

R&D profitability: the role of risk and Knightian uncertainty

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Abstract This paper provides the first empirical attempt of linking firms' profits and investment in R&D revisiting Knight's (Risk, uncertainty and profit, Hart, Schaffner & Marx, Boston, 1921) distinction between uncertainty and risk. Along with the risky profit-maximising scenario, identifying a second, off-setting, unpredictable bias that leads to heterogeneous returns to R&D investments is crucial to fully understand the drivers of corporate profits. Consistently with the Knightian theory that relates risk to profitability, we model the impact of risk and uncertainty *on profits* and provide a first empirical attempt to model the effect of ambiguity, a particular type of uncertainty, *on R&D returns*.

Keywords R&D investment · Operating profits · Uncertainty · Ambiguity · Risk premium

Disclaimer The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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1 Introduction

The expected returns to R&D investment are typically subject to strong uncertainty. Innovations can be thought as unique events, and the process aimed at producing them (i.e. R&D investment) is an intrinsically uncertain economic activity.

In R&D intensive industries, market failures are a consequence of, among other reasons, uncertainty/risk and appropriability of a firm's results of its R&D efforts. Although the terms risk and uncertainty are often used interchangeably (Alvarez and Barney 2007), they have different meanings and cause different types of market failure. While uncertainty (the lack of information and predictability of outcomes) hinders the decision making, risk results in a reduction of the total R&D investment or in a shift to short-term projects, at the expenses of longer-term projects which could potentially have higher social return rates (Tassey 1997). This distinction becomes relevant in the field of entrepreneurship. Because uncertainty is at the base of the emergence of new opportunities, information and technological resources can be even more critical than financial ones in explaining entrepreneurial outcomes (Kuratko et al. 2015). Therefore, both from an entrepreneurial and innovation policy development perspective, it is key to understand and explain the separate effects that uncertainty and risk have on business outcomes.

Using the EU Industrial R&D Investment Scoreboard data on a sample of the top corporate R&D investors worldwide, this paper provides the first empirical attempt of linking firms' profits and investment in R&D revisiting Knight's (1921) distinction between uncertainty and risk. In particular, Knight used the word 'risk' to describe the "measurable uncertainty", where the possible outcomes are known and they can be classified in groups with assigned probabilities "either through calculation *a priori* or from statistics of past experience" (Knight 1921, p. 232). The 'true' uncertainty, on the other hand, applies to situations where no probability can be computed, as agents do not have the information necessary to assign a probability measure "because the situation dealt with is in a high degree unique" (Knight 1921, p. 233). For Knight, such uncertainty is the essence of entrepreneurial activity, without which there could be no profits in a (perfectly) competitive setting, since the probabilistically predictable extra margins profits would be eliminated (Noorderhaven 2003; Freytag and Thurik 2007).

Bronk (2011) named "ontological uncertainty" the implausibility to imagine a firm having a model of well-founded expectation of the additional benefits it may derive from future-generation products whose nature is not yet known. This type of uncertainty is emblematically associated with radical innovations that shift the parameters of the market. The future opportunities and risks are simply not known and learnt only at the times of discoveries. Standard models in economics assume that agents use probabilities to quantify types of uncertainty regardless of their source or nature. Specifically, the literature of economics of innovation on the returns to R&D investments either omits the uncertainty from the drivers of profitability (Hall et al. 2010; Coad and Rao 2010; Bogliacino and Pianta 2013) or it captures only the measurable uncertainty, i.e. risk (Dixit and Pindyck 2012; Bloom and Reenen 2002; Doraszelski and Jaumandreu 2013). Recently, Ghosal and Ye (2014) showed that uncertainty has a different impact on employment growth for firms of different size, with negative effects mainly found for smaller businesses.

With this paper, we contribute to the literature on corporate entrepreneurship (Ireland et al. 2009; Morris et al. 2011; Kuratko et al. 2015) by examining the returns to entrepreneurial investment such as R&D, and by exploring the effect of both risk and Knightian

or 'true' uncertainty. In particular, additional to the 'predictable' part of the uncertainty faced by the company, we consider what the economic analysis refers to as *ambiguity*. The notion of ambiguity derives from the interpretation of uncertainty as the lack of predictability due to the lack of sufficient information (think of the Schrödinger's cat hypothetical experiment; Schrödinger 1935) or to the complexity of information.

