Innovation and stock market performance: A model with ambiguity-averse agents

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Empirical evidence on stock prices shows that firms investing successfully in radical innovation experience higher stock returns. This paper provides a model that sheds light on the relationship between the degree of firm innovativeness and stock returns, the movements of which capture expectations on firm's profitability and growth. The model is grounding on Neo-Schumpeterian growth models and relies on the crucial assumption of radical innovation, characterized by "ambiguity" or Knightian uncertainty: due to its uniqueness and originality, no distribution of probability can be reasonably associated with radical innovation success or failure. Different preferences (α-maxmin, Choquet) are here compared. Results show that the assumption of ambiguity-aversion is crucial in determining higher returns in the presence of radical innovation and that the specific definition of expected utility shapes the extent of the returns. This result holds also in the case of endogenous innovation; risk attitude plays no role.

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1. Introduction

This paper focuses on the relationship between innovation and stock market returns, and investigates it through a model depicting innovation as an ambiguous decision. Firms that are more R&D intensive are characterized by a higher degree of idiosyncratic risk: the price of their stocks may decline due to an event that specifically affects the firm but not the market as a whole. The more radical the innovative process, the stronger the uncertainty of expected future profits: breakthrough innovation is characterized by Knightian uncertainty (Knight, 1921) or ambiguity, because no distribution of probability can be associated with the success of the investment in R&D. Investing in radical innovation creates both favourable expectations for its future growth and fears that the investment will lead to a "dry hole". Since people prefer to act on known rather than unknown or vague probabilities (Ellsberg, 1961; Epstein and Wang, 1994), models relying on the Bayesian paradigm (i.e. on the assumption that a probability measure can represent the likelihood of events adequately) are contradicted by evidence and unable to predict behavior in contexts where information is uncertain.

Insofar, scholars have explained a firm's innovative attitude with its dimension and/or the intensity of market competition (Mazzucato, 2006). However, investing in innovation strongly affects the firm's stock value: the entrepreneur who wants to push the value of his firm upwards should enhance the firm's chances of future success, and being innovative is the main way to reach this goal. As asset pricing is a function of the stochastic discount factor incorporating firm level risk, the revenues of highly innovative firms should be higher than that of non-innovative firms'.

Managers and business strategists seem to be well-aware of this relationship. For instance, Forbes publishes every year a list of the most innovative companies by calculating the "innovation premium" as the proportion of a company's market value that cannot be accounted for from the net present value of cash flows of its current products in its current markets: this is the "premium" the stock market gives a company because investors expect it to launch new offerings and enter new markets that will generate even bigger income streams. Furthermore, management and strategy consulting firms such as Booz & Company have consistently shown over the past years that there is no long-term correlation between the amount of money a company spends on its innovation efforts and its overall financial performance; instead, what matters is how companies use that money and other resources, as well as the quality of their talent, processes, and decision making, i.e. how it deals with uncertain outcomes.

Some previous works (Campbell and Shiller, 1988; Mazzucato and Semmler, 1999; Campbell, 2000; Mazzucato, 2003; Mazzucato and Tancioni, 2005; 2012) have emphasized the existence of a link between the degree of innovative disruptiveness and the volatility of stock returns at the firm level. So far, very few theoretical studies have been devoted to the relationship between innovation and stock returns. We introduce a model that summarizes the key mechanisms behind this link and that emphasizes the prominent role of ambiguity in affecting the decisions related to radical innovation and the consequences of agents' ambiguity-aversion. The model compares the α-maxmin preferences introduced by Ghirardato et al. (2004) to Choquet expected utility in Schmeidler (1989)'s formulation. We also show that smoother ambiguity-aversion *à la* Klibanoff et al. (2005) in this specific case falls into the limiting case of α-maxmin preferences.

In the model, the introduction of a disruptive innovation is captured by allowing the firm to use a radically new input the cost of which is sunk and the returns of which are ambiguous: the aim is to disentangle the economic forces determining the stochastic discount factor that represents the reward that investors demand for bearing ambiguity.

The results show that the more a firm is innovative, the higher the idiosyncratic ambiguity level and the higher the stochastic discount factor. Furthermore, while risk attitude plays no role, the specific form of ambiguity strongly shapes the results. Finally, introducing endogenous innovation does not affect the results.

2. Related literature

Radical breakthroughs are leading forces in driving long-run growth of modern economies. The "radical" and "incremental" labels belong mostly to the managerial literature and fail to offer univocal description of the difference between the two concepts (Battaggion and Grieco, 2009). Although the use of a strict dichotomy could be questionable, scholars agree on the fact that radical innovation has the potential to push the technological frontier of a firm or even sector and may allow a firm to enter new markets (Beck at al., 2016). Thus, a radical innovation is a product, process, or service that embodies a new technology that results in a new market infrastructure (Garcia and Calantone, 2002) offering "significant improvements in performance or cost that transform existing markets or create new ones" (Leifer et al. 2001).

