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Optimal Patent Design with Uncertainty and Loss-Averse Innovators

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ABSTRACT

Although representing a major engine of economic growth, incremental innovations might not be stimulated enough when patent breadth and patent length are not designed properly. In this paper we model the choice between breakthrough and incremental innovations in the context of a neo-Schumpeterian growth model that accounts for the introduction of new goods and related sunk costs and that assumes uncertainty-averse and loss-averse innovators. Our findings show that innovators' choice in terms of novelty is shaped by patent breadth and length, that affect both the private and the social values of innovation. Accounting for innovators' uncertainty and loss aversion challenges the standard results on optimal patent design.

Keywords: Patent breadth, Patent length, Incremental innovation, Breakthrough innovation, Uncertainty aversion, Loss aversion.
JEL Classification: D60, D81, O32.

1. Introduction

Rosenberg (1982) defines incremental innovation as the unsung hero of modern economic growth. In several sectors and technologies (e.g. chemicals, engineering, software), no single innovation is path- breaking, but the cumulative effects of minor product changes are large. As emphasized by Puga and Trefler (2010), "even the most sophisticated innovations - those that actually generate patents - are just better

mouse traps that incrementally improve on existing auto parts technology (p. 64): most innovators stand "on the shoulders of giants" (Schotchmer, 1991, p. 29) and several technical improvements build on a foundation provided by earlier innovators. Nonetheless, conventional incremental improvements and cost reduction strategies are considered insufficient for getting a competitive advantage (Sorescu, Chandy and Prabhu, 2003): breakthrough innovations are of fundamental importance, and understanding the related decision process might eventually make their development easier and less expensive.

Being aware of how innovators respond to incentives that favor small improvements of the existing technology or path-breaking innovations is therefore crucial to delineate practices to stimulate specific types of innovative projects. This paper presents a theoretical model that studies the choice between breakthrough and incremental innovations under the key assumptions of uncertainty-averse and loss-averse innovators. We believe that the standard assumption of agents' risk aversion – typically used in the existing literature - does not reflect the peculiarity of a decision on the innovative strategy to follow, especially in case of the introduction of a new technology, when no odds can be attached to the probability of success and abandoning the existing technology might end up into a failure. This theoretical framework allows to investigate the set of policy tools that can create incentives to invest in breakthrough or incremental innovations like patent breadth and length.

Most economics literature on patenting has looked at innovations in isolation, without focusing on the externalities that early innovators produce on later innovators. Our contribution starts from the idea that, when technology grows cumulatively, there may be a large discrepancy between the social value of an innovation and the private one, i.e. the profit collected by the innovator. On one hand, the innovation may be very valuable because it generates spillover benefits for future innovators. On the other hand, future innovators represent a competitive threat and the innovator fears that her profit flow will be terminated by the introduction of a better product.

Therefore, we posit that the cumulative nature of research poses problems for the design of patent law that are concerned with optimal patent breadth and length. The paper thus addresses the following research questions: should patents be narrow, so that they effectively expire at an endogenous time when a better product is made? Or should they be relatively broad, so that the effective patent life coincides with the statutory patent life? Furthermore, should patent be long or short-lived? As noted by Gallini (2002), the theoretical literature shows that, in case of cumulative research, stronger patents may discourage subsequent research on valuable, but potentially infringing, follow-on inventions (see also Merges and Nelson, 1990; Scotchmer, 1991). Several studies (e.g. O'Donoughue et al., 1998) address the issue of patent breadth as compared to patent length and emphasize the presence of a trade-off between the rate of innovation and monopoly distortions.

Our main results show that, when agents are uncertainty and loss-averse, and patent breadth is narrow, agents do not invest in path-breaking innovations; in contrast, uncertainty and loss-neutral agents exhibit the same likelihood to invest in incremental or breakthrough innovations. Only when patent breadth is large, loss-averse agents prefer breakthrough innovations. These outcomes are exacerbated by high volatile environments. In the light of these findings, a government promoting path-breaks (or, in contrast, sustaining improvements of the existing technology) can shape innovators' incentives by designing patent length and breadth properly. Policy implications can be drawn not only concerning the firm or market where the innovation takes place, but also on the effects of path-breaking innovations introduced in industrialized countries on developing countries. In fact, the empirical evidence shows a dramatic rise of incremental innovation in low-wage countries (Puga and Trefler, 2010), and the patent law of industrialized countries or areas might affect the incentives to invest in incremental innovation of firms located in developing countries, reducing their main (and maybe unique) possibility of growth.

The rest of the paper is structured as follows. In Section 2, we briefly review the literature. Section 3 reports the model. In Section 4, we discuss possible implications and provide our conclusions.

