical uncertainty positively affects the decision to start an R&D project. If there exists an opportunity to resolve uncertainty through exploratory research with an option to continue (or abandon), higher initial uncertainty increases the positive effect of success in the first-stage R&D, while the downward risk in case of failure is limited. This finding illustrates the main difference between market payoff uncertainty, which induces a firm to wait for more information before undertaking the investment and technical uncertainty, which cannot be resolved just by simply waiting.

Our model demonstrates that the strategic effect of innovating is determined by both the degree of innovation and its entry prevention capability. Under inevitable entry the incentive for the incumbent to innovate is lower, because the strategic effect of innovation is too weak to provide the incumbent with an advantageous competitive position. Under preventable entry the incentive for the incumbent to innovate is higher compared to a monopoly situation, because of the strong strategic effect of innovating.

Considering the effect of uncertainty on welfare, we conclude that on the one hand increased uncertainty may affect expected welfare positively, because of the asymmetric characteristic of option valuation: in case the project is abandoned midstream any negative outcome is as "bad" as the other. On the other hand, increased uncertainty can cause a change in the strategy of the incumbent. The resulting welfare effect of this change is ambiguous and depends on four components: (a) entry cost, (b) incumbent's R&D investment, (c) consumer surplus, and (d) firms' profits.

The analysis of the effect of entry cost on welfare has shown that it is possible to have a scenario where at the same time entering the market is optimal for the entrant, while it is not socially desirable for the social planner. In such cases the regulator has an incentive to lower the entry cost and in this way make entry welfare improving, or raise it to prevent the entrant from entering.

To summarize, we conclude that the model presented in this paper has proven capable of catching the complex relationships between factors of technical uncertainty and strategic interaction under new technology entry threat while preserving its simplicity and capability to produce analytically tractable implications. It is shown that besides capacity investment (Dixit and Stiglitz (1977)), limit pricing (Hoppe and Lee (2003)), and patenting (Gilbert and Newbery (1982)), also investment in the nonpatented R&D, while taking into account time to complete and technical uncertainty, can be used as an entry deterrence strategy. As topic for a future inquiry we are very much interested in the case of product innovation under technical uncertainty, which will require the analysis of a differentiated product setting.

7 Appendix

Proof. Proposition 1

The Incumbent makes its decision considering the current mode of entry. As the entry cost f is known, the Incumbent knows exactly which entry strategy will be played by the Entrant. The decision-making process of the Incumbent can be formalized in the following way.

The firm's performance depends on the fact whether or not the new technology is developed. Therefore, we define the following decision variables:

1) i_1, which equals 1 if the firm decides to invest in the first-stage R&D and equals 0 otherwise;

2) i_2, which equals 1 if the firm decides to invest in the second-stage R&D and equals 0 otherwise.

To preserve the sequencing properties of the decisions we assume that $i_1 = 1$ is a necessary, but not sufficient condition for $i_2 = 1$ to hold.

First, assume that the investment decision was taken ($i_1 = 1$) and the first stage R&D is completed.

If the first-stage R&D is successful, then $E(h|S) = -h$. Facing the second-stage R&D decision, the firm solves the following problem:

$$\max_{i_2} E(\pi_2|S) = \pi_{inc}(K) + i_2 \frac{1}{r} \pi_{inc}(0) + (1 - i_2) \frac{1}{r} \pi_{inc}(K) - i_2[(1 - \beta)I - h].$$

The function $E(\pi_2)$ is linear in i_2. Therefore $i_2 = 1 = \arg\max_{i_2} E(\pi_2|S)$ only if

$$\frac{\partial \pi_2}{\partial i_2} = \frac{1}{r} \pi_{inc}(0) - \frac{1}{r} \pi_{inc}(K) - [(1 - \beta)I - h] \geq 0,$$

and $i_2 = 1 = \arg\max_{i_2} E(\pi_2|U)$ only if $\Delta^S_{inc,2} = \frac{1}{r} \Delta\pi_{inc} - [(1 - \beta)I - h] \geq 0$.

Similarly, if the first-stage R&D is a failure, then $E(h|U) = h$ and $i_2 = 1 = \arg\max_{i_2} E(\pi_2|U)$, if $\Delta^U_{inc,2} = \frac{1}{r} \Delta\pi_{inc} - [(1 - \beta)I + h] \geq 0$.

It is evident that if $\Delta^U_{inc,2} > 0$, then $\Delta^S_{inc,2} > 0$.