This paper concentrates on the uncertain nature of radical innovations. A radical innovation is a unique event that cannot be interpreted within a group of instances or in the light of similar occurrences (Knight, 1921): thus, it can be considered a good example of "Knightian uncertainty" or "ambiguity" that may end up as a market revolution but also as a dramatic and costly failure. Foreseeing the probability of success on the basis of R&D expenditure levels is a task that "can only partially be addressed by past data" (Athanassoglou et al., 2012). Uncertainty derives from several factors, such as the type of processed knowledge (e.g. Dewar and Dutton, 1986; Henderson, 1993), the interaction between firm-specific capabilities and institutions (e.g. Nord and Tucker, 1987) in determining the outcome, the difficulty to anticipate consumers' reactions and to figure out the eventual opening up of a new market and consequent applications (e.g. Henderson and Clark, 1990; O'Connor, 1998). Decision makers are typically disturbed by ambiguous situations, and the empirical evidence shows pervasive ambiguity-aversion (e.g. Ellsberg, 1961; Sarin and Weber,1993; Chesson and Viscousi, 2003; Gilboa, 2004), although more recent works question that its occurrence is systematic and relate it to specific contexts (e.g. Trautmann et al., 2008; Butler et al., 2011).

As for radical innovations, in the asset price context decisions are affected by substantial uncertainty: the structure of the aggregate dividends process is vague for naïf investors but also for expert analysts who have the benefit of hindsight. Both the experimental and the market evidence (Camerer and Weber, 1992) shows that agents perceive ambiguity differently from risk. Therefore, the Bayesian approach needs to be extended, as in Epstein and Wang (1994): investors cannot estimate reliable probabilities of gains and make a good calculation of expected values. If we account for ambiguity attitudes, investing in radical innovation is not only a consequence of evaluations on performance and costs, but might be dramatically affected by cognitive burdens. Managerial enquiries testify that ambiguity-aversion, together with inertia and compartmentalized thinking, may constitute a learning barrier to the development of drastically new paths: firms tend to proceed as they always did, preserving the status quo rather than capitalizing on market information (Adams et al., 1998). Still, radical innovation occurs, and innovators with accumulated experience have been shown to be more efficient in searching and combining knowledge components (Fleming, 2001).

Interest in radical innovations is due not only to firm perspectives on profits and market share, but also to the importance in determining the dynamic of expected long-run growth. Stock prices reflect these expectations, in general based on fundamentals, but also affected by irrational exuberance, bandwagon phenomena, herd behaviours, and over-reactions. Mazzucato (2006) reviews the main results on the empirical relationship between innovation and the volatility of stock returns, and observes that "there is a missing link between the industrial economics literature on innovation and uncertainty and the finance literature on risk and the volatility of stock prices". There are, however, various studies that focus on the effect of innovation on the level of stock prices. Jovanovic and MacDonald (1994) relate the evolution of the average industry stock price level to the current stage of the industry life-cycle: they claim that the average stock price falls just before the shakeout occurs because a disruptive innovation causes a sudden drop in present product price, which is detrimental for incumbents. Jovanovic and Greenwood (1999) link stock prices to innovation in a model where innovation causes new capital to destroy old capital: since it is incumbents who are quoted on the stock market, innovations by new firms determine an immediate decline in the stock market because investors with perfect foresight anticipate this damage to old capital. Proxying innovative input with patents, Pakes (1985) shows that unexpected changes in patents and in R&D are associated with relevant changes in the market value of the firm, although in the presence of large variance that may reflect an extremely dispersed distribution of the values of patented ideas.

In general, the empirical evidence shows a relationship between stock prices and successful innovation having a positive impact on a firm's profits and growth, consistent with the idea that stock prices reflect expectations about discounted future profits. Furthermore, in phases characterized by radical innovation, firms that are seen as both probable winners and losers will experience volatility in their stock prices (Pastor and Veronesi, 2006). Uncertainty about a firm's average future profitability, which can be thought as uncertainty about the average future growth rate of a firm's book value, increases a firm's fundamental value (Pastor and Veronesi, 2003). This is because innovation often causes a shake-up of market shares, diminishing the power of the incumbents who have an incentive to preserve the status quo. In this situation, current performance is not a good indicator of future performance: investors are more likely to be influenced by the speculation of other investors, leading to high volatility (Campbell and Shiller, 1981).

3. The model

The model is grounded on Romer's (1994) and Aizenman's (1997) neo-Schumpeterian models of growth in their closed-economy version, enriched by assumptions on agents' ambiguity attitude. We consider two different specifications of preferences in the case of ambiguity: the former reflects Ghirardato et al. (2004)'s expected utility definition, the latter Choquet's (1955) one - in Schmeidler's (1989) formulation.