Our main contribution consists in testing some of the hypotheses that have been advanced by the theoretical literature on industrial and innovation economics. The first set of conjectures concerns the impact of risk and uncertainty *on profits*. The Shumpeterian theory relating risk to profitability assumes that entrepreneurs require a higher return for taking on more risk, a so-called "risk premium" (Tobin 1958). Using profit volatility as a measure of risk (Markowitz 1952; Hurdle 1974), we test whether its correlation with the profits is positive as predicted by the 'risk-premium hypothesis'. Concerning the impact of uncertain and ambiguous investment environment on profits, theoretical predictions point to a negative relationship. In fact, to cope with the highly unpredictable discovery process, firms tend to adopt a routinised behaviour when facing times of strong uncertainty and tend to lower their R&D effort. The lowered R&D effort may result in a lower innovation rate and, ultimately, in lower profits (Cozzi and Giordani 2011; Becker 2004; Dosi and Egidi 1991).

The second set of hypotheses regards the effect of risk and uncertainty *on R&D returns*. The hypothesis concerning the impact of risk on the returns to R&D follows the risk-bearing rationale (Chambers et al. 2002; Chan et al. 2001), i.e., the presence of risk yields to positive R&D returns. Additionally, using a proxy of ambiguity, we advocate the work of Chen and Epstein (2002) that shows how asset returns can be expressed as a sum of a risk premium and an ambiguity premium, i.e. the presence of both risk and ambiguity may lead to higher R&D returns than when ambiguity is not taken into account. Furthermore, similarly to Ghosal and Ye (2014), we verify whether the impact of risk varies across firm size.

In what follows, we test these assumptions and present evidence on the relation between R&D investment, risk and the uncertainty of future benefits from those investments. In the next Section, we discuss the difference between risk and uncertainty and briefly

review both theoretical and empirical literatures that have dealt with the relationship between uncertainty and R&D. Section 3 describes the data and the empirical methodology. Section 4 presents and discusses the results. Section 5 concludes.

2 Risk, uncertainty and ambiguity

In his famous dissertation “Risk, Uncertainty and Profit” (1921) Frank H. Knight made its central distinction between measurable risk and immeasurable uncertainty. Risk is a situation where it is possible to calculate the probabilities associated with a range of scenarios, while uncertainty is a situation where neither its probability distribution nor its mode of occurrence is known, because, for example, the situation is unique. Few years later, Keynes (1936) focused on forecast and valuation over the expected returns to investments and stated that they “cannot be uniquely correct, since our existing knowledge does not provide a sufficient basis for a calculated mathematical expectation”. Although the differentiation between risk and uncertainty has been somewhat overlooked by the neo-classical literature (Hodgson 2011), it may be crucial to understand the variability of profits. Bronk (2011) and Lane and Maxfield (2005) examined and discussed the nature and sources of immeasurable uncertainty. In particular, Bronk (2011) made the relevant distinction between ‘ontological’ and ‘epistemological’ uncertainty. Figure 1 reports an exemplification of the taxonomy of uncertainty, classifying various types of uncertainty according to

the knowledge of events or outcomes, and to the knowledge of the probability.

Ontological uncertainty refers to a situation where the nature of an event and its associated probability to happen are not known. This type of uncertainty “implies the impossibility of knowing even the categories and possible nature of what has yet to be created or yet to evolve” (Bronk 2011, p. 9). Very few studies investigated the impact that this sources of uncertainty have on R&D investment and innovation. One of the first economist to tackle the impact of this type of uncertainty on R&D and profitability is Sutton (2006), who offered a theoretical framework to address the fundamental difference between a probabilistic setting and one in which the firm faces a set of unique, unrepeatable circumstances. Sutton (2006) explored the relationship between firm’s investment in capabilities (e.g. know-how), profitability and survival using a model of Knightian uncertainty.¹ Sutton’s (2006) theoretical model predicts that, in a Knightian uncertain environment, investing in capabilities matters for the firm’s survival, but depending upon the costs of “mastering know-how”, it may or may not lead to higher profitability.