2. Related literature

The difference between breakthrough and incremental innovations can be easily figured out. However, there are many dimensions along which authors calibrate the degree of innovativeness (Battaggion and Grieco, 2009): the level of risk implied in the strategy (e.g. Kaluzny, Veney and Gentry, 1972; Duchesneau, Cohn and Dutton, 1979; Hage, 1980; Cardinal, 2001), obviously greater in the case of radical breakthroughs; the type of processed knowledge (e.g. Dewar and Dutton, 1986; Henderson, 1993), that might involve completely new developments or simply enlarge the existing base; performance improvement and cost reduction (e.g. Nord and Tucker, 1987), that reflect the higher investment needed to move onto a new trajectory; the eventual opening of a new market and consequent applications (e.g. O'Connor, 1998; Henderson and Clark, 1990), that might derive from a revolutionary contribute. If we involve the concept of "technological trajectory", incremental innovations aim at giving better answers to questions shaped by the existing paradigm, whereas radical innovations represent a shift onto alternative trajectories and respond to different needs.

No matter the country, patent law establishes a few criteria for an innovation to be patented: novelty, nonobviousness and usefulness. Novelty requirements, seen as a minimum quality increment required to follow-up products, have already been analyzed in papers such as Green and Scotchmer (1995), Matutes et al. (1996), O'Donoghue et al. (1998) and Hopenhayn and Mitchell (2001, 2006). Interestingly, Prokop et al. (2009) find that increasing the novelty requirement does not necessarily increase either the profits or, consequently, the investment levels of the initial innovator; in a similar flavor, Banbury and Mitchell (1995) show that it is the introduction of incremental innovations that leads to greater likelihood of business survival.

Patent breadth represents a "quality threshold" such that, if the subsequent innovator discovers a product of quality higher than this threshold, then this product is deemed not to infringe the patent. Therefore, patent breadth determines how profit is divided in each period of the patent, whereas patent length determines the total profit that is collected by the firms jointly (Green and Scotchmer, 1995). As emphasized by Gallini (2002), when research is sequential and builds upon previous discoveries, patents assuring a broader protection may impede rather than promote innovation, contrary to conventional belief. However, this cost might be mitigated by licensing and other arrangements that permit the use of technology during the life of a patent.

Scotchmer (1991) introduces the notion of "effective patent life". In her model, she assumes that all innovations are patentable, whether they infringe another patent or not. Even though patent life is infinite and each innovator can fully appropriate the flow benefits of his innovation during his market incumbency, the patent effectively terminates when another firm invents a better product. To emphasize this intuition, we define effective patent life as the expected length of time for which an innovator remains the incumbent.

If the literature addresses the role of patent protection extensively, as emphasized above, however no previous works jointly consider the effects of technology growing cumulatively, and of innovators' cognitive attitudes. The choice of investing in a breakthrough innovation is not only a consequence of evaluations on performance and costs: a key role in determining the decision between following revolutionary or established trajectories is played by cognitive attitudes such as uncertainty aversion and loss aversion. This insight is consistent with the fact that breakthrough innovation generally seems not to take place in established firms but to be conveyed by new competitors.

Managerial enquiries testify that inertia, compartmentalized thinking and ambiguity constitute learning barriers to the development of drastically new paths: entrepreneurs and firms tend to proceed as they always did, preserving the status quo rather than capitalizing market information (Adams, Day and Dougherty, 1998). This outcome, on one hand, derives from the difficulties arising when an organization needs to change established routines and reframe the problem situation. On the other hand, lock-in to sub-optimal technologies (e.g. Farell and Soloner, 1985; Arthur, Ermoliev and Kaniovsky, 1987; Witt, 1997; Banerjee and Campbell, 2009) may be due the emergence of network externalities and increasing returns to adoption for consumers (Katz and Shapiro, 1985; Choi, 1994).

In the aim of reproducing realistically the way the decisions in the domain of innovation occur, our model fills into the existing research gap by incorporating these distortions when evaluating incentives to invest in path-breaking versus incremental innovations and the value of profits when different regimes of protection are available.

3. The model

The model grounds on Romer (1994)'s and Aizenman (1997)'s Neo-Schumpeterian models of growth in their closed-economy version. Furthermore, it incorporates Schmeidler-Gilboa's assumptions on agents' uncertainty aversion (loss-aversion is introduced in Section 4.2.). In general, the Neo-Schumpeterian models account for the introduction into an economy of new or improved types of goods and take explicit account of the fixed costs that limit the set of goods that firms can introduce. Furthermore, they do not capture explicitly the strategic interactions in oligopoly settings (in this departing from theliterature in industrial organization).

The crucial premise in the neo-Schumpeterian models is that every economy faces virtually unlimited possibilities for the introduction of new goods, where the term "good" is used in the broadest possible sense: it might represent an entirely new type of physical good, or a quality improvement; it might beused as a consumption good, or as an input in production. Here, the introduction of a new capital good represents an innovation.