At time 0 the firm makes the decision about the first stage R&D and solves:

$$\begin{aligned} \max_{i_1} E(\pi_1) &= i_1 i_2 \frac{1}{r(1+r)} \pi_{inc}(0) + (1 - i_1 i_2) \frac{1}{r(1+r)} \pi_{inc}(K) - \\ &\quad i_1 \beta I - i_1 i_2 \frac{1}{1+r} [(1 - \beta)I + E(h)], \\ &\quad \text{given } i_2 = \arg\max_{i_2} E(\pi_2). \end{aligned}$$

Similar to the previous problem it holds that $i_1 = 1 = \arg\max_{i_1} E(\pi_1)$, only if

$$\frac{\partial E(\pi_1)}{\partial i_1} = i_2 \frac{1}{r} \Delta\pi_{inc} - \beta I - i_2 \frac{1}{1+r} [(1 - \beta)I + E(h)] \geq 0.$$

If $\Delta^U_{inc,2} > 0$, then $i_2 = 1 = \arg\max_{i_2} E(\pi_2)$ regardless the outcome of the first-stage R&D. In this case $E(h) = 0$ and the following holds

$$i_1 = 1 = \arg\max_{i_1} E(\pi_1), \text{ if } \Delta_{inc,NPV} = \frac{\Delta\pi_{inc}}{r(1+r)} - \beta I - \frac{(1 - \beta)I}{1+r} \geq 0. \quad (1)$$

If $\Delta^U_{inc,2} < 0$ and $\Delta^S_{inc,2} < 0$,then we always obtain $i_2 = 0 = \arg\max_{i_2} E(\pi_2)$ and the following holds

$$\text{if } i_2 = 0 = \arg\max_{i_2} E(\pi_2), \text{ then } i_1 = 0 = \arg\max_{i_1} E(\pi_1), \text{ because } \frac{\partial E(\pi_1)}{\partial i_1} = -\beta I < 0.$$

In the situation where $\Delta^U_{inc,2} < 0$, but $\Delta^S_{inc,2} > 0$, we obtain that $i_2 = 1 = \arg\max_{i_2} E(\pi_2|S)$ and $i_2 = 0 = \arg\max_{i_2} E(\pi_2|U)$. Therefore, it is required that the first-stage research is successful ($E(h|S) = -h$) in order to continue the project, which yields

$$i_1 = 1 = \arg\max_{i_1} E(\pi_1|S), \text{ if } \Delta^S_{inc,NPV} = \frac{\Delta\pi_{inc}}{r(1+r)} - \beta I - \frac{(1 - \beta)I - h}{2(1+r)} \geq 0. \quad (2)$$

Conditions (1) and (2) provide the optimal initial R&D investment decision of the firm.

The relation between $\Delta_{inc,NPV}$ and $\Delta^S_{inc,NPV}$ is described by the following expression:

$$\Delta_{inc,NPV} = \Delta^S_{inc,NPV} + \frac{\Delta^U_{inc,2}}{2(1+r)}. \tag{3}$$

If $\Delta^U_{inc,2} > 0$, then $\Delta_{inc,NPV} > \Delta^S_{inc,NPV}$ and it is possible to have $\Delta_{inc,NPV} > 0$, while $\Delta^S_{inc,NPV} < 0$. On the other hand, if $\Delta^U_{inc,2} < 0$, then $\Delta^S_{inc,NPV} > \Delta_{inc,NPV}$, and it is possible to have $\Delta^S_{inc,NPV} > 0$, while $\Delta_{inc,NPV} < 0$.

Specify $\Delta_{inc,1} = \max\{\Delta_{inc,NPV}, \Delta^S_{inc,NPV}\}$. Then the condition

$$i_1 = 1 = \arg\max_{i_1} E(\pi_1), \text{ if } \Delta_{inc,1} = \max\{\Delta_{inc,NPV}, \Delta^S_{inc,NPV}\} \geq 0$$

allows to consider all the possible ways of obtaining a profitable R&D project, which proves statement i) of the proposition.

Finally, it can be easily shown that if $\Delta_{inc,1} \geq 0$, then it always holds that $\Delta^S_{inc,2} > 0$, which finalizes the proof for statement ii) of the proposition. ■

Proof. Proposition 2.