Epistemological uncertainty, or ambiguity, relates to a situation where things could be in principle known but they are not known in practice, due to the lack or the complexity of information that agents need to handle.² To make an example, the first time an

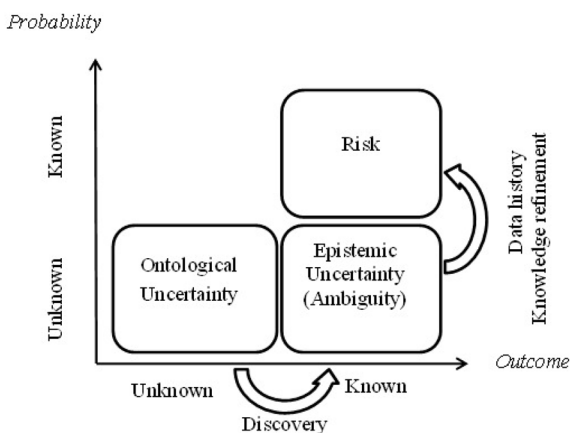


Fig. 1 Taxonomy of uncertainty. *Source:* Own construction

¹ Sutton’s (2006) modelling of Knightian uncertainty rests on the hypothesis of rational, profit-maximising firms facing an environment that cannot be described probabilistically. Subjective probabilities can be assigned to outcomes, but these cannot be updated.

² The term complexity can refer to the massive amount of information to which economic agents are exposed (market characteristics, technological information, etc.) and the unmanageable costs both in terms of money and time that would be necessary to collect and analyse the relevant data in order to make an optimal decision. The term complexity can also refer to the difficulty of making ex-ante predictions in dynamic non-linear systems. In fact, the economy is permanently in disruptive motion as agents explore, interact, learn, and adapt. These disruptions snowball into larger phenomena. One driver of disruption is technological change, and “a novel technology is not just a one-time disruption to equilibrium, it is a permanent ongoing generator and demander of further technologies that themselves generate and demand still further technologies” (Arthur 2009). This is a more technical definition of complexity that belongs to complexity economics literature. The interested reader is referred to Arthur (2009) for a review.

economy had undergone an economic crisis, the event was unknown and unpredictable. Once the economic crisis has been observed (see “Discovery” in Fig. 1), it is plausible to assume that there is going to be another one, but the data necessary to form a forecast and the complexity of factors influencing a future crisis render the event known but unpredictable.

Ellsberg (1961) introduced the notion of ‘ambiguity’ to refer to situations in which the likelihoods of events are too imprecise to be properly summarised by probabilities because the available information is incomplete and/or imperfect. The sensitivity towards uncertainty, i.e. ambiguity attitude, has been intensively investigated by the literature on decision under uncertainty (Gilboa and Schmeidler 1989; Gajdos et al. 2008). According to this strand of studies, when objective probabilities are not known, they can be replaced by subjective ones, so that problems of decision under uncertainty are reduced to simpler problems of decision under risk. The embodiment of subjective expected utilities theories in the empirical framework have found two channels (de Palma et al. 2008): experiments in the field of cumulative prospect theory (Tversky and Kahneman 1992) and random utility models (McFadden 2001) applied to discrete choice models. In this latter econometric literature (see Train 2003), the ambiguity enters in the form of a weighting function that scales the individual-specific utility functions by their perceptions and beliefs. These weighting functions take usually a parametric form, and the estimated parameters confirm that the perception of a risky event shape the weighting function (Loomes et al. 2002; Abdellaoui et al. 2011). Generally the results confirm the aversion of individuals towards ambiguity.

In the fields of economics of uncertainty and financial economics, many studies have reported evidence of anomalies in the returns to equity. The so-called “equity risk-premium puzzle” (ERP puzzle), or variance premium puzzle, is an observed anomaly for which the equity returns are excessive with respect to risk (Mehra and Prescott 1985). Studies on ambiguity aversion have tried to explain the ERP puzzle. The suggested hypothesis is that if ambiguity is present in decision-making process, the overall attitude towards risk may be accentuated, which will increase the ERP level (Chen and Epstein 2002; Bollerslev et al. 2009; Miao and Wang 2011).

