Optimal R&D Investment Strategies Under the Threat of New Technology Entry

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Abstract[3]

This paper studies R&D investment decisions of a firm facing the threat of new technology entry. The R&D project is subject to technical uncertainty. The incumbent can successfully prevent entry by innovating. However, in an entry deterrence situation the resulting monopoly is different from a monopoly without entry threat, because potential competition has achieved that the monopolist firm completed the R&D project, which it otherwise would not have done.

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Greater technical uncertainty stimulates initiating exploratory R&D and can result in implementation of more expensive research projects. This is a result of the limited downside risk of the project: it does not matter whether the outcome of an initial R&D stage is disappointing or very disappointing, since in both cases the firm will simply abandon the project. The welfare analysis shows that the threat of entry may reduce welfare in case of entry deterrence.

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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. The Introduction ends with a presenting our main results and the paper's contents.

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 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)). In our paper technical uncertainty results in a random outcome of 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 (see also Kort (1998) and Schwartz and Moon (2000)). A typical characteristic of technical uncertainty is that it cannot be resolved by waiting. The firm can obtain information about the true cost of R&D only by starting the R&D project.

R&D cost uncertainty is modeled in a different way, compared to Kort (1998) or Schwartz and Moon (2000). Instead of employing a stochastic Wiener process, we introduce a simple two-stage R&D process with 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)). This opportunity can be worthwhile in case completion of the R&D project 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.

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 will show that increased uncertainty raises the incentive to start up the R&D project, which implies that the entry deterrence power of R&D is larger.

In the context of strategic interactions the model is related to 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; 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 production 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.

The firm can use R&D as an entry deterrence instrument. 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.

The welfare analysis shows that a threat of entry is socially undesirable if the positive effect of bringing a more cost-efficient technology to the market is outweighed by the R&D investment cost that the incumbent has to incur when it chooses for the active entry reaction strategy. On the other hand, entry has a positive effect on welfare in case entry cost is lower than the total increase in consumer and producer surplus, and it is not optimal for the incumbent to complete the R&D project.

The paper is organized as follows. The model is presented in Section 2, whereas Section 3 determines the equilibrium. Section 4 contains the welfare analysis. We discuss the model's robustness in Section 5. Finally, conclusions and topics for further research are presented in Section 6.

2 The Model

Consider an incumbent firm, which produces at a unit cost K. Then there is a potential entrant firm that has a better technology in a sense that it allows it to produce at a smaller unit cost, which for simplicity is put to zero. The firms engage in price (Bertrand) competition, and 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-stage R&D process with an uncertain outcome of the first stage. After the second stage is completed, the incumbent is able to produce more efficiently from that moment. 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 in a sense that 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 positive, 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

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

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.

The incumbent has a time lead over the entrant in the sense that it 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 unit production cost drops from K to zero), it will become available at time $t = 2$. If the entrant decides to enter, it incurs the entry cost f and it will also produce with zero unit cost at time $t = 2$. Therefore, the final market structure will be realized in the last time period.

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 only from the firm asking the lowest price, i.e.

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

The normalized inverse market demand function is $D(p) = 1 - p$.

3 Equilibrium

This section presents the equilibrium of the game developed in the previous section. First, the payoffs are determined for different scenarios. Then we proceed by presenting the different entry regimes and optimal incumbent behavior under these regimes. This is followed by analyzing the effects of uncertainty on incumbent behavior. Finally, a section on entry deterrence strategies is presented.

3.1 Payoffs.

The following situations can occur:

i) The entrant does not enter and the incumbent remains a monopolist in the market. The monopolist will set $p^*(K) = \frac{1+K}{2}$ if it does not innovate and $p^*(0) = \frac{1}{2}$ if it does. The corresponding profits will be $\pi^*(K) = \frac{(1-K)^2}{4}$ and $\pi^*(0) = \frac{1}{4}$.

ii) The entrant considers entry. If the incumbent does not invest in R&D,

the entrant can enter and charge $p^*_{ent}(K) = K - \varepsilon$, and push the non-innovating incumbent from the market. If the incumbent invests in R&D, the entrant will realize that after entering the equilibrium price will be equal to the marginal cost, i.e. $p^*_{ent}(0) = p^*_{inc}(0) = 0$, resulting in $\pi^*_{ent}(0) = \pi^*_{inc}(0) = 0$. Consequently, since the entry cost f is strictly positive, the entrant will not enter if it knows that the incumbent will obtain the new technology.