Define h^* such that $\Delta^S_{inc,NPV} = 0$, which implies that $h^* = -\frac{1}{r}\Delta\pi_{inc} + 2\beta(1+r)I + (1-\beta)I$, where

$$\Delta\pi_{inc}(f \leq f^{EP}, K \in [0, \frac{1}{2})) = \frac{K - K^2}{4.5}$$

and

$$\Delta\pi_{inc}(f \leq f^{EP}, K \in [\frac{1}{2}, 1)) = \frac{1}{9}.$$

Solving equation $h^* = (1-\beta)I$ for K gives us

$$K^*_{inc} = \frac{1}{2} \pm \frac{\sqrt{1 - 18r\beta(1+r)I}}{2} \text{ for } f \leq f^{EP}, K \in [0, \frac{1}{2}),$$

and no solution for $f \leq f^{EP},\ K \in [\frac{1}{2}, 1)$.

The value of interest is $K^*_{inc} = \frac{1}{2} - \frac{\sqrt{1-18r\beta(1+r)I}}{2}$, which lies inside the interval $[0, \frac{1}{2})$. This root takes up real values if the following condition holds:

$$I < \frac{1}{18r\beta(1+r)}. \tag{4}$$

The change in h^* corresponding to the change in K is:

$$\frac{\partial h^*}{\partial K} = \frac{2K-1}{4.5r} < 0 \text{ for } K \in [0, \frac{1}{2}).$$

For any $K < K^*_{inc}$ we obtain $h^* > (1-\beta)I$. This means that for any feasible value of the mean preserving spread $h < (1-\beta)I$ the conditional investment gain $\Delta^S_{inc,NPV}$ preserves its sign, i.e. an increase in uncertainty does not affect the firm's strategic choice.

It holds that:

$$\frac{\partial \Delta_{inc,NPV}}{\partial h} = 0, \text{ and } \frac{\partial \Delta^S_{inc,NPV}}{\partial h} > 0.$$

For values of $K > K^*_{inc}$ we observe the following facts:

i) If $\Delta_{inc,NPV} < 0$, then the R&D can start only if $\Delta_{inc,1} = \Delta^S_{inc,NPV} > 0$, which is positively affected by an increase in uncertainty and becomes positive as uncertainty exceeds h^*.

ii) If $\Delta_{inc,NPV} > 0$, the project is launched regardless the level of uncertainty.

Once the project is started, the next relevant criterion is the project abandonment decision criterion $\Delta^U_{inc,2}$, for which it holds that:

$$\frac{\partial \Delta^U_{inc,2}}{\partial h} < 0,$$

which indicates the negative relationship between technical uncertainty and the decision to continue research and development. ■

Proof. Proposition 5.

Under conditions of inevitable entry and non-drastic innovation, the new technology profit gain of the incumbent is:

$$\Delta\pi_{inc}(K \in [0, \frac{1}{2})) = \pi_{inc}(0) - \pi_{inc}(K) = \frac{2K - 2K^2}{4.5}.$$

If innovation is drastic the new technology profit gain is:

$$\Delta\pi_{inc}(K \in [\frac{1}{2}, 1)) = \pi_{inc}(0) = \frac{1}{9}.$$

The monopolist considers

$$\Delta\pi_m = \pi_m(0) - \pi_m(K) = \frac{2K - K^2}{4}.$$

We conclude that $\Delta\pi_m > \Delta\pi_{inc}(K \in [0, 1))$, so that the profit gains of the monopolist are higher than those of the incumbent. The investment gains of both types of agents are positively related to their profit gains. This implies that $\Delta_{m,1} > \Delta_{inc,1}$, and $\Delta^U_{m,2} > \Delta^U_{inc,2}$. ■

Proof. Proposition 6.

Under conditions of entry prevention, the new technology profit gain of the Incumbent is given by:

$$\Delta\pi_{inc}(K \in [0, \frac{1}{2})) = \pi_m(0) - \pi_{inc}(K) = \frac{5 + 16K - 16K^2}{36},$$

if innovation is non-drastic, and

$$\Delta\pi_{inc}(K \in [\frac{1}{2}, 1)) = \pi_m(0) = \frac{1}{4},$$

if innovation is a drastic one.

For the monopolist this profit gain equals

$$\Delta\pi_m = \pi_m(0) - \pi_m(K) = \frac{2K - K^2}{4}.$$

Since $\Delta\pi_{inc} > \Delta\pi_m$, the gains of the Incumbent are higher than those of the monopolist . The investment gains of both types of agents are positively related to their profit gains, so that $\Delta_{inc,1} > \Delta_{m,1}$, and $\Delta^U_{inc,2} > \Delta^U_{m,2}$. ■

Proof. Proposition 8.