The literature on R&D and real option valuation of R&D projects offers both theoretical and empirical predictions. Cozzi and Giordani (2011) incorporated the economic agents’ ambiguous beliefs about the innovative process in a neo-Schumpeterian growth framework. Their theoretical model predicts that when agents (e.g. companies) face “a complex and changing environment, a relatively high α (ambiguity aversion) embodies a cautious evaluation of profitable opportunities of investment, and gives rise to a persistently low R&D-effort behaviour, and viceversa” (Cozzi and Giordani 2011, p. 306). The authors alleged that the lowered investment in R&D could lead to lower profits. Their theoretical prediction helps to explain the evidence of the heterogeneous R&D efforts across countries due to different cultural/country-specific attitudes towards ambiguity, and the impact on the variability of profits. Dobbelaere et al. (2008) and Pennings and Sereno (2011) calculated the probability to start a R&D project and its option value, respectively, given the presence of ‘technical’ and economic uncertainty. In Dobbelaere et al. (2008), the authors showed, both theoretically and empirically, that when firms operate in favourable ‘technical’ (cost) uncertainty and market uncertainty conditions (i.e., a firm experiences an increase in demand or a decrease in the cost of R&D), an increase of market volatility increases the likelihood of undertaking R&D. The good and bad states of technical and market uncertainty are modelled as independent lotteries, and the firm does not have a priori knowledge on the outcome. Pennings and Sereno (2011), with a case study on one of the largest oncology-focused R&D companies in Europe, show that both types of uncertainty have a positive impact on the R&D option value. However, in their modelling framework, what they define as technological uncertainty, often interchanging the terminology, is the measurable risk of failure of pharmaceutical R&D projects at different stages of the project.³

Aside from the aforementioned few papers that discussed and empirically tackled the issue of ‘true’ uncertainty relative to R&D and profitability of

³ In Pennings and Sereno (2011), the risk of failure and abandoning the project is modelled as a function on the “arrival intensity of important information” (Pennings and Sereno 2011, p. 376) which is depending on the firm’s estimations of the probabilities of success of the previous stages.

R&D projects, most of the literature focused on the relation between measurable uncertainty (e.g. volatility, risk), and the returns to physical and intangible investments, such as R&D. The results across literatures are heterogenous. For example, Czarnitzki and Toole (2011) using the variance of the firms' revenues to proxy for the market volatility found that uncertainty about market returns significantly reduces firm-level R&D investment. Differently, the empirical finance literature (Chan et al. 2001; Chambers et al. 2002; Pastor and Pietro 2003; Vo 2013) reported evidence of higher returns to R&D investments when the investment scenario involves more risk and volatility. In particular, Chan et al. (2001) pointed at the mispricing rationale for this positive correlation between risk, R&D intensity and firms' profitability. The hypothesis of mispricing suggests that when R&D expenditure is high, investors tend to understate profits because it is recorded as an expense on the accounting balance sheets, and overstate the earnings when R&D is low. Thus, the value created by the R&D spending tends to be understated in the period in which it takes place, but results in higher future excess returns. Chambers et al. (2002), Pastor and Pietro (2003), and Vo (2013) tested both the hypotheses of mispricing and the risk-bearing hypothesis that R&D intensive firms will earn high returns as a consequence of a risk premium. In general, their empirical results suggest that the positive association between R&D levels and returns is mainly due to the compensation for bearing risk. They find that high R&D intensity companies (which generally have poor past returns) tend to earn larger excess returns (in excess of the risk-free returns). They also find R&D intensity to be positively associated with return volatility. Although these studies control for size, none of them explores if and how the impact of risk or uncertainty changes across firms of different size. A relevant exception is represented by Ghosal and Ye (2014), who find that the impact of uncertainty on employment growth is different for small and large businesses.

Taking stock of both the theoretical and the empirical work, we test some of the hypotheses advanced in these literatures concerning the role played by risk and ambiguity in business activities and explore differences between small and large businesses.

3 Empirical setting

In this section we propose an empirical framework to disentangle the impact of risk, firm-level and country-level ambiguity attitude on companies' profits and on investment returns. After a brief description of the dataset, we discuss the measure used to proxy ambiguity and the regression model.