We conclude that this price competition model never results in a duopoly market structure. The game tree is presented in Figure 1.

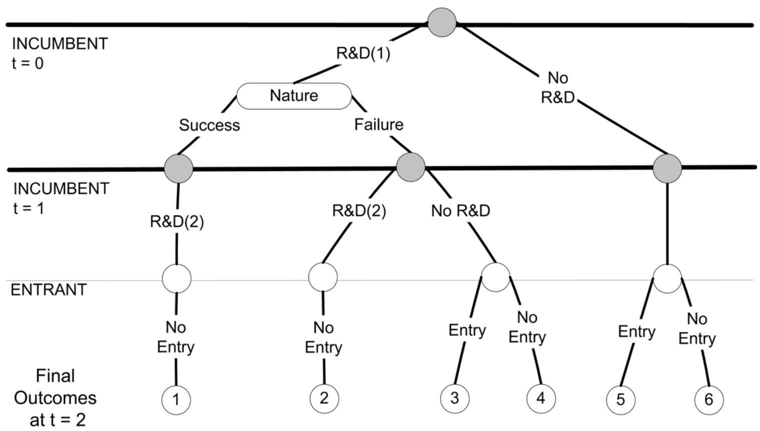

Figure 1: The game of R&D investment under the threat of entry.

Below we present the incumbent's and entrant's payoffs corresponding to the bottom row outcomes in Figure 1. We ignore the incumbent's monopolistic profits received at times *0* and *1*. These profits equal $2\pi(K)$ and are the same for any outcome of this game, so that they do not affect the incumbent's investment decisions. The incumbent's (top row) and the entrant's (bottom row) payoffs are:

$$v(1) = \begin{cases} \pi(0) - I + h \\ 0 \end{cases}$$

$$v(2) = \begin{cases} \pi(0) - I - h \\ 0 \end{cases}$$

$$v(3) = \begin{cases} -\beta I \\ \pi(0) - f \end{cases}$$

$$v(4) = \begin{cases} \pi(K) - \beta I \\ 0 \end{cases}$$

$$v(5) = \begin{cases} 0 \\ \pi(0) - f \end{cases}$$

$$v(6) = \begin{cases} \pi(K) \\ 0 \end{cases}$$

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 consider entering the market if profits are higher than the entry cost, i.e. if $\pi(0) - f \geq 0$. If the incumbent develops the new technology, the entrant will decide not to enter, because the equilibrium profits in duopoly will be zero.

To determine the optimal R&D investment strategy of the incumbent, we examine its decisions backwards in time starting at time $t = 1$. If the first-stage

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):

$$\Delta_2^U = \Delta\pi - [(1-\beta)I+h],$$

where the superscript "U" refers to the unsuccessful first stage research, and the subscript "*2*" denotes the second-stage investment decision of the incumbent. $\Delta\pi$ is the new technology profit gain (or just the profit gain) given by

$$\Delta\pi = \pi(0) - \pi(K).$$

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

$$\triangle_2^S = \Delta\pi - [(1-\beta)I-h].$$

The incumbent's decision to start the project is based on two different optimal investment criteria. One is the unconditional investment criterion, based on which we can derive whether 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

$$\triangle_{NPV} = \frac{1}{2} \triangle_2^S + \frac{1}{2} \triangle_2^U - \beta I \geq 0.$$

The other criterion is the conditional (or 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

$$\triangle_{NPV}^S = \frac{1}{2} \triangle_2^S - \beta I \geq 0.$$

The following proposition 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 project start criterion

$$\Delta_1 = \max(\Delta_{NPV}, \Delta_{NPV}^S) \geq 0$$

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 first-stage R&D fails and $\Delta_2^U \geq 0$.

Proof. See Appendix. ∎

Considering the different strategies of the entrant, the incumbent must adjust the values of its new technology profit gain $\Delta\pi$ accordingly.

If *entry is feasible* (i.e. $f \leq \pi(0)$), the incumbent knows that the entrant will consider entry at time $t = 1$. This implies that the entrant will push the incumbent out of the market, if the incumbent does not invest in R&D. So the criteria are calculated based on

$$\Delta\pi(f \leq \pi(0)) = \pi(0).$$

Finally, if *entry is not feasible*, then the incumbent acts as a monopolist so that

$$\Delta\pi(f > \pi(0)) = \pi(0) - \pi(K).$$

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

Employing Proposition 1 we can formulate two other propositions about the effect of uncertainty on the incumbent's decisions in different entry regimes.