If it is optimal for the Incumbent to develop a new technology, entry will take place only if it is inevitable and it will always result in a symmetric duopoly regardless of the degree of innovation.

Depending on the value of the current entry cost, the social planner considers the expected welfare function $E(W)$, which is defined by the following expressions:

$$\begin{aligned} \text{if } f &< f^{EP},\ E(W_{IE}) = \frac{1}{2}W(1) + \frac{1}{2}W(5), \\ \text{if } f^{EP} &\leq f < \infty,\ E(W_{EP+NE}) = \frac{1}{2}W(2) + \frac{1}{2}W(6), \end{aligned}$$

where

$$\begin{aligned} W(1) &= \frac{4}{9r(1+r)} - \frac{(1+r\beta)I - h}{1+r}, \\ W(2) &= \frac{3}{8r(1+r)} - \frac{(1+r\beta)I - h}{1+r}, \\ W(5) &= W(1) - \frac{2h}{1+r}, \\ W(6) &= W(2) - \frac{2h}{1+r}. \end{aligned}$$

It follows that

$$\frac{\partial E(W_{IE})}{\partial f} < 0$$

and

$$\frac{\partial E(W_{EP+NE})}{\partial f} = 0.$$

It can be shown that $E(W_{IE}) > E(W_{EP+NE})$ for $f < f^*$, and $E(W_{IE}) < E(W_{EP+NE})$ for $f > f^*$, where $f^* = \frac{5}{72r}$. We know that $f^{EP} = \frac{1}{9r}$, thus $f^* < f^{EP}$. Therefore, there indeed exist values of $f^* < f < f^{EP}$ in the inevitable entry region, for which the duopoly provides lower levels of welfare than the monopoly. ■

Proof. Proposition 9.

If it is not optimal for the Incumbent to develop a new technology, entry will take place either when it is inevitable or preventable.

The social planner considers the following values of the expected welfare function:

$$\begin{aligned} \text{if } f &< F^{EP}, \text{ then } E(W_{IE+EP}) = W(9), \\ \text{if } F^{EP} &\leq f < \infty, \text{ then } E(W_{NE}) = W(10), \end{aligned}$$

where

$$\begin{aligned} W(9) &= \frac{11K^2 - 8K + 8}{18r(1+r)} - f, \\ W(10) &= \frac{3(1-K)^2}{r(1+r)}. \end{aligned}$$

It follows that

$$\frac{\partial E(W_{IE+EP})}{\partial f} < 0$$

and

$$\frac{\partial E(W_{NE})}{\partial f} = 0.$$

It can be shown that $E(W_{IE+EP}) > E(W_{NE})$ for $f < f^*$, and $E(W_{IE+EP}) < E(W_{NE})$ for $f > f^*$, where

$$f^* = \frac{3K^2 + 2K - 1}{24r} \text{ for } 0 \leq K < \frac{1}{2}$$

and

$$f^* = \frac{-3K^2 + 6K}{8r} \text{ for } \frac{1}{2} \leq K < 1.$$

Assume that $0 \leq K < \frac{1}{2}$ and, therefore, $F^{EP} = \frac{(1+K)^2}{9r}$. Comparing f^* and F^{EP}, we can show that for $K < K^* = \frac{1}{3}$ it holds that $f^* < F^{EP}$. Correspondingly, for $K \geq K^*$ we have $f^* \geq F^{EP}$. Thus, for $K < K^*$ and $f^* < f < F^{EP}$ it holds that $E(W_{IE+EP}) < E(W_{NE})$, which proves statement i).

Now assume that $\frac{1}{2} \leq K < 1$. The corresponding non-feasible entry border is $F^{EP} = \frac{1}{4r}$. For any level of drastic innovation K, we have $f^* \geq F^{EP}$. Therefore, when the entry cost falls in the interval $[0, F^{EP}]$, it is true that $E(W_{IE+EP}) > E(W_{NE})$, which proves statement ii). ■

7.1 Bertrand Competition

Consider two firms producing identical goods. Firms choose prices to maximize their profit functions

$$\max_{\{p_i\}} \pi_i(p_i, p_j) = (p_i - c)D_i(p_i, p_j)$$

while consumers buy goods from the firm with a lower price, i.e.

$$D_i(p_i, p_j) = \begin{cases} D(p_i), \text{ if } p_i < p_j, \\ \frac{1}{2}D(p_i), \text{ if } p_i = p_j, \\ 0, \text{ if } p_i > p_j. \end{cases}$$

Solution of the Bertrand competition mode implies that firms both charge competitive price $p_i^* = p_j^* = c$.