3.1 Data

We estimate the corporate returns to R&D and to physical capital using a sample of firms contained in the EU Industrial R&D Investment Scoreboard.⁴ This is a scoreboard analysis of top corporate R&D investors worldwide, which the Institute of Prospective Technological Studies (Joint Research Centre, European Commission) has conducted annually since 2004. The dataset contains economic and financial data of the top 2000 world R&D investors and covers the 2004–2012 period. In particular, starting from top ranked companies for 2012, historical financial data are collected to analyse their trajectories along the time period considered. Data are collected from the companies' published accounts and refer to the ultimate parent company in the case of consolidated groups. The key variable of the EU R&D Scoreboard is the cash investment in R&D (as from international accounting standards) that the companies funded themselves, excluding those undertaken under contract for customers such as government or other companies. Given that the R&D figures refer to R&D expenditures of conglomerates, companies are likely to run different R&D projects. The observed R&D expenditure may refer to an unobserved number of projects at different stages of development. Therefore, with the available data we are likely to capture the average impact of risk and ambiguity rather than the specific impact at different project stages.

In addition to R&D, data on net sales, operating profit, capital expenditure, number of employees and market capitalisation are reported. The EU R&D Scoreboard economic data are nominal and expressed in Euros with all foreign currencies converted at the exchange rate of the year-end closing date (31 December). The country attributed to a given company

⁴ <http://iri.jrc.ec.europa.eu/>.

refers to the country where the headquarter is located. Although headquarters are concentrated in a relatively small set of countries, the subsidiaries of top corporate R&D investors are located in more than 200 economies, where the levels of risk and uncertainty may be different. However, corporate R&D performers seemingly concentrate the majority of their subsidiaries in the very same area where the headquarters are located (see Dernis et al. 2015; Tübke et al. 2015 for a focus on European based companies), where most of the R&D decisions are typically taken.

All the economic figures have been deflated using the GDP deflators published by the World Bank, and using 2004 as the reference year. For companies located in the Cayman Islands, we applied the World average deflator. In the case of companies based in Taiwan (Chinese Taipei), we used the “Implicit GDP Price Indices” taken from the OECD-MSTI database. The EU R&D Scoreboard covers nearly all the more important players in term of R&D investments in the World (especially in mid-high and high-tech sectors) and accounts for nearly 90 % of the total world corporate R&D expenditure (European Commission 2013).

3.2 Risk and uncertainty proxies

Among the approaches to deal with risk, we advocate that of Markowitz (1952) who used variance of losses as a risk measure. Similarly, in this paper, to obtain an idiosyncratic deviation risk measure, we take the standard deviation of operating profits

$$\text{risk}_i \equiv \sqrt{\frac{1}{T} \sum_{t=1}^T (\text{OP}_{it} - \overline{\text{OP}}_i)^2}.$$

In addition, we derive an indicator of market volatility of sector j at time t that takes into account time-varying factors influencing the specific type of business or sector in which a firm operates. To do so, we take the average first-differences of profits in industry j at time t ,

$$\Delta \text{risk}_{jt} \equiv \sqrt{\frac{1}{N} \sum_{i=1}^N (\text{OP}_{ijt} - \text{OP}_{ijt-1})}.$$

To proxy for uncertainty, we take a firm-level measure of ambiguity attitude. The indicator of ambiguity is constructed following the logic of info-gap decision theory (Ben-Haim 2006). The info-gap theory defines

as “severe” a type of uncertainty deriving from the information gap between an ‘estimate’ and a ‘possibility’. An info-gap model of uncertainty can be formulated as follows. Let $\tilde{r}(\text{R}\&\text{D}, \text{PhyCap}, \omega)$ denote the expected profits as a function of investment in R&D, physical capital and other quantities ω , such as human capital, managerial ability, industry diversification, macroeconomic shocks such as policy changes etc., based on the best available information. The actual profit function $r(\text{R}\&\text{D}, \text{PhyCap}, \omega)$ deviates in an unknown manner from the estimated model $\tilde{r}(\text{R}\&\text{D}, \text{PhyCap}, \omega)$. As we do not have information on the likelihood of the various alternative profit functions, a simple info-gap model can be formulated as the unbounded family of sets of all functions whose deviation from $\tilde{r}(\text{R}\&\text{D}, \text{PhyCap}, \omega)$ is not larger than a fixed value α :

$$\mathfrak{R}(\alpha, \tilde{r}) = \{r(\text{R}\&\text{D}, \text{PhyCap}, \omega) : |r(\text{R}\&\text{D}, \text{PhyCap}, \omega) - \tilde{r}(\text{R}\&\text{D}, \text{PhyCap}, \omega)| \leq \alpha\}, \alpha \geq 0 \tag{1}$$