In this section, we assume that the firm lives two periods: in period 0, it decides the type of innovation to invest in, and (if it is the case) sustains the sunk costs needed for a breakthrough innovation; in period 2, production takes place (this assumption will be relaxed later on). We consider an innovating firm who produces a final good Z by using labor (L) and N capital goods x_i according to the following production function:

$$Z = L^{1-\alpha} \sum_{i=1}^{N} x_i^{\alpha} \qquad (1)$$

with $0 < \alpha < 1$.

The production of capital good x_n takes place using the services of labour according to the function $x_n = L_n$ where L_n stands for the labour in activity n, whereas L is the labour employed in the production of the final good. For simplicity, w is the real wage and represents the marginal cost of producing both the capital goods and the final good.

The new capital good n can be introduced either as a small improvement on the existing technology (incremental innovation) or as a disruptive opening up of a new technology (breakthrough innovation). The degree of novelty determined by the innovation is labelled Δ: obviously, Δ is higher in case of breakthrough innovations.

Standard cost minimization implies that the demand for capital good i is:

$$x_i^d = \left(\frac{\alpha}{p_i}\right)^{\frac{1}{1-\alpha}} L \qquad (2)$$

Each producer faces a demand whose elasticity is 1/(1-α).

3.1 Uncertainty-averse innovators

In the way of capturing agents' attitude towards risk and uncertainty, this model follows the Schmeidler- Gilboa approach, that is based on the assumption that agents are both risk and uncertainty (in the sense of Knightian uncertainty) averse. If the innovator is a risk-neutral Bayesian agent, she would assign a uniform distribution to the returns of innovation. The only information available is that the project return is bounded between L and H, where L < H. The expression represents the expected return of the investment in innovation, where the probability assigned to both the successful and unsuccessful outcome (H and L respectively) is ½ and is independent to the degree of vagueness about the outcomes of innovation: a risk-neutral Bayesian agent will refer to this expression as the expectedreturn. However, as emphasized by Ellsberg (1961), agents behave differently than in this Bayesian description in two aspects: (1) they are unable to summarize the uncertainty in the form of a unique prior distribution, and (2) attach an extra-cost to invest in a breakthrough innovation that might be interpreted as n "uncertainty premium". In the Schmeidler-Gilboa approach, Knightian uncertainty induces uncertainty-averse innovators to prefer more transparent information and therefore to discount by using a "hurdle rate" that is higher than the risk-free interest rate. The introduction of a new capital good $n$by means of a path-breaking innovation requires an "up-front capacity investment" which is specific to the new capital good, whereas the marginal cost of all the current capital goods is equal to w. There are two periods, denoted by $t = 0, 1$. Adding capital good n requires a sunk cost specific to that good; the innovator commits its investment at the beginning of period 0, whereas production takes place in period 1. For simplicity, we assume that the dependence of the sunk cost on n is linear and is normalized at 1 (we assume it is known). On the contrary, future revenues are uncertain due to the fact that the new technological trajectory can be successful or not (and this is not known *a priori).* We label χ the random shock that describes the degree of uncertainty of the innovation that affects future revenues. Technology is established in period 0, and production takes place in period 1. At the beginning of period 0, prior to the realization of χ, the innovating firm chooses its R&D investment. For simplicity, we normalize χ to be either low ($\chi = 1 - \delta$) or high ($\chi = 1 + \delta$), $\delta \geq 0$, but assume that the precise probability of each state is unknown and ▯ represents the range of possible outcomes of the random variable χ. Ameliorations of the existing technology are assumed to involve no uncertainty on the profitability of the technology (as it is the current one): $\chi = 1$ (and $\delta = 0$) captures the case of incremental innovation, where, in the absence of uncertainty, the innovator evaluates projects by applying a risk-free interest rate, denoted by r. A representative producer of the x_i capital good follows a markup rule, charging $p_i = \frac{w}{\alpha}$ for its input. Adding capital good n will lead to profits equal to

$$\Pi_n(\chi) = \frac{\chi(w)^{-\alpha'}kL}{1+r} - n \qquad (3)$$

where $k = \frac{1-\alpha}{\alpha}\alpha^{\frac{2}{1-\alpha}}$ and $\alpha' = \frac{\alpha}{1-\alpha}$.

As the incremental innovation implies neither risk or uncertainty, profits from an improved product (Π_n^{in}) are obtained when $\chi = 1$:

$$\Pi_n^{in} = \Pi_n\,(1) = \frac{\chi(w)^{-\alpha'}kL}{1+r} - n \qquad (4)$$

In contrast, investing in a breakthrough innovation exposes the innovator to Knightian uncertainty. A useful decision rule in these circumstances is to maximize a utility index that provides a proper weightfor the exposure to uncertainty. The procedure we follow consists of constructing two statistics. The firstis the "worst scenario" wealth, denoted by $\underline{\Pi}$. The second is the "expected wealth" if one attaches a uniform prior to the distribution of the profits, denoted by $E_u(\Pi)$. The shortcoming of $E_u(\Pi)$ is that it does not put any weight to the uncertainty regarding the outcome of the innovation. To correct this shortcoming, we use a decision rule that maximizes the innovator's utility U as a weighted average of the above two statistics:

$$U = c\,\underline{\Pi} + (1-c)E_u(\Pi) \qquad (5)$$

where $0 \le c \le 1$ represents the degree of uncertainty aversion embodied in the decision to invest, with $0 \le c \le 1$. When c goes to zero, we have the case of a risk-neutral Bayesian agent who attributes a uniform prior to the two events. A larger c indicates less confidence about the assigned probabilitiesand greater uncertainty aversion.

Labelling U_{bt} the innovator's utility deriving from a radical breakthrough, we get

$$U_{bt} = \Pi_0 + (1-c\delta)\frac{\chi(w)^{-\alpha'}kL}{1+r} - n \qquad (6)$$

The innovator's utility deriving from a incremental innovation (called U_{in}) is

$$U_{in} = \Pi_n^{in} = \Pi_0 + (1-c\delta)\frac{\chi(w)^{-\alpha'}kL}{1+r} - n \qquad (6)$$

Proposition 1. *An uncertainty-averse agent will invest in a breakthrough innovation if* $W > n(1+\overline{r})$. Proof In the absence of any investment in innovation, firm's profit are Π_0. The investment in a breakthrough innovation will be undertaken if it increases the expected utility:

$$c\left[\Pi_0 + (1-\delta)\frac{\chi(w)^{-\alpha'}kL}{1+r} - n\right] + (1-c)\left[\Pi_0 + \frac{(w)^{-\alpha'}kL}{1+r} - n\right] > c\Pi_0 + (1-c)\Pi_0 \qquad (7)$$

If we label $W = (w)^{-\alpha'}kL$ and $\overline{r} = \frac{r+c\delta}{1-c\delta}$, we get $W > n(1+\overline{r})$. We assume $0 < \delta < \frac{1}{c}$ to ensure a positive discount rate.

Proposition 2. *An uncertainty-averse agent will invest in an incremental innovation if* $W > n(1+r)$.

Proof As an investment in incremental innovation does not imply uncertainty, we get this inequality by assuming $\delta = 0$ (due to $\chi = 1$).

Alternatively, the Proposition above holds for an uncertainty-neutral agent investing in a breakthrough innovation ($U_{in} = U_{bt}$).

Proposition 3. *Breakthrough innovations are less likely to be chosen by uncertainty-averse agents. This effect is stronger as volatility increases.*

Proof It is easy to see that the inequality in Proposition 2 determines a less demanding condition for the investment to be chosen than the one in Proposition 1. Hence, Knightian uncertainty-aversion induces behavior where the innovator discounts by a hurdle rate $\overline{r}$ that exceeds the risk-free rate r. The effective discount factor is adjusted upwards by a factor $\frac{1}{1-c\delta}$ that accounts for a measure of uncertainty aversion (c) times a measure of the worst scenario loss (δ), that captures volatility.

In other words, in order to induce the introduction of a breakthrough innovation, the expected revenues should exceed the risk-free yield by a premium proportional to the aversion to uncertainty times a measure of the dispersion of the random profit variable. This equation predicts that an increase in the range of possible returns will make investment in path-breaking innovations less likely: the LHS of the equation is not modified, while the RHS goes up. In these circumstances, higher volatility will reduce investment in breakthrough innovations. If the uncertainty is large, breakthrough innovations will not take place.

3.2 Breakthrough innovations with loss-averse agents

As discussed above, loss aversion might affect agents decisions in case of breakthrough innovation. Loss aversion is the tendency of agents to be more sensitive to reductions in their wealth than to increases in their wealth, where reductions and increases are relative to a reference point. We follow Gul (1991) and Aizenman (1998) in modelling an agent who maximizes a weighted sum of utility, where the weights deviate from the probabilities in order to reflect loss aversion. The preferences of a loss-averse agent may be summarized by $[U(x), \beta]$ where is the conventional utility function of wealth x and $\beta \geq 0$ is a parameter measuring the degree of loss aversion. Let us denote by $V(\beta)$ the expected utility of a loss-averse agent who attaches extra disutility to circumstances where the realized income is below the "status quo" income. In the case of radical innovation, the producer attaches extra disutility to a realized profit that is below Π_0. The loss-averse expected utility equals the conventional expected utility (that here is additionally weighted by c in order to account for uncertainty aversion), adjusteddownwards by a measure of loss-aversion times the expected loss:

$$V(\beta) = c\,\underline{\Pi} + (1-c)E_u(\Pi) - \beta[V(\beta)] - \underline{\Pi} \qquad (8)$$