In the setting of our R&D and production game the following situations are candidates for the equilibrium.

i) The Entrant decides not to enter and the Incumbent is a monopolist in the market. With the market demand specified as $Q = 1 - p$, the monopolist will set $p_m^*(K) = \frac{1+K}{2}$. Under such condition the Incumbent's R&D investment decision is made on the basis of the investment criterion defined as

$$\Delta_m = \max(\Delta_{m,NPV}, \Delta_{m,NPV}^S).$$

The first component of this criterion is

$$\begin{aligned} \Delta_{m,NPV} &= p_m^*(0)(1 - p_m^*(0)) - p_m^*(K)(1 - p_m^*(K)) - \frac{(1 + r\beta)I}{1 + r} \Longrightarrow \\ \Delta_{m,NPV} &= \frac{K^2}{4} - \frac{(1 + r\beta)I}{1 + r}, \end{aligned}$$

and the second is

$$\begin{aligned} \Delta_{m,NPV}^S &= p_m^*(0)(1 - p_m^*(0)) - p_m^*(K)(1 - p_m^*(K)) - \frac{(1 + r\beta)I - h}{1 + r} \Longrightarrow \\ \Delta_{m,NPV}^S &= \frac{K^2}{4} - \frac{(1 + r\beta)I - h}{1 + r}. \end{aligned}$$

ii) The Entrant enters. If the Incumbent does not invest in R&D, the Entrant can charge $p_{ent}^*(K) = K - \varepsilon$, and push the non-innovating Incumbent from the market. If the Incumbent invests in R&D, the equilibrium price is driven all the way to zero, because every firm has incentive to undercut the opponent and monopolize the market. Both the Entrant and the Incumbent have spent certain sums of money in the form of entry cost and R&D investment. Thus, the undercutting game brings they into the situation when they both have negative payoff by setting the price $p_{ent}^*(0) = p_{inc}^*(0) = 0$.

Analyzing these possible equilibria we conclude that no duopoly provides a positive payoff Nash equilibrium for this game. Therefore we must look for the equilibrium among three possible monopoly cases.

The first is the monopoly of the Incumbent without R&D investment. The first condition for this scenario is that the entrant does not enter because $f > \frac{1}{r}\pi_m = \frac{1}{4r}$. Having Incumbent not investing in R&D can happen either because the R&D has not started or because the project was abandoned due to the failure of the first stage. The necessary condition for both these outcomes is $\Delta_{m,NPV} < 0 => K^2 < \frac{4(1+r\beta)I}{1+r}$.

The second is the monopoly of the Incumbent with R&D investment. It still holds for the Entrant that $f > \frac{1}{4f}$. And necessary and sufficient condition for the Incumbent to have started the R&D given the fact of its completion is $\Delta^S_{m,NPV} > 0 => K^2 > \frac{4[(1+r\beta)I-h]}{1+r}$.

Thirdly, the last monopoly has the Entrant as the only company in the market. The entry is profitable if $f < \frac{1}{4f}$ and the Incumbent will not invest in R&D if $K^2 < \frac{4(1+r\beta)I}{1+r}$.

7.2 Asymmetric Information

In the case of full information considered in the paper, the Entrant at time 1 knows whether or not the Incumbent will have new technology. Therefore there is no element of uncertainty in its decisions.

Consider the entry conditions with asymmetric information. It is rational to assume that, because the Entrant already has developed the same technology and knows what is required to carry out the R&D, it will know whether or not the Incumbent has started the R&D and whether or not this decision is conditional on the outcome of the first-stage R&D. But the Entrant is not able to observe the Incumbent's second-stage decision (which takes place at time 1) and the outcome of its first-stage R&D. In this case the Entrant must account for the chance that the Incumbent will abandon its R&D after the first stage.

If the Incumbent does not start R&D observing $\Delta_{inc,NPV} < 0$ and $\Delta^S_{inc,NPV} < 0$, the entry condition of the Entrant is $\frac{1}{r}\pi_{ent}(K) - f > 0$ for drastic innovation and $\frac{1}{r}\pi_m(0) - f > 0$ for non-drastic one. This condition is equivalent to f falling into the Entry Prevention and Inevitable Entry regions defined before in the full information case (see Figures 2 and 8).