The parameter α represents the epistemological uncertainty horizon. The larger the value of α , the greater the range of unknown variation. To retrieve an estimate of the functions whose deviation is nowhere greater than α , we use the following empirical interpretation of the info-gap model in (1) and define an *ambiguity parameter*, amb_{it} , as follows:

$$\text{amb}_{it} \equiv |\text{OP}_{it} - E(\text{OP}_{it} | \text{R}\&\text{D}_{it-1}, \text{PhyCap}_{it-1}, \omega_{it})|, \tag{2}$$

where we take the absolute deviation of the residual term of a regression that estimates the expected returns to R&D and to physical capital and other control variables ω_{it} . We assume that the set of functions deviating from the entrepreneur’s forecast model is bounded and corresponds to the forecast error, which includes both the expected ranges of favourable and unfavourable business scenarios. The ambiguity parameter also captures the individual attitude towards ambiguity, i.e. how the companies react to the self-assessed amb_{it} .

The number of factors influencing both profits and investments (physical capital and R&D) dynamics can be large, ranging from firm-level characteristics, such as the availability of human capital resources, or global industry diversification strategies, to sectoral and macroeconomic characteristics. With the

available data, we can only control for a limited set of such characteristics. In particular, the vector of control variables

$$\omega_{it} = (\gamma_i, \delta_t, \theta_i)$$

includes firm random effects, γ_i , to proxy for unobserved individual level characteristic, such as the corporate structure or the managerial ability, time dummies, δ_t , to approximate macroeconomic shocks common to all companies, and the volatility of the public opinion of a company’s net worth (market capitalisation), θ_i . This is defined as the firm-level standard deviation of market capitalisation normalised by the industry-level standard deviation, i.e. $\theta_i = \sigma_i(\text{MarketCap})/\sigma_j(\text{MarketCap})$, and it is meant to control for the variation in market specific factors which is not necessarily related to the company.

The variable θ_i is assumed to capture the shareholders’ incomplete information over the profitability of the company. In fact, according to the ERP puzzle rationale (observed returns on stocks higher than expected), θ_i may include also the subjective return expectations of the shareholders.

Ghosal and Ye (2014) use a similar methodology to proxy for the unsystematic, or unforeseeable component of GDP, inflation, fuel and stock market indexes evolution. In their paper, they use the squared error from a second-order autoregressive model to examine the impact of uncertainty on employment dynamics.

3.3 Empirical specification

In line with the literature on R&D returns, we examine the returns to physical capital and R&D investment when companies face a risky, uncertain, complex and dynamic environment. To assess the impact of risk and ambiguity on companies’ profits and profitability of R&D, we adopt a mediated linear regression model (Pearl 2001; Imai et al. 2010a, b). The theoretical predictions reviewed in Sect. 2 suggests that ambiguity may have both a direct impact on the firm profits, but also it can account for part of the relationship between R&D investment and operating profits (see Fig. 2). In this context, the aim of mediation analysis is to disentangle the average direct and indirect impact of ambiguity on operating profits. A simple way to obtain estimates of the causal path in Fig. 2 is to multiply the regression coefficients of two models (Sobel 1982).

The product of coefficients approach proposed by Sobel (1982) is constructed as follows:

$$M1 : \quad OP_{it} = \beta_0 + \beta_1 OP_{it-1} + \beta_2 \log(\text{R\&D})_{it-1} + \beta_3 \log(\text{PhyCap})_{it-1} + \gamma_1 \text{risk}_i + \gamma_2 \Delta \text{risk}_{jt} + \gamma_3 \text{amb}_{it} + \epsilon_{it}$$

$$M2 : \quad \text{amb}_{it} = \delta_0 + \delta_1 \log(\text{R\&D})_{it-1} + v_{it},$$

where OP are the operating profits arising from the sale/disposal of businesses or fixed assets, $\log(\text{R\&D})$ is the logarithm of the cash R&D investment founded by the companies themselves. The logarithm of physical capital, $\log(\text{PhyCap})$, is the (capitalised) expenditure used by a company to acquire or upgrade physical assets.