Proposition 4. *A loss-averse agent invests in a breakthrough innovation if $W > n(1+\hat{r})$.*

Proof In the absence of any investment in innovation, firm's profit are Π_0. A loss-averse agent willinvest in a breakthrough innovation if $V(\beta) > c\,\Pi_0 + (1-c)\Pi_0$, where

$$V(\beta) = c\left[\Pi_0 + (1-\delta)\frac{\chi(w)^{-\alpha'}kL}{1+r} - n\right] + (1-c)\left[\Pi_0 + \frac{(w)^{-\alpha'}kL}{1+r} - n\right] - \beta\left[V(\beta) - \Pi_0 - (1-\delta)\frac{\chi(w)^{-\alpha'}kL}{1+r} + n\right] \quad (9)$$

That leads to $(w)^{-\alpha'}kL > n(1+\hat{r})$. If we level $\hat{r} = \frac{r+c\delta-\beta(1-\delta)}{1-c\delta+\beta(1-\delta)}$, we get to $W > n(1+\hat{r})$.

Proposition 5. *Breakthrough innovations are less likely to be chosen by loss-averse agents. This effect is stronger as volatility increases.*

Proof It is easy to see that the inequality in Proposition 7 determines a more demanding condition for the investment to be chosen than the one in Proposition 1. In fact, loss-aversion induces behaviour where the innovator discounts by a hurdle rate r that exceeds the risk-free rate $\bar{r}$ and the hurdle rate $\bar{r}$. The effective discount factor is adjusted upwards by a factor $\frac{1}{1-c\delta+\beta(1-\bar{\delta})}$ that, as before, accounts for a measure of uncertainty aversion times a measure of the worst scenario loss $(-c\delta)$. Furthermore, this factor accounts for a measure of loss aversion (β) *per se* and for a measure of loss aversion times a measure of the worst scenario loss ($-\beta\delta$). As β increases, the hurdle rate increases and the firm is less likely to invest in innovation. Loss aversion induces behaviour where the innovator discounts by ahurdle rate that - again - exceeds the risk free rate and also exceeds the hurdle rate $\bar{r}$. In fact, discount factor r is adjusted downward by a factor proportional to the combined effect of the measures of loss aversion (β) times losses deriving from unsuccessful innovation $(1-\delta)$. When $\beta > 0$, $\hat{r} = \bar{r}$.

3.3 Introducing patent law: Patent breadth

As summarized by Hopenhayn and Mitchell (2001), a patent is defined by its breadth, its length, and its origination and/or renewal fee. We call L the length of time for which the protection lasts, and B the set of products that at any given time may be prevented by the patent-holder, i.e. the patent's breadth. Generally speaking, patent protection reduces social welfare because it generates market power for the innovator (several works have emphasized this result from Nordhaus, 1969 on); however, it is necessary because inventions are costly to produce but may be costless to reproduce.

In the previous sections, we have assumed that each innovator could enjoy the revenues of her own innovation. However, this assumption should be specified better, as the effective value of a breakthrough innovation should (or should not) account for the additional value of subsequent extensions, that are made possible by the initial path-break.

As emphasized in the introduction, the patent law addresses the issue of innovation cumulativeness by referring to the concept of "patent breadth". Patent breadth individuates the threshold of minimumrequirement of quality improvement that is needed to consider the subsequent innovation "new" and "non-obvious": such an innovation does not infringe any previous patent and another patent can be claimed. Obviously, this threshold can be more or less extended. For sake of simplicity, we consider the two extreme cases only: large versus narrow patent breadth. Then, we evaluate and compare the incentives to innovate in presence of uncertainty and losses averse agents versus neutral agents.

From now on, we modify the assumption of two-period firm's life: the firm lives T periods: in period 0, it decides the type of innovation to invest in; in period 2, production takes place and the innovation can be patented; patent protection expires in period T.

By definition, the path-breaking innovator always satisfies the applicability requirement of novelty and non-obviousness established by the patent law: once applied, the innovation is protected until patent expiration (in T). This occurs no matter the extent of patent breadth (the condition $\Delta > B$ always holds for breakthroughs).

In contrast, for the incremental innovation the degree of novelty Δ might be above or below the threshold of patent breadth B established by the law. When $\Delta > B$ holds, the incremental innovator does not infringe the earlier patent (that is not covering this specific extension of the earlier patent) and can get profits from the new improvement; when $\Delta > B$ holds, the incremental innovator does infringe the earlier patent and gets zero profit. In other words, only when the threshold of novelty and non-obviousness of any improvement of the original innovation is narrow (i.e. when $B < \Delta$), firms gets profits from investing in incremental innovation before T. In the limit case where $B \to 0$, only breakthrough innovation are profitable.

3.3.1 Large patent breadth

When patents are broad ($B < \Delta$), incremental innovators infringe the earlier patent and get no profits. Let us evaluate the cumulative amount of profits that accrue to the path-breaking innovators until the end of patent protection T.

With uncertainty-averse innovators, we get

$$\overline{U}^T{}_{bt} = \Pi_0 + \frac{\chi(w)^{-\alpha'}kL}{1+\bar{r}} - n + \frac{\chi(w)^{-\alpha'}kL}{(1+\bar{r})^2} + \cdots + \frac{\chi(w)^{-\alpha'}kL}{(1+\bar{r})^T} = \Pi_0 + W\sum_{t=1}^{T}\left(\frac{1}{1+\bar{r}}\right)^t - n \quad (10)$$

With uncertainty-averse and loss-averse innovators, innovators, we get

$$\widehat{U}^T{}_{bt} = \Pi_0 + \frac{(w)^{-\alpha'}kL}{1+\hat{r}} - n + \frac{\chi(w)^{-\alpha'}kL}{(1+\hat{r})^2} + \cdots + \frac{\chi(w)^{-\alpha'}kL}{(1+\hat{r})^T} = \Pi_0 + W\sum_{t=1}^{T}\left(\frac{1}{1+\hat{r}}\right)^t - n \quad (11)$$

Proposition 6. *When patent breadth is large, investing in breakthrough innovation is more profitable no matter the agent's attitude toward uncertainty and losses.*

Proof this result derives from the inequality $U^T{}_{bt} > \overline{U}^T{}_{bt} > \widehat{U}^T{}_{bt} > U^T{}_{in}$.

In particular, $U^T{}_{bt} = \frac{(w)^{-\alpha'}kL}{1+r} - n$ that, in this case, is different from $U^T{}_{in}$ that is equal to 0 due to the earlier patent infringement.

3.3.2 Narrow patent breadth

When patent breadth is narrow ($B < \Delta$), an incremental innovation can stop the effective life of the earlier patent and get profits until the end of its own patent life:

$$U^T{}_{in} = \Pi_0 + \frac{\chi(w)^{-\alpha'}kL}{1+r} - n + \frac{\chi(w)^{-\alpha'}kL}{(1+r)^2} + \cdots + \frac{\chi(w)^{-\alpha'}kL}{(1+r)^T} = \Pi_0 + W\sum_{t=1}^{T}\left(\frac{1}{1+r}\right)^t - n \qquad (12)$$

Proposition 7. *When patent breadth is narrow, breakthrough innovations are less likely to be chosen by uncertainty-averse and loss-averse agents.*

Proof as $r < \bar{r} < \hat{r}$, it is trivial to show that $U^T{}_{in} > \bar{U}^T{}_{bt} > \hat{U}^T{}_{bt}$ With uncertainty and loss neutral agents, the condition $U^T{}_{in} = U^T{}_{bt}$ holds and the two types of innovation are equally likely to be pursued.

The last two propositions emphasize a finding that has important policy implications: innovators' attitudes to different degrees of novelty is not enough to understand which innovative pattern will be pursued. Crucially, it is patent breadth that do shape incentives in favour of incremental versus breakthrough innovations.

3.3.3 Patent length

Let us now turn to investigate the role of patent length T. As broad patents imply no revenues for incremental innovation, we evaluate the optimal patent length only in the case of narrow breadth. As an extreme case of long-lived patents, we first consider the case when $T \to \infty$. For incremental innovations, we get:

$$U^\infty{}_{in} = \Pi_0 + W\sum_{t=1}^{\infty}\left(\frac{1}{1+r}\right)^t - n = \Pi_0 + W\left(1 + \frac{1}{r}\right) - n \qquad (13)$$

Similarly, for breakthrough innovations we get

$$\hat{U}^\infty{}_{bt} = \Pi_0 + W\sum_{t=1}^{\infty}\left(\frac{1}{1+\hat{r}}\right)^t - n = \Pi_0 + W\left(1 + \frac{1}{\hat{r}}\right) - n \qquad (13)$$

Where $U^\infty{}_{in} > \hat{U}^\infty{}_{bt}$.

This inequality holds for finite values of T, as shown in the following proposition.

Proposition 8. *An increase in patent length T increases the cost of uncertainty and loss aversion.*

Proof recalling the properties of finite geometrical series, we get

$U^T{}_{in} = \Pi_0 - n + W\sum_{t=1}^{T}\left(\frac{1}{1+r}\right)^{T-2}$ and $\hat{U}^T{}_{bt} = \Pi_0 - n + W\sum_{t=1}^{T}\left(\frac{1}{1+\hat{r}}\right)^{T-2}$

Both $U^T{}_{in}$_in and $\hat{U}^T{}_{bt}$_btincrease in T. It means that the impact of patent length on the innovator's utility is positive for both breakthrough and incremental innovations, but is stronger in case of incremental innovations.

When patent breadth is narrow, incentives to invest in breakthrough can be enhanced by extending patent length. However, uncertainty and loss aversion should be compensated by establishing a higher level of T in order to get the same level of utility in absence of uncertainty and loss aversion.

Summing up, patent breadth and length both have positive effects for the earlier breakthrough innovator (the larger the patent breadth and the longer the patent life, the higher the utility), but these effects turn out to be opposite when evaluating the utility of the later incremental innovator (the narrower the patent breadth and the longer the patent life, the higher the utility). Therefore, a proper calibration should be used to mitigate monopoly losses.

3.4 Welfare analysis

Let's turn to the analysis of the welfare generated by different patent regimes. In the absence of uncertainty, the number of capital goods is

$$N = \frac{W}{1+r} \qquad (14)$$

If all firms are uncertainty-averse and share the same uncertainty aversion index c, the number of capital goods (N) is determined by:

$$\bar{N} = \frac{W}{1+\bar{r}} \qquad (15)$$

with $N > N$ as 0<(1-cδ)<1. Therefore, uncertainty reduces the number of new activities.

When we account for loss aversion (and assume that all producers share both the same uncertainty aversion index c and the same loss aversion index β) the number of capital goods $\widehat{N}$ is determined by

$$\widehat{N} = \frac{W}{1+\hat{r}}$$

The GDP is given by the sum of labour and entrepreneur income[1].

When patent breadth is large ($B > \Delta$), the social gain of a breakthrough innovation with uncertainty- averse agents is described by the following expression

$$\bar{Y}^{T}{}_{bt} = \bar{U}^{T}{}_{bt} + \bar{I}^{T}{}_{bt} \qquad (16)$$

Where $I^{T}{}_{bt}$ represents the aggregate labour income of uncertainty-averse that equals

$$\bar{I}^{T}{}_{bt} = \frac{w}{1+\bar{r}}\bar{\Lambda}$$

with Λindicating the sum of aggregate labour in the intermediate goods x_i and in the final good Z respectively, i.e. $\Lambda = NL_n + L_Z$. As above, $\bar{\Lambda}$ represents the aggregate labour in case of a path breaking innovation and uncertainty-averse agents, with $\bar{\Lambda} = \bar{N}L_n + L_Z$.

When accounting for loss aversion, the two previous expressions become

$$\hat{Y}^{T}{}_{bt} = \widehat{U}^{T}{}_{bt} + \hat{I}^{T}{}_{bt} \qquad (17) \quad \text{and}$$

$$\hat{I}^{T}{}_{bt} = w\widehat{\Lambda}\sum_{t=1}^{T}\left(\frac{1}{1+\hat{r}}\right)^{t}$$

where $\widehat{\Lambda}$ represents the aggregate labour in case of a path breaking innovation and loss-averse agents,

with $\widehat{\Lambda} = \widehat{\mathrm{N}}\mathrm{L}_n + \mathrm{L}_Z$.

When patent breadth is narrow ($B < \Delta$), an incremental innovation might be profitable and the numberof capital goods produced in the economy is higher. The GDP is given by

$$Y^{T}{}_{in} = U^{T}{}_{in} + I^{T}{}_{in} \qquad (18) \quad \text{and}$$

$$I^{T}{}_{in} = w\Lambda\sum_{t=1}^{T}\left(\frac{1}{1+r}\right)^{t}$$

where Λ represents the aggregate labour in case of an incremental innovation, with $\Lambda = \mathrm{N}L_n + L_Z$.

Proposition 9. *Narrow patent breadth reduces the social welfare of uncertainty-averse and loss-averse agents.*

Proof As $r < \bar{r} < \hat{r}$ and $N > \bar{N} > \widehat{N}$ it is trivial to show that $I^{T}{}_{in} > \bar{I}^{T}{}_{bt} > \hat{I}^{T}{}_{bt}$. With uncertainty-neutral and loss-neutral agents, the condition $I^{T}{}_{in} = I^{T}{}_{bt}$ holds and the two types of innovations generate the same level of social gain.

This proposition replicates the typical finding of a drop in social welfare when a patent is strong, both in terms of breadth and length (see Gallini, 2002). The peculiarity of our finding is that such a drop originates from the interaction of two form of cognitive distortions, i.e. loss aversion and uncertainty aversion. Interestingly, this bias can be mitigated by reducing the level of vagueness δ that originates loss aversion: expert or educated entrepreneurs might be able to interpret complex and vague signals from highly volatile environments, as shown in the following proposition.

[1] In the Neo-Schumpeterian models setup, consumers' surplus is not affected by the increase in the number of goods: the whole consumers' surplus is extracted by monopolistically competing firms producing capital goods.

Proposition 10. An increase in innovators' experience levels increases the welfare generated by breakthrough innovations.