Proposition 2 *In the case of non-feasible entry, $f > \pi(0)$, 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 when original unit cost is lower than

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

ii) positively affects the firm's decision to start R&D when it faces a project with *negative NPV and $K > K^*$.*

iii) negatively affects the firm's decision to continue the project with positive NPV and $K > K^*$.

Proof. See Appendix. ■

Proposition 3 *Under conditions of feasible entry $f \leq \pi(0)$, increased uncertainty about the outcome of R&D while keeping the mean fixed:*

i) positively affects the incumbent's decision to start R&D when it faces a project with negative NPV;

ii) negatively affects the incumbent's decision to continue a project with non-negative NPV.

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

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.

Result ii) of Proposition 2 and result i) of Proposition 3 refer to the scenario where $\Delta_{NPV} < 0$. Then it is optimal for the firm to undertake the first-stage of the R&D project only when uncertainty is sufficiently large so that $\Delta^S_{NPV} \geq 0$. 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. The limited downside risk of the R&D project is crucial here: it does not matter whether the first stage R&D outcome is disappointing or very disappointing, since in both cases the firm simply abandons the project.

Result iii) of Proposition 2 and result ii) of Proposition 3 refer to the case where $\Delta_{NPV} \geq 0$. We conclude that if the firm starts R&D, it will always complete the project if uncertainty is small so that $\Delta_2^U \geq 0$. In case uncertainty is large and $\Delta_2^U < 0$, it will be 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 Pindyck (1991) and 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. 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 Blockade and Entry Deterrence

In case the entry cost falls below monopoly profits, the entrant considers entry. Then, the only way for the incumbent to prevent entry and stay in the market is to innovate. The possible strategies are entry blockade, entry deterrence, and shut down. 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 (Tirole (1988)). 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.

Proposition 4 *If entry is feasible, i.e.* $f \leq \pi(0)$*, 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. If entry is feasible, the new technology profit gain of the incumbent is given by:

$$\Delta\pi(f \leq \pi(0)) = \pi(0) = \frac{1}{4}.$$

For the monopolist this profit gain equals

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

Since $K \in [0, 1)$, it holds that $\Delta\pi(f \leq \pi(0)) > \Delta\pi(f > \pi(0))$. Hence, 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

$\Delta_1(f \leq \pi(0)) > \Delta_1(f > \pi(0))$, and $\Delta_2^U(f \leq \pi(0)) > \Delta_2^U(f > \pi(0))$. ■

This proposition implies that the entry threat stimulates the incumbent to undertake the R&D project. Parameter K serves as a measure for the strategic effect in the sense that a smaller K implies a stronger strategic effect of R&D investment. In case K is large the R&D project is also attractive for the monopolist without entry threat, implying that entry blockade prevails. Entry deterrence occurs for smaller values of K, where the monopolist profit gain $\Delta\pi(f > \pi(0))$ is not large enough to compensate for the R&D investment costs, while the entry threat makes the profit gain of the incumbent $\Delta\pi(f \leq \pi(0))$ independent of K.

Hence, if the entry cost is low enough to make entry feasible, 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 frameworks where innovations could be patented, while here the entrant already possesses the new technology.

If the incumbent completes the R&D, entry is prevented and the monopoly is preserved. But the monopoly resulting from entry prevention is different from the one without entry threat. In the situation where $\Delta_1(f \leq \pi(0)) > 0 > \Delta_1(f > \pi(0))$, the entry deterrence case takes place; the monopolist without potential competition would stay with the same old technology, while the incumbent facing the entry threat undertakes the R&D to preserve its monopoly position. Therefore, potential competition has a positive effect on innovating activities.