Neo-Schumpeterian models explicitly allow for an introduction into an economy of new or improved types of goods: their peculiarity consists of taking explicit account of the fixed costs that limit the set of goods and of showing that these fixed costs matter in a dynamic analysis conducted at the level of the economy as a whole. This contrasts with the standard approach in general equilibrium analysis, in which fixed costs are assumed to be of negligible importance in markets. Models of endogenous growth theory differ from the models in Romer (1986, 1987, 1990) and Lucas (1988), which emphasize external increasing returns, and from the models in Jones and Manuelli (1990) and Rebelo (1991), which are grounded on perfect competition and assume that capital can be accumulated forever without driving its marginal product to zero; both the external effects and perfect competition models of endogenous growth assume that new goods do not matter at the aggregate level. Furthermore, new growth models also depart from the literature on industrial organization because they do not capture explicitly the strategic interaction emerging when there is only a small number of firms in a market.

The crucial premise in 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 be used as a consumption good, or as an input in production. Here, the introduction of a new capital good represents an innovation.

The firm goes through two periods: in period *0*, it decides whether to innovate or not, and (if it is the case) sustains the sunk costs needed for a breakthrough innovation; in period *1*, production takes place. We consider an innovating firm that produces a final good Z by using labor L and N capital goods x_i according to the following production function:

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

with $0 < \beta < 1$. Labor's share of total income is $1 - \beta$ and, in the aggregate, the share of all capital goods is β. The equation follows the Dixit and Stiglitz's (1977) and Ethier's (1982) specification of constant elasticity aggregator of the capital goods x_i, with the elasticity of substitution among the various capital goods that is equal to $\frac{1}{1-\beta}$. The production of the generic capital good x_i takes place using the services of labor according to the function $x_i = L_i$ where L_i stands for the labor in activity *i* aimed at producing capital good x_i, while *L* is the labor employed in production of the final good. For simplicity, as standard in this literature *w* is the real wage and represents the marginal cost of producing both the capital goods and the final good.

Among the set of possible capital goods x_i, a new capital good x_n can be introduced either as a small improvement in the existing technology (incremental innovation) or as a disruptive opening up of a new technology (radical innovation). Because capital good x_n is a new kind of capital good that is not a perfect substitute for the existing ones (as, in general, all capital goods x_i are not perfect substitutes for each other), β must be different from 1. Following Romer (1994), we assume that the firm has property rights over the invention of capital good x_n, thus the firm can charge the simple monopoly price for the units of x_n used in the economy. The derived demand for x_n from a firm that produces *Z* according to the technology specified in (1) is:

$$p(x_n) = \beta L^{1-\beta} x_n^{\beta-1} \qquad (2)$$

where $p(x_n)$ is the price of capital good x_n. From this expression, it follows that, no matter what level of x_n the firm decides to supply, monopoly pricing let it capture only a fraction β of the increase in output that introducing x_n induces. For any selected level of x_n[1], output Z goes up by $L^{1-\beta}x_n^{\beta}$, but the firm gets only $p(x_n)x_n = \beta L^{1-\beta}x_n^{\beta}$. Denoting $p = \frac{w}{\beta}$, we can rewrite (2) as

$$(x_n)^d = \frac{1}{1-\beta}\frac{L}{p} \tag{3}$$

We assume the firm evaluates projects by applying a risk-free interest rate, denoted by r. Therefore, adding capital good x_n will lead to profits equal to

$$\pi_n(\chi) = \frac{\chi(\mathrm{p}-\mathrm{w})\mathrm{x_n}}{1+r} - n = \frac{\chi\,(\mathrm{w})^{-\frac{\beta}{1-\beta}}}{1+r}\frac{1-\beta}{\beta}\beta^{\frac{2}{1-\beta}}L - n = \frac{\chi\,\mathrm{W}}{1+r} - n \tag{4}$$

where $= \frac{1-\beta}{\beta}\beta^{\frac{2}{1-\beta}}$, $\beta' = \frac{\beta}{1-\beta}$ and $W = (\mathrm{w})^{-\beta'}\mathrm{kL}$.

3.1 Innovation with α-maxmin expected utility

The most familiar model of choice under uncertainty follows Savage (1954) in assuming that agents maximize expected utility according to subjective priors[2] (Subjective Expected Utility, henceforth SEU): agents are uncertain about payoffs, but there is no uncertainty about the model and the probabilities associated with each state of the world are known. This means that agents are not equipped to distinguish between risk (known probabilities) and ambiguity (unknown probabilities): agents who maximize SEU do not care about ambiguity.

[1] Demand for labor is omitted because we focus on demand for capital since innovation occurs through the introduction of a new capital good.

[2] The subjective expectations that agents formulate on probabilities are assumed to be "rational": the assumption of rationality *per se* does not specify the exact expectations that people hold but asserts that agents hold objectively correct expectations conditional on the information they possess (Manski, 2004). More on this in footnote 3.

As the empirical evidence strongly departs from this hypothesis (e.g. Knox, 2003; Guiso et al., 2008), we assume preferences that accounts for ambiguity-aversion. This section presents a specification of preferences that summarizes a broader spectrum of agents' behavior traits than SEU, i.e. Ghirardato et al. (2004)'s α-Maxmin Expected Utility (henceforth α-MEU). It represents an extension of Gilboa-Schmeidler or maximin approach (henceforth MEU, see Gilboa and Schmeidler, 1989). We will show below that SEU and MEU preferences are encompassed in the specification of α-Maxmin Expected Utility.