If the R&D investment decision is taken with $\Delta_{inc,NPV} > 0$ and $\Delta^U_{inc,2} > 0$, the Entrant will enter only if $\frac{1}{r}\pi_{ent}(0) - f > 0$, because it is clear that the Incumbent will certainly obtain the new technology by time 2. This is the same as the case of Inevitable Entry under full information

But if the research is started with $\Delta_{inc,NPV} < 0$ and $\Delta^S_{inc,NPV} > 0$, it is not known beforehand whether the project will be abandoned or not. Therefore, the Entrant may enter if $\frac{1}{2r}\pi_{ent}(0) + \frac{1}{2r}\pi_{ent}(K) - f > 0$ with non-drastic innovation and $\frac{1}{2r}\pi_{ent}(0) + \frac{1}{2r}\pi_m(0) - f > 0$ with drastic one.

Compare the Entrant's strategies in case the acquisition of new technology by the Incumbent is conditional to the outcome of the first stage R&D. If the Entrant has full information or the Incumbent's strategy does not depend on uncertainty, then the Entrant's decision is based on observing f falling into different entry regions as shown in the left graph in Figure 8. If information is asymmetric and completion of the R&D depends on the outcome in the first stage, the Entrant makes its decisions based on f observed in the regions shown in the right graph in Figure 8.

We see that uncertainty under asymmetric information makes the Entrant to refrain from entry in the region where it otherwise would have entered knowing that the first stage R&D was not successful. The expected payoff under asymmetric information is lower than the full information payoff observed in case the Incumbent fails to develop the new technology. And, similarly, asymmetric information causes the Entrant to enter in the region where its full information payoff given the Incumbent's success is lower than the expected payoff when the outcome of the first-stage R&D cannot be observed. In this case the Entrant may end up with a net loss if the Incumbent is successful in R&D.

7.3 Entrant as First Mover

Let us assume that the Entrant makes its entry decision first. The Incumbent observes the Entrant's action and decides about investing in R&D. The information available to the Entrant is the same as in the asymmetric information case: the Entrant knows all the characteristics of the Incumbent's R&D, but can not observe the outcome of the first stage and the second-stage decision.

The Incumbent's optimal strategy in this case is based on the observed action of the Entrant. If the Entrant enters, the Incumbent's R&D decisions are based on the same assumptions as in the case of inevitable entry in the main model (see Figure 4), i.e. the Incumbent can choose out of different entry accommodation strategies. If entry does not occur, the Incumbent's problem is equivalent to that of a monopolist.

Backward induction of this game produces us first the set of Incumbent's strategies, which are to be considered by the Entrant. As it was said above, the Entrant can precisely infer about the Incumbent's investment gains. Therefore, knowing that the R&D project is located, for example, in the Passive Accommodation area of Figure 4, the Entrant enters if it observes $\frac{1}{r}\pi_{ent}(K) - f > 0$ (non-drastic innovation) or $\frac{1}{r}\pi_m(0) - f > 0$. If the Incumbent will obtain the new technology unconditionally (Active Accommodation), the entry will take place if it is profitable for the Entrant in the duopoly, i.e. $\frac{1}{r}\pi_{ent}(0) - f > 0$. But if the Incumbent's strategy is conditional on the outcome of the first-stage R&D, the Entrant must consider its expected payoffs $\frac{1}{2r}\pi_{ent}(0) + \frac{1}{2r}\pi_{ent}(K) - f > 0$. The Entrant's decision logic is same as in the case when the Entrant makes its decision after the Incumbent under conditions of asymmetric information (see Figure 8).

But because the Entrant moves first, its entry influences the Incumbent's innovation decision. As it is shown in Proposition 5, inevitable entry prevents the Incumbent from investing in innovations, in which it could have invested if it was a monopolist. In case the Incumbent's decision is conditional on success in the first stage the negative effect of entry becomes only stronger. It is clearly seen that the Entrant's expected payoff in this case is higher than in the case where the Incumbent starts and finishes the R&D unconditionally. If the

Incumbent faces the project, which will be abandoned midstream in case the first stage fails, the Entrant will enter more readily, and this entry will prevent the Incumbent from even trying to start such an R&D.

There is an additional effect of preceding entry on Incumbent's payoffs which occurs when innovation is drastic. Under drastic innovation, entry leads to a situation when the Incumbent can not produce anymore. In this case the Incumbent must take into account that if it starts R&D, then its production profits for two periods must be forgone. Nonetheless, these losses do not influence the Incumbent's new technology profit gains $\Delta\pi_{inc}$ and its decision to start R&D.

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