4 Welfare Analysis

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

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

so that

$$W(\cdot) = \pi(\cdot) - C(\cdot, f, I) + CS(\cdot),$$

where

$$CS(\cdot) \equiv \frac{q(\cdot)^2}{2},$$

and $C(\cdot, f, I)$ are the costs related to the R&D investment and entry in each particular case. Knowing that $\pi(\cdot) = q(\cdot)^2$ we obtain that

$$W(\cdot) = \frac{3}{2}\pi(\cdot) - C(\cdot, f, I).$$

The way uncertainty influences the incumbent's strategies and welfare is not straightforward. If it is not optimal to invest in R&D, uncertainty does not influence 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 if the incumbent exercises the option to abandon the project if the outcome of the first stage is unfavorable. Then it holds that in case of failure in the first stage, the incumbent will abandon the project regardless the size of h, so that any negative outcome is as "bad" as the other. But if the first stage is successful, an increase in h means 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. First, consider the case where entry is feasible and the strategy switch takes place when $\Delta_{NPV} < 0$ and Δ_{NPV}^{S} becomes positive. For values of h below the critical level h^{*} the incumbent will not start the R&D project and the expected welfare is $E(W(h < h^{*})) = W(5)$ ("5" corresponds to outcome 5 in the bottom row of Figure 1, i.e. the incumbent will shut down and the entrant will enter). The threshold value h^{*} is given by

$$\begin{aligned} h^{*} &= \arg(\Delta_{NPV}^{S} = 0), \\ h^{*} &= -\Delta\pi + (1+\beta)I. \end{aligned}$$

When h passes the threshold, the expected welfare becomes $E(W(h \geq h^{*})) =$

$\frac{1}{2}W(1) + \frac{1}{2}W(3)$ (either the incumbent innovates and prevents entry, or the incumbent will abandon R&D, shut down and allow the entrant to enter). This implies that

$$\begin{aligned} E(\Delta W(h^*)) &\equiv E(W(h \geq h^*)) - E(W(h < h^*)) \\ &= \frac{1}{2}(W(1) + W(3)) - W(5) = \frac{1}{2}\left(f - \frac{1}{4}\right). \end{aligned}$$

In a similar manner we treat the change in welfare when $\Delta_{NPV} \geq 0$ and Δ_2^U changing its sign from positive to negative. This occurs when h increases beyond h_*, where the incumbent will switch from unconditional completion of R&D to the strategy where the R&D project is abandoned in case the first stage is not successful. The threshold value h_* is defined as

$$\begin{aligned} h_* &= \arg(\Delta_2^U = 0), \\ h_* &= \Delta\pi - (1 - \beta)I. \end{aligned}$$

For $h \leq h_*$ the incumbent will finish the R&D project regardless the outcome of the first stage and the expected welfare is $E(W(h \leq h_*)) = \frac{1}{2}W(1) + \frac{1}{2}W(2)$ (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 $E(W(h >$

$h_*)) = \frac{1}{2}W(1) + \frac{1}{2}W(3)$, and

$$E(\Delta W(h_*)) \equiv E(W(h > h_*)) - E(W(h \leq h_*)) = \frac{1}{2}(W(3) - W(2)) = \frac{1}{2}\left(-f + \frac{1}{4}\right).$$

We conclude that the welfare effect of the strategy downgrade in case $\Delta_{NPV} \geq 0$ and Δ_2^U becoming negative is equal but opposite in sign to the effect of the strategy upgrade in case $\Delta_{NPV} < 0$ and Δ_{NPV}^S becoming positive.

Existence of a feasible entry scenario requires that $f \in (0, \frac{1}{4}]$. Therefore, for any value of f in this interval the effect of the strategy switch will be negative if increased uncertainty makes the firm decide to start R&D and positive if increased uncertainty makes the firm decide to abandon the project when the first R&D stage is unsuccessful.

Now consider the strategy switch under conditions of no feasible entry (monopoly). In this case we have

$$E(\Delta W(h^*)) = \frac{1}{2}(W(1) + W(4)) - W(6) = \frac{2K - K^2}{16},$$
$$\text{and } E(\Delta W(h_*)) = \frac{1}{2}(W(4) - W(2)) = -\frac{2K - K^2}{16}.$$

It holds that $2K - K^2 > 0$ for $K \in [0, 1)$. Hence, the welfare effect of an uncertainty induced strategy switch of the monopolist is positive if it leads to starting R&D and negative if it makes the abandonment of R&D optimal in case of negative first stage R&D outcome, which is the opposite of what we obtained in the case of feasible entry.