If the innovator were a SEU agent, she would assign a uniform distribution to the returns of innovation. The only information available is that the project return is bounded between $\underline{\boldsymbol{R}}$ and $\overline{\boldsymbol{R}}$, where $\underline{\boldsymbol{R}} < \overline{\boldsymbol{R}}$. The expression $\frac{\underline{\boldsymbol{R}}+\overline{\boldsymbol{R}}}{\mathbf{2}}$ represents the expected return of the investment in innovation, where the probability .assigned to the unsuccessful outcome $\underline{\boldsymbol{R}}$ is $\frac{\mathbf{1}}{\mathbf{2}}$: an ambiguity-neutral Bayesian agent will refer to this expression as the expected return.

The α-MEU innovator, on the contrary, bears the ambiguity of the returns of each state of the world. As emphasized by Ellsberg (1961), agents[3] are unable to summarize uncertainty in the form of a unique prior distribution. Therefore, they attach an extra cost to invest in a radical innovation that might be interpreted as an "ambiguity premium". The parameter α measures their ambiguity attitude on the set of logically possible priors: although agents typically exhibit ambiguity-aversion, α-MEU preferences account also for ambiguity-seeking behavior.

The introduction of a new capital good x_n by means of a radical 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*, as anticipated above. Adding capital good x_n requires a

[3] An expert agent might be capable to formulate subjective distributional probability also in highly uncertain environments (Cooke, 1991; O'Hagan et al., 2006), relying on sophisticated techniques such as, for instance, stochastic programming (e.g. Keppo and Zwaan, 2011) or the determination of the option value of an innovation (e.g. Siddiqui et al., 2007). However, in practice an expert can only make a finite number (and usually a rather small number) of statements of belief about a random variable (Garthwaite et al., 2005): even when familiar with probabilities and their meaning, experts might face difficulties in assessing a probability value for an event accurately.

sunk cost *n* specific to that good; the innovator commits to its investment at the beginning of period *0*, whereas production takes place in period *1*. Future revenues are uncertain due to the fact that the new technological trajectory may or may not be successful (and this is not known a priori). For simplicity, we normalize the random shock χ to be either low ($\chi = 1 - \delta$) or high ($\chi = 1 + \delta$), with $\delta \geq 0$[4]. SEU agents assume that the probability assigned to both the successful and unsuccessful outcomes ($\overline{R}$ and $\underline{R}$ respectively) is *1/2* and is independent of the degree of ambiguity about the innovation outcomes; for α-MEU agents the precise probability of each state is unknown and δ represents the range of possible outcomes of the random variable χ: the larger the range of values that future revenues might take, the larger the ambiguity level .

Incremental improvements in the existing technology are assumed to involve no ambiguity in the profitability of the technology: in this case, $\delta = 0$ and $\chi = 1$. Therefore, in the presence of incremental innovation, both SEU and α-MEU investors evaluate projects by applying the ambiguity-free interest rate *r* .

Investing in disruptive innovation, on the contrary, exposes the innovator to ambiguity.

The α-MEU innovator's decision rule can be depicted as to maximize an utility index that provides a proper weight for the exposure to ambiguity**.** The procedure we follow consists of constructing two statistics. The first is the "worst scenario" wealth, denoted by $\underline{\pi}$; the second is the "best scenario" outcome $\overline{\pi}$; α is the degree of α–maxmin ambiguity-aversion embodied in the decision to invest, with $0 \leq \alpha \leq 1$. The agent maximizes the following statistics:

$$U = \alpha\underline{\pi} + (1 - \alpha)\overline{\pi} \qquad (5)$$

[4]As emphasized in Einhorn and Hogarth (1982), in ambiguous situations people use an anchoring-and-adjustment strategy in which an initial probability is used as the anchor, and adjustments are made for ambiguity. This means that, for instance, receiving new information reduces ambiguity because reduces the range of possible outcomes without changing the anchor probability.

A larger α indicates higher ambiguity-aversion: when α goes to zero, we have the case of a ambiguity-seeking agent, who accounts for the best outcome only. When α equals 1, we have the case of extreme ambiguity-aversion (MEU preferences, please see below for a more detailed description). When α equals 1/2, we have the case of an agent who attributes a uniform prior to the two events, i.e. ambiguity-neutral Bayesian as in SEU preferences.

Investment in a disruptive innovation will be undertaken if it increases the expected utility:

$$\alpha\left[\frac{(1-\delta)W}{1+r}\right]+(1-\alpha)\left[\frac{(1+\delta)W}{1+r}\right]-n>0$$

that leads to $n<\frac{W}{1+\tilde{r}}$, where $(1+\tilde{r})=\frac{1+r}{1+\delta(1-2\alpha)}>1+r$.

Proposition 1. *An agent with α-MEU preferences evaluates projects by applying a SDF denoted by* $\tilde{r}$ *such that* $(1+\tilde{r})=\frac{1+r}{1+\delta(1-2\alpha)}$*. In presence of ambiguity-aversion, an innovative firm's SDF is higher than a conservative firm's SDF and investment in innovation occurs when the following condition holds:* $<\frac{W}{1+\tilde{r}}$.