Proof A way of capturing the role of innovators' experience in the model is assuming that an expert innovator is able to reduce the vagueness of the possible outcomes related to a path-breaking innovations. Therefore, an expert innovator faces a lower value of δ . Let us evaluate the impact of δ on loss-averse agents' discount rate: since $\frac{\partial(1+\hat{r})}{\partial\delta} < 0$, expert innovators face a lower hurdle rate. Furthermore, since $\frac{\partial\hat{Y}}{\partial\delta} < 0$, with expert innovators welfare increases.

4. Discussion and conclusions

Being aware of the determinants that shape the decision between small improvements of the existing technology or path-breaking innovations helps in delineating practices to stimulate specific types of innovative projects. Everybody says that breakthrough innovation is important (e.g. Leifer, O'Connor and Rice, 2001): consensus has emerged that conventional incremental improvements and cost reduction strategies are insufficient for getting a competitive advantage (Sorescu, Chandy and Prabhu, 2003) as direct consequence of worldwide diffusion of knowledge and industrial capability. Therefore, understanding radical innovation might eventually make their course shorter, less sporadic, less expensive, and less uncertain.

The paper presents a Neo-Schumpeterian model that accounts for the introduction of new goods and captures the related sunk costs. The analysis grounds on Aizenman (1997)'s work that investigates the effect of uncertainty aversion when a multinational firm modifies the set of capital goods by introducing a new one whose production is located in a developing country (where uncertainty in production costs is high). The present paper enlarges the analysis by accounting for loss aversion, that plays a major role in path-breaking innovations, as they imply the abandonment of the existing technology and possible consequent losses. Knightian uncertainty and loss aversion characterize breakthrough innovations as opposed to incremental innovations where only measurable uncertainty is involved.

As first remark, the paper explains the reluctance to open new technological trajectories by showing that, if agents are uncertainty and loss averse, both aversions may interact, potentially magnifying the welfare costs of uncertainty and losses related to a path-breaking innovation. A decision in favour of a cumulative development of the existing technology, as in case of incremental innovation, is far to be suboptimal.

The interaction of two key aspects drives the model: (1) the cumulative and sequential development of R&D (and technological trajectory); (2) the cognitive distortions deriving from uncertainty and loss aversion. These two forces shape both private and social gains of innovation. Patent law, and in particular the design of patent breadth and length, represents a key instrument to direct innovators' efforts toward a specific direction. In general, broad patents may accelerate innovation, but since infringing improvements must be licensed, broad patents concentrate market power by consolidating quality improvements in the hands of one firm. In markets with sequential innovation, inventors of derivative improvements might undermine the profit of initial innovators through competition. Profit erosion can be mitigated by broadening the first innovator's patent protection and/or by permitting cooperative agreements between initial innovators and later innovators (Green and Scotchmer, 1995). When agents suffer the burden of loss-aversion, a broad patent might represent a device to compensate the loss related to a path-breaking innovation. This result supports the robustness of traditional findings on the private gains - due to broad patents - as opposed to social losses: a stronger protection undermines the innovation disclosure and diffusion. The peculiarity of our setup, however, is that it provides an alternative interpretation of the broad patents cost (see Gallini, 1992), i.e. the cost of loss- aversion. It disappears if innovators' attitude is modified, for instance due to education or learning or experience: vagueness of uncertainty is reduced and then broad patents are no more necessary.

In brief, these are the main results of the analysis. When patent breadth is narrow, incentives to invest in breakthrough can be enhanced by extending patent length. However, uncertainty and loss aversion should be compensated by establishing a longer patent life in order to get the same level of utility in absence of uncertainty and loss aversion. Patent breadth and length both have positive effects for the earlier breakthrough innovator (the larger the patent breadth and the longer the patent life, the higher the utility), but these effects turn out to be opposite when evaluating the utility of the later incremental innovator (the narrower the patent breadth and the longer the patent life, the higher the utility). Therefore, a proper calibration should be used to mitigate monopoly losses.

This finding replicates the typical outcome of a drop in social welfare when a patent is strong, both in terms of breadth and length (see Gallini, 2002). The peculiarity of our result is that such a drop originates from the interaction of two forms of cognitive distortions, i.e. loss aversion and uncertainty aversion. Interestingly, this bias can be mitigated by reducing the level of vagueness that originates loss aversion: expert or educated entrepreneurs might be able to interpret complex and vague signals from highly volatile environments correctly. If patents are broad, incentives to invest in breakthrough innovations are stronger. A reduction in uncertainty, due to a less vague environment or to the innovator's ability and experience, might modify incentives such that narrow protection is equally favourable that a broad one.

Finally, patent breadth and length within industrialized countries patent law should be designed in order to account for further implications on low-wage countries, where a dramatic rise of incremental innovations is occurring and might represent a crucial source of growth.

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