To understand these effects, note that in the case without entry threat the social incentive to innovate is higher than the private incentive, because the firm does not internalize the raise in consumer surplus. For this reason an uncertainty increase resulting in a strategy upgrade (downgrade) leads to a welfare increase (decrease). On the other hand, when entry is feasible, the incumbent's incentive to innovate can be higher than the social incentive, because the latter does not assign positive value to the fact that innovation can prevent entry. Therefore, the welfare effects from strategy upgrades/downgrades can have opposite effects compared to the case without entry threat, as shown above.

We summarize this discussion in the following proposition.

Proposition 5 *Increased uncertainty about the outcome of R&D while keeping the mean fixed:*

i) does not affect expected welfare, if $\Delta_{NPV} \geq 0$ *and* $\Delta_2^U \geq 0$*, or if* $\Delta_{NPV}^S < 0$*;*

ii) positively affects expected welfare, if $\Delta_{NPV} < 0$ *and* $\Delta_{NPV}^S \geq 0$*, or if* $\Delta_{NPV} \geq 0$ *and* $\Delta_2^U < 0$*;*

iii) under conditions of feasible entry: negatively affects expected welfare, if an increase in h *makes* Δ_{NPV}^S *positive, and positively affects expected welfare, if an increase in* h *makes* Δ_2^U *negative;*

iv) under conditions of non-feasible entry: positively affects expected welfare, if an increase in h *makes* Δ_{NPV}^S *positive, and negatively affects expected welfare, if an increase in* h *makes* Δ_2^U *negative.*

It is clear that under feasible entry, increased uncertainty induces no change in the expected consumer and producer surplus, because the market will always have one firm producing with the new technology. If the incumbent innovates, it continues to be a monopolist, and, otherwise, the entrant enters and becomes the only firm in the market. The price of preserving the monopoly for the incumbent is the R&D cost, while for the entrant the price of becoming the monopolist equals the entry cost.

If the incumbent employs an entry deterrence strategy, it is only required that the expected cost of this decision (the R&D investment) falls below the expected benefit (the monopoly profits with new technology). Then at the same time it can hold that R&D investment costs are strictly higher than the entry cost. In other words, from a welfare point of view it is cheaper to obtain the new technology as a result of entry rather than investing in R&D.

Potential competition can lead to welfare reduction in case of entry deterrence. This happens when the increase in consumer surplus (the innovation reduces cost of production leading to a lower output price, which in turn raises the consumer surplus) is outweighed by the negative effect of R&D investment cost on the firm's payoff. This negative effect of R&D spending is present, because under entry deterrence it holds that R&D investment would not be optimal in case there was no entry threat.

If entry is not feasible, R&D is carried out only when it is profitable to do so. Then the total effect of obtaining a new technology is positive, because the reduced unit cost of production increases profits and reduces price, where the latter then raises consumers surplus.

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 surplus by business stealing. In our case, as just explained, potential competition can influence welfare negatively under entry deterrence. On the other hand, entry has a positive effect on welfare in case it is not optimal for the incumbent to finish the R&D project and entry cost is sufficiently low. The entrant brings a more cost-efficient production technology to the market which increases consumers surplus. Hence, entry is welfare increasing if the entry cost falls below the sum of the increases in consumer surplus and monopoly profits. This scenario gives us an example of entry-driven creative destruction (Aghion and Howitt (1992)), which has 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 Cournot competition and imperfect information.

So far we considered the case of Bertrand competition where two firms compete in prices. Now we discuss the problem of R&D investment with new technology entry threat in a Cournot competition setting. Bertrand competition always results in a monopoly. In the case of Cournot quantity competition there are possible duopoly outcomes. In the Cournot setting we need to distinguish between the cases of non-drastic and drastic innovation (Tirole, (1988)). Non-drastic innovation corresponds to the case of a relatively low $K \in [0, \frac{1}{2})$. Then the innovation is not strong enough for the entrant to drive the not innovating incumbent out of the market. On the other hand, if we observe drastic innovation (bringing a relatively large $K \in [\frac{1}{2}, 1)$ to zero), the entrant will actually force the incumbent to exit, in case the latter does not innovate.

We define intervals of entry cost f that determine three types of entry: inevitable entry, entry prevention, and no entry threat. Inevitable entry occurs if the entrant will enter the market regardless of the actions of the incumbent. This scenario does not occur under Bertrand competition. In the entry prevention case the entrant will enter only if the incumbent does not complete the R&D project. As in the Bertrand setting, here we can distinguish between blockaded and deterred entry. In the case of no entry threat the incumbent behaves as a monopolist.