The Stochastic Discount Factor (SDF) is a random variable the realization of which is always positive: it generalizes the notion of discount factor to an uncertain world. The immediate consequence of Proposition 1 is that the stocks of a firm investing in radical innovation promise higher returns than the stocks of a more conservative firm: this occurs in order to pay investors back for their capability to bear ambiguity with respect of investments that do not involve ambiguous outcomes. The assumption of α-maxmin preferences permits to distinguish between ambiguity and ambiguity-aversion: we define δ as the degree of vagueness, i.e. the amount of "objective" ambiguity on the possible values the random shock assumes; a further interpretation of δ can be in terms of volatility of stock returns (see the discussion below). On the other hand, the parameter α captures the "subjective" attitude towards ambiguity. The second interesting implication regards the effects on SDF of ambiguity and ambiguity-aversion. With α-MEU preferences, the SDF rises in ambiguity and in ambiguity-aversion: the more innovation is disruptive and "vague" in its returns, the higher the SDF; the higher the degree of ambiguity-aversion, the higher the SDF.

If there is no ambiguity (as in case of incremental innovation), or if investors are ambiguity-neutral, the SDF is just a constant *r* that converts future expected payoffs into present value. Thus, investment in a radical innovation will be undertaken if:

$$E_u(\pi) = \frac{W}{1+r} - n > 0 \tag{6}$$

that leads to $n < \frac{W}{1+r}$.

For SEU agents who do not care about the ambiguous returns of radical innovation, a new capital good is introduced only if its sunk cost is lower than the expected profit that must be discounted at a rate *r*: the same condition holds both when the introduction of capital good x_n is an improvement of the existing technology and when it opens a new technological trajectory.

Proposition 2. *With SEU preferences, the investor evaluates projects by applying an ambiguity-free SDF denoted by* $r < \tilde{r}$ *and invests in innovation when the following condition holds:* $n < \frac{W}{1+r}$.

Improving the existent technology and introducing a totally new one makes no difference from the SEU decision-maker point of view: stock returns have the same stochastic discount factor, no matter how conservative or disruptive is a firm's strategy. Since SUE preferences reflect the situation of an agent who is unable to distinguish between risk and ambiguity, the parameter δ is equal to *0* both in case of radical and incremental innovation.

On the other hand, MEU preferences represent the case of extreme ambiguity-aversion, where agents act as if they take a worst-case assessment of the utility deriving from innovation. The “worst scenario” is equal to the expected wealth multiplied by (1 - δ) because it only accounts for to the situation where the random shock hits the firm negatively. Equation (5) becomes $U = \alpha\underline{\pi} + (1 - \alpha)E_u(\pi)$. Thus, investment in a disruptive innovation will be undertaken if:

$$\alpha \frac{(1-\delta)W}{1+r} + (1-\alpha)\frac{W}{1+r} - n > 0$$

that leads to $n < \frac{W}{1+\bar{r}}$, where $(1+\bar{r}) = \frac{1+r}{1-\alpha\delta} > 1 + r$.

Proposition 3. *With MEU preferences, an innovative firm’s SDF is higher than a conservative firm’s SDF and is equal to* $(1+\bar{r}) = \frac{1+r}{1-\alpha\delta} > 1 + r$.

A typical critique to Gilboa and Schmeidler’s (1989) model is that it implies extreme ambiguity-aversion, or even “paranoia” (Epstein and Schneider, 2010). Klibanoff et al. (2005; 2009) present a model with smoother ambiguity where agents’ preferences are built such that the agent computes the certainty equivalent over all the possible state of nature and takes the minimum. The utility function can be solved in two stages: first, the expected utilities are calculated for all the priors in the corresponding set and a set of expected utilities is obtained. Second, the distorted expectation described above is taken by aggregating a transformation of these expected utilities with respect to the second order prior, i.e., the updated belief over the latent state. The transformation of the expected utilities captures the agent's ambiguity attitude; in particular, if the transformation is concave, then the agent is ambiguity-averse while if it is affine then the agent is ambiguity-neutral and simply maximizes a subjective expected utility. Since we assume utility to be a linear function of profits, ambiguity à la Klibanoff et al. (2005) falls into α-maxmin expected utility.

The following section describes an alternative form of smooth ambiguity attitude.

3.2 Innovation with Choquet expected utility

The following paragraph presents an alternative specification where ambiguity implies non-additive probabilities. Schmeidler's (1989) version of Choquet expected utility model differs from Savage's expected utility model in not necessarily assuming probability to be additive: agent's beliefs are represented by a unique but non-additive probability. Schmeidler refers to them as non-additive probabilities, and requires them to be positive and monotone with respect to set inclusion. Such mathematical entities are also known as "capacities": the capacity in the model can be interpreted as a lower bound on probabilities.

The agent maximizes the following statistics:

$$U = \frac{1}{2}\underline{\pi} + \left(\frac{1}{2} - \alpha\right)\overline{\pi} \qquad (7)$$

where α is the degree of pessimism or underconfidence in the assumed probability distribution. Consequently, $(1-\alpha)$ can be interpreted as the degree of confidence.

When α equals *0*, we have the case of ambiguity-neutrality, as in SEU preferences; when α equals ½, we have the case of extreme ambiguity-aversion of MEU preferences. In general, a larger α indicates higher ambiguity-aversion in the sense of lower confidence about the assigned probabilities, i.e. on the correctness of the model.

Investment in radical innovation will be undertaken if it increases the expected utility:

$$\frac{1}{2}\left[\frac{(1-\delta)W}{1+r}\right]+(\frac{1}{2}-\alpha)\quad\left[\frac{(1+\delta)W}{1+r}\right]-n\quad>0 \qquad (8)$$

that leads to $n<\frac{W}{1+\hat{r}}$ where $(1+\hat{r})=\frac{1+r}{1-\alpha(1+\delta)}$.

Having either ambiguity or ambiguity-aversion equal to zero leads to SEU preferences. It is the interaction between ambiguity and ambiguity-aversion that determines the SDF, but underconfidence in the model matters *per se*.

When $\alpha=1$ (extreme pessimism), the SDF is negative: an investor should be paid to invest, and we have the extreme case of no trading. In general, a positive discount factor and consequently trade are possible if $\delta<\frac{1}{\alpha}-1$, i.e. when the degree of ambiguity is not too large with respect to the amount of ambiguity that agents are able to tolerate.

In this framework, the impact of perceived ambiguity on the expected returns from innovation expresses the nature and intensity of the psychological bias revealed by decision makers under ambiguity that might be called α-ignorance.

Proposition 4. *With Choquet ambiguity-averse agents, an innovative firm's SDF is higher than a conservative firm's SDF; the lower the degree of confidence, the higher the SDF.*

The SDF increases in the degree of pessimism in the correctness of the model $(1-\alpha)$; in case of extreme optimism, the SDF turns to the SDF we get in the case of SEU preferences. Interestingly, in case of Choquet preferences, the SDF is higher than SDF with SEU preferences also in the presence of incremental innovation, i.e. with unambiguous investment.

The last proposition emphasizes two key findings: first, innovators who appear very confident in their knowledge of a new technology do not apply a hurdle rate when discounting objectively ambiguous profits. Second, when investors feel extremely optimistic in their knowledge of the model, there is no need of compensation for an ambiguous investments and there could be no difference in stock revenues of high innovative and conservative firms.

Some previous versions of Choquet expected utility involve distorting probability measures: if the distortion function is concave, then the least favorable events receive increased weight and the most favorable events are discounted, reflecting pessimism. Thus, instead of the uniform weighting implicit in the expected utility criterion and in this version of Choquet preferences, other models accentuate the weight of the least favourable events and reduce the weight assigned to the most favorable events or, alternatively, exaggerate the likelihood of the more favorable events and downplay the likelihood of the worst outcomes.

4. Effects of risk aversion

This section removes the assumption of the decision maker's risk neutrality and reconsiders the ambiguity models introduced above in this perspective.

Let $u \geq 0$ the utility function: we assume that u is C^2, $u' > 0$ and $u'' \leq 0$. It is straightforward to show that, with SEU preferences, the agent invests in innovation when $n < u\left(\frac{W}{1+r}\right) < \frac{W}{1+r}$, i.e., with respect to the case of risk neutrality, he needs to face a lower cost to decide to invest.

With α-MEU preferences, investment in a disruptive innovation will be undertaken if

$$\alpha[(1-\delta)\ u\left(\frac{W}{1+r}\right)] + (1-\alpha)[(1+\delta)u\left(\frac{W}{1+r}\right)] - n > 0$$

that leads to $n < \frac{W}{1+\tilde{r}'}$, where $(1+\tilde{r}') = \frac{1+r'}{1+\delta(1-2\alpha)} > 1+r'$.

With Choquet preferences, the agent invests if

$$\frac{1}{2}\left[(1-\delta)u\left(\frac{W}{1+r}\right)\right] + (\frac{1}{2}-\alpha)\left[(1+\delta)u\left(\frac{W}{1+r}\right)\right] \quad > 0$$

that leads to $n < \frac{W}{1+\hat{r}'}$ where $(1+\hat{r}') = \frac{1+r'}{1-\alpha(1+\delta)}$.

Proposition 5. *Propositions 1-4 hold for risk averse agents too, and risk attitude does not affect the agents' behaviour.*

This finding is in line with Dow and Werlang (1992a). They show that, in the case of Knightian uncertainty, there is an interval of prices within which the agent neither buy nor sell the asset: the interval is bounded by two reservation prices that depend only on the beliefs and on uncertainty aversion, and not on attitude toward risk. In a similar vein, Veronesi (2000) shows that, in the presence of noisy information signals on future dividends, the upper bound to the equity premium is not affected by risk aversion: this make the equity premium puzzle even more difficult to explain, since assuming a high degree of risk aversion is not enough to explain actual equity premia.

5. An extension: introducing endogenous innovation

In the previous sections we have left apart any description on how the capital goods x_n is produced. In this section, a Research & Development technology for inventing the new good is specified. Different ways of doing this are illustrated by Romer (1990), Rivera-Batiz and Romer (1991), and Grossman and Helpman (1991). Introducing an R&D sector allows us to account also for the fact that technological change is typically endogenous, in the sense that it arises from intentional investment decisions made by profit-maximizing agents, although the relationship between the amount of money a company spends on its innovation efforts and its performance is highly imperfect[5]. Final output Z is now expressed as a function of labor L, physical capital disaggregated into an finite number N of distinct types of capital goods x_i, and human capital H. In this

[5] Gambardella (1995) compares the "random search" phase with the "guided search" phase of the pharmaceutical industry, and provides some insight on why there may be less uncertainty associated with high innovation.

environment, a simple functional form for output is the following version of the Cobb-Douglas production function:

$$Z = H^{\gamma}(L)^{1-\beta}\sum_{i=1}^{N}(x_i)^{\beta-\gamma} \tag{9}$$

where γ represents the share of total income that is attributable to human capital (with $0 < \gamma < 1$ and $\beta > \gamma$). Once the firm R&D lab has produced a design for capital good x_n, it can obtain an infinitely lived patent on that design.

Demand for x_n is derived following the same steps shown in Section 3:

$$(x_n)^d = \left(\frac{\beta-\gamma}{p}\right)^{\frac{1}{1+\gamma-\beta}} H^{\frac{\gamma}{1+\gamma-\beta}} L^{\frac{1-\beta}{1+\gamma-\beta}} \tag{10}$$

Adding capital good x_n will lead to profits equal to

$$\pi_n(\chi) = \frac{\chi(\mathrm{p}-\mathrm{w})\mathrm{x_n}}{1+r} - n = \frac{\chi\,(\mathrm{w})^{-\frac{\gamma-\beta}{1+\gamma-\beta}}}{1+r}\frac{1-\beta}{\beta}\beta^{\frac{1}{1+\gamma-\beta}} H^{\frac{\gamma}{1+\gamma-\beta}} L^{\frac{1-\beta}{1+\gamma-\beta}} - n = \frac{\chi\,\bar{\bar{W}}}{1+r} - n \tag{11}$$

where $\bar{\bar{\mathrm{k}}} = \frac{1-\beta}{\beta}\beta^{\frac{1}{1+\gamma-\beta}}$, $\bar{\bar{\beta}}' = -\frac{\gamma-\beta}{1+\gamma-\beta}$, $\rho = \frac{\gamma}{1+\gamma-\beta}$ and $\bar{\bar{W}} = (\mathrm{w})^{-\bar{\bar{\beta}}'}\bar{\bar{\mathrm{k}}}\mathrm{H}^{\rho}\mathrm{L}^{1-\rho}$. Since $\frac{\partial\bar{\bar{W}}}{\partial H} > 0$, the SDF increases in H and in γ, suggesting that stronger effort in R&D and higher R&D productivity have a positive impact on stock returns. Furthermore, the specification of preferences does not affect this result, as in the case of exogenous innovation. In fact, propositions 1-4 hold with W replaced by $\bar{\bar{W}}$.

Proposition 6. *Propositions 1-4 hold for endogenous innovation too, and the endogeneity of* *innovation does not affect the agents' behavior*.

6. Comparison among ambiguity models

The sections above presented two alternative models of decision making that allow for non-neutral approaches to ambiguity. The question is now how should we select the model to work with when investigating the relationship between stock returns and firm innovativeness. As emphasized by Gilboa and Marinacci (2011), there are alternative approaches to this problem. First, one may compare the different models by a "horse-race": the model that best explains the observed phenomenon should be used for prediction. Alternatively, in the light of the theoretical difficulties in selecting a specific model, one may try to obtain general conclusions within a class of models, without committing to a particular theory of decision making. This approach has been suggested in the context of risk by Machina (1982). In his well-known paper, Machina has shown that, for some applications, economists need not worry about how people really make decisions, since a wide range of models are compatible with particular qualitative conclusions. A similar way of proceeding has been suggested for decisions under uncertainty. An example of this approach is the notion of biseparable preferences, as in Ghirardato and Marinacci (2002): biseparable preferences assume smoothness and monotonicity and include both α-maxmin and Choquet preferences. Ghirardato and Marinacci (2001) provide a definition of ambiguity-aversion that does not depend on the specific model of decision making and applies to all biseparable preferences. This allows for a general approach to preferences under ambiguity which, similarly to Machina (1982), remains silent regarding the actual structure of preferences, thereby offering a highly flexible model. In this perspective, α-maxmin preferences have been shown to be general enough to encompass both the case of ambiguity-neutrality and maximum ambiguity-aversion, and allow for an interpretation in terms of confidence in the decision model. Furthermore, they are compatible also with an ambiguity-seeking attitude: as summarized in Section 2, the empirical evidence shows that, in several situations and contexts, decision makers do seek ambiguity. In the case of disruptive firms, positive announcements on perspective profits, such as news on financial results and sales, might be interpreted as signals for success in radical innovation and cause investors to reduce ambiguity-aversion and increase the demand for stocks. When capturing stock price reactions, a Choquet Expected Utility has the advantage of accounting also for investors' inertia: in the case of extreme pessimism on own capability to understand how financial markets work, such as, for instanc,e in the worst moments of a financial crisis, no SDF, although high, is able to stimulate investment. Assuming α-maxmin preferences, on the contrary, emphasizes the agents' tendency to choose acts where they do not end up bearing ambiguity.