In the Sobel approach, the indirect effect is obtained by multiplying the partial regression effect of ambiguity at time t (amb_{it}) on OP, γ_3 , and the simple regression coefficient of the second model where the lagged R&D investment predicts the level of ambiguity, δ_1 . Therefore, the indirect effect is given by $\gamma_3 \delta_1$. Alternatively, to obtain the indirect effect of the change in ambiguity on profits, we plug in the estimated direct impact of R&D on ambiguity,

$$IE(\text{amb})_{it} = \hat{\delta}_1 \log(\text{R\&D})_{it-1},$$

in the first model (M1). The coefficient is obtained through a first-differences estimation, as there could be firm-level characteristics that are correlated.

Our profit estimation model for a company i at time t becomes

$$OP_{it} = \beta_0 + \beta_1 OP_{it-1} + \beta_2 \log(\text{R\&D})_{it-1} + \beta_3 \log(\text{PhyCap})_{it-1} + \gamma' x_{it} + \delta_t + \eta_j + \zeta^c + \epsilon_{it} \tag{3}$$

$$x'_{it} = (\text{risk}_i, \Delta \text{risk}_{jt}, \Delta \text{amb}_{it}, IE(\text{amb})_{it}).$$

where we control for both indirect effect of R&D mediated by ambiguity and for the direct impact of the change in ambiguity on operating profits. In fact, the vector x contains the measures of firm-level and

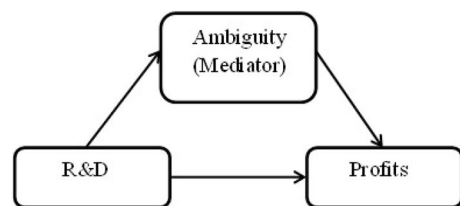


Fig. 2 Mediation model. Source: Own construction

industry-level risk, the first difference in firm-level ambiguity, Δamb_{it} , and the intermediate variable that measures the indirect contribution of ambiguity in explaining the impact of R&D on operating profits. The remainder term, $\delta_t + \eta_j + \zeta^c + \epsilon_{it}$, accounts for yearly, sectoral, country effects, and a measurement error, respectively. Despite Sect. 2 identified a number of channels through which ambiguity and risk may increase or reduce the profitability of R&D, the presented empirical set up has the ability to derive only their net effects.

Summary statistics of the variables used for the empirical analysis are presented in Table 1, where averages, medians, standard deviations and numbers of observation are shown. The dependent variable, the operating profits, OP, the investment in R&D, R&D, and the investment in physical capital, PhyCap, are expressed in Euro billion. The $\log(\text{R\&D})$ and $\log(\text{PhyCap})$ are the natural logarithms of these variables. All the variables expressed in levels are left-skewed.

Below the summary statistics, we also report the Pearson's correlation matrix to facilitate the understanding of the relationship between variables, without a priori

causation implication. Firm-specific risk, tangible and intangible investments (physical capital and R&D) and operating profits are correlated. However, only physical capital and R&D have a high correlation value (0.62). Also, the firm-level ambiguity indicator is negatively associated with the operating profits.

4 Results and discussion

Most of the literature in innovation economics focused on the relationship between firm performance and R&D adopting either a knowledge capital production function à la Griliches (1979) (Doraszelski and Jaumandreu 2013), or an accounting approach, where the focus is on the relationship between accounting-based performance measures and R&D investments (Lev 2000). Our paper adopts this latter approach, as we estimate Eq. (3) to quantify the impact of investment in intangible and tangible assets, risk and ambiguity on firm future profits, using financial data on the top world R&D investors contained in the EU R&D Scoreboard.

To alleviate potential endogeneity problems due to simultaneity of the decision to invest and profits, we take lagged control variables. The first differences of firm-level ambiguity are taken at time t , i.e. the same time in which the company observes its current level of profits. The estimation results of the mediated linear regression model are reported in Table 2, where results from six alternative specifications are displayed. We control for fixed industry effects, for macroeconomic shocks that might affect the firms in the sample, and for