The monopolistic outcomes of Bertrand competition are equivalent to the outcomes of Cournot competition under entry prevention and drastic innovation, and under no entry threat. However, Cournot can also result in other market structures like a symmetric duopoly, where both the incumbent and the entrant produce with the new technology, or an asymmetric duopoly, where the incumbent retains the old technology and the entrant enters.

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. On the other hand, 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 that 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. We conclude that 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 decision.

6 Conclusions

R&D investment decisions of an incumbent firm, 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 and the power of the strategic effect; 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 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 the degree of innovation. Under feasible entry the incentive for the incumbent to innovate is higher compared to a monopoly situation without entry threat, because by innovating the incumbent can prevent entry.

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 negative if it encourages the incumbent to prevent entry by starting the R&D project and positive if increased uncertainty induces abandonment after a negative first-stage R&D outcome.

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 process innovation, while taking into account time to complete and technical uncertainty, can be employed an entry prevention 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 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.

Below we use notation $\pi_{inc}(\cdot)$ to denote the incumbent's profits in general, which can vary depending on the entrant's decision. In case of feasible entry it holds that $\pi_{inc}(0) = \frac{1}{4}$ if the incumbent innovates and $\pi_{inc}(K) = 0$ if it does not. If entry is not feasible, we have that $\pi_{inc}(0) = \frac{1}{4}$ and $\pi_{inc}(K) = \frac{(1-K)^2}{4}$.

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:

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

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

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

so that

$$\Delta_2^S = \Delta\pi - [(1-\beta)I - h] \geq 0,$$

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

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

$$\Delta_2^U = \Delta\pi - [(1-\beta)I + h] \geq 0.$$

It is evident that if $\Delta_2^U > 0$, then $\Delta_2^S > 0$.

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

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

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

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

If $\Delta_2^U > 0$, 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

$$i_1 = 1 = \arg\max_{i_1} E(\pi_1), \text{ if } \Delta_{NPV} = \Delta\pi - I \geq 0. \quad (1)$$

If $\Delta_2^U < 0$ and $\Delta_2^S < 0$, 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 $\Delta_2^U < 0$, but $\Delta_2^S > 0$, 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

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

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:

$$\Delta_{inc,NPV} = \Delta^S_{NPV} + \frac{\Delta^U_2}{2}. \quad (3)$$

If $\Delta^U_2 > 0$, then $\Delta_{NPV} > \Delta^S_{NPV}$ and it is possible to have $\Delta_{NPV} > 0$, while $\Delta^S_{NPV} < 0$. On the other hand, if $\Delta^U_2 < 0$, then $\Delta^S_{NPV} > \Delta_{NPV}$, and it is possible to have $\Delta^S_{NPV} > 0$, while $\Delta_{NPV} < 0$.

Specify $\Delta_1 = \max\{\Delta_{NPV}, \Delta^S_{NPV}\}$. Then the condition

$$i_1 = 1 = \arg\max_{i_1} E(\pi_1), \text{ if } \Delta_1 = \max\{\Delta_{NPV}, \Delta^S_{NPV}\} \geq 0$$

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 $\Delta_1 \geq 0$, then it always holds that $\Delta^S_2 > 0$, which finalizes the proof for statement ii) of this proposition. ∎

Proof. Proposition 2.

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

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

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

$$K^*_{inc} = 1 \pm \sqrt{1 - 8\beta I}.$$

The value of interest is $K^* = 1 - \sqrt{1 - 8\beta I}$, which lies inside the interval $[0, 1)$. This root takes up real values if the following condition holds:

$$I < \frac{1}{8\beta}.$$

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

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

For any $K < K^*$ 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 Δ^S_{NPV} preserves its sign, i.e. an increase in uncertainty does not affect the firm's strategic choice.

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

i) If $\Delta_{NPV} < 0$, then the R&D project will be started only if $\Delta_1 = \Delta^S_{NPV} > 0$, which is positively affected by an increase in uncertainty and becomes positive as uncertainty exceeds h^*.