When discussing theoretical and empirical identification, another possibility is including second moments in the analysis: in ambiguous situations, subjective probability distributions will in general differ from actual distributions, and so the variance bound can be violated in a probabilistic sense, leading to excess volatility. The finance literature shows that there is a link between stock market returns and volatility, where more uncertain (i.e. more volatile) assets generally show the highest returns. The few studies that analyze stock price dynamics and innovation jointly relate the latter to the changes in the stock price level or in volatility of stock prices (e.g. Jovanovic and MacDonald, 1994; Schiller, 2000) and are mainly concerned with aggregate innovation dynamics. On the contrary, Mazzucato and Tancioni (2008) provide some firm-level evidence on the relation between the dynamics of uncertainty and innovation specific characteristics, and empirically establish a positive and contemporaneous relationship between idiosyncratic risk and innovation intensity, although without controlling for the disruptiveness of innovation. When agents' preferences satisfy Savage's (1954) axiom, it is natural to assume that they update according to Bayes rule: updating under uncertainty occurs under the Demspter-Shafer rule and implies higher volatility (Dow and Welang, 1992b). According to Cambell et al. (2000), high volatility is often associated with lower explanatory power of the market model for a typical stock and might be captured by the case of underconfidence in Choquet specification. Furthermore, with underconfident agents, Choquet preferences imply higher SDF than SEU preferences also in the absence of volatility: an interesting way of comparing the effectiveness of the two models could be testing whether SDF of innovative firms are higher than SDF of conservative firms in period of low volatility.

7. Discussion and conclusions

There is overall agreement that radical innovation is important (e.g. Leifer et al., 2001): consensus has emerged that conventional incremental improvements and cost reduction strategies are insufficient for obtaining a competitive advantage (Sorescu et al., 2003) as a direct consequence of worldwide diffusion of knowledge and industrial capability. Understanding radical innovation may eventually make their course shorter, less sporadic, less expensive. Furthermore, understanding radical innovation may shed light on stock market prices both in terms of level and volatility. The empirical evidence shows that firm innovativeness is positively related to firm value as measured by stock returns. This is due to the compensation that investors need to get when bearing the ambiguity involved in radical innovation. Ambiguity characterizes radical innovations as opposed to incremental innovations, where only measurable uncertainty is involved.

The paper presents a neo-Schumpeterian model that accounts for the introduction of new goods and captures the related sunk costs. The crucial hypotheses we introduce are that (a) radical innovation is an ambiguous decision, and (b) investors are ambiguity-averse. We suggest two possible ways of capturing ambiguity. The first, based on Ghirardato et al.'s (2004) approach, presents smooth ambiguity and allows for both ambiguity seeking and ambiguity-aversion behaviour too; the second, based on Schmeidler's (1989) version of Choquet's notion of capacity, interprets ambiguity-aversion as underconfidence on the correctness of the model the decision makers use to interpret the real world. Results are robust to differences in risk attitudes and to the introduction of endogenous innovation, and show that it is ambiguity-aversion that makes the difference between radical and incremental innovation so crucial: if agents were ambiguity-neutral, then radical innovation would not bring about higher stock prices than incremental innovation. In the presence of ambiguity, modelled as a larger set of possible priors, firms will be more willing to invest in incremental innovation rather than bet on investing on more disruptive ones, and investors should be compensated for their investment in stocks the returns of which are ambiguous. In a Subjective Expected Utility model, the firm's probability of being successful in introducing a radical innovation would be known, and the investor would switch, at a certain price, from demanding this firm's stocks to offering them. This is no longer the case when the probability of success is unknown. In this situation, in presence of ambiguity-averse investors, there will be an interval of prices at which neither buying nor selling will seem attractive, and an ambiguity-averse agent will choose to hold an unambiguous portfolio of stocks of a more conservative firm. In particular, an agent who is maximally ambiguity-averse will always choose to hold an unambiguous portfolio, no matter the relative prices of stocks. By contrast, an agent who maximizes expected utility with respect to a subjective prior will choose to hold equal quantities of two stocks only if the ratio of prices is equal to the ratio of subjective probabilities.

This may explain both why people refrain from trading in certain markets, and why entrepreneurs exhibit inertial behavior with respect of engaging in the exploration of new technologies. It can also explain why, at times of higher volatility, one may observe lower volumes of trade: with a larger set of probabilities that are considered possible, there will be more investors who decide neither to buy nor to sell.

Conflict of interest

The authors declares that she has no conflict of interest.

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