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

Once the project is started, the next relevant criterion is the project abandonment decision criterion Δ_2^U, for which it holds that:

$$\frac{\partial \Delta_2^U}{\partial h} < 0,$$

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

8 References

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Aghion, P. and P. Howitt (1992), A Model of Growth Through Creative Destruction, *Econometrica*, Vol 60, pp. 323-351.

Arrow, K. (1962), The Economic Implications of Learning by Doing, *The Review of Economic Studies*, Vol. 29, pp. 155-173.

Carruth, A., A. Dickerson, and A. Henly (2000), What Do We Know about Investment under Uncertainty, *Journal of Economic Surveys*, Vol. 14, pp. 119-153.

Dasgupta, P. and J. Stiglitz (1980), Industrial Structure and the Nature of Innovative Activity, *The Economic Journal*, Vol. 90, pp. 266-293.

Doraszelski, U. (2003), An R&D Race with Knowledge Accumulation, *Rand Journal of Economics*, Vol. 34, pp. 19-41.

Dixit, A and R. Pindyck, (1994), Investment under Uncertainty, *Princeton University Press*, NJ.

Dixit, A. and J. Stiglitz (1977), Monopolistic Competition and Optimum Product Diversity, *American Economic Review*, Vol. 67, pp. 297-308.Gilbert, R. and D. Newbery (1982), Preemptive Patenting and the Persistence of Monopoly, *American Economic Review*, Vol. 72, pp. 514-526.

Hoppe, H. and I. Lee (2003), Entry Deterrence and Innovation in Durable Goods Monopoly, *European Economic Review*, Vol. 47, pp. 1011-1036.

Kamien, M. and N. Schwartz (1971), Expenditure Patterns for Risky R and D Project, *Journal of Applied Probability*, Vol. 8, pp. 60-73.

Kort, P.M. (1998), Optimal R&D investments of the firm, *OR-Spectrum*, Vol. 20 , pp. 155-164.

Kulatilaka, N. and E. Perotti (1998), Strategic growth options, *Management Science*, Vol. 44, pp. 1021-1031.

Lint, O. and E. Pennings (1998), R&D as an Option on Market Introduction, *R&D Management*, Vol 28, pp. 279-287.

Loury, G. (1979), Market Structure and Innovation, *The Quarterly Journal of Economics*, Vol. 93, pp. 395-410.

Mankiw, N. and M. Whinston (1986), Free entry and Social Efficiency, *Rand Journal of Economics*, Vol. 17, pp. 48-58.

Moscarini, G. and L. Smith (2001), The Optimal Level of Experimentation, *Econometrica*, Vol. 69, pp. 1629-1644.

Pindyck, R. (1991), Irreversibility, Uncertainty, and Investment, *Journal of Economic Literature*, Vol. 29, pp. 1110-1148.

Reinganum J., (1983), Uncertain Innovation and the Persistence of Monopoly, *American Economic Review*, Vol. 73, pp. 741-748.

Rosenbloom, R., and C. Christensen (1998), Technological Discontinuities, Organizational Capabilities, and Strategic Commitments, in G. Dosi, D. Teece, J. Chytry (eds.) *Technology, Organization, and Competitiveness.* Perspectives on Industrial and Corporate Change, Oxford, Oxford University Press.

Schwartz, E. and M. Moon (2000), Evaluating Research and Development Investments, in: Brennan, M.J., Trigeorgis, L. (eds.): Project Flexibility, Agency and Competition, *Oxford University Press*, New York, pp. 85-106.

Smit J. and L. Trigeorgis (1997), R&D Option Strategies, *Working Paper*, University of Chicago, August 1997.

Symeonidis, G. (2003), Comparing Bertrand and Cournot Equilibria in a Differentiated Duopoly with Product R&D, *International Journal of Industrial Organization*, Vol. 21, pp. 39-55.

Thomas, L. (1999), Incumbent Firms' Response to Entry: Price, Advertising, and New Product Introduction, *International Journal of Industrial Organization*, Vol. 17, pp. 527–555.

Tirole, J. (1988), The Theory of Industrial Organization, *MIT Press*, Cambridge, MA.

Van Biesebroek, J. (2003), Productivity Dynamics with Technology Choice: An Application to Automobile Assembly, *Review of Economic Studies*, Vol. 70, pp. 167-198.

Weeds, H. (2002), Strategic Delay in a Real Options Model of R&D Competition, *Review of Economic Studies*, Vol. 69, pp. 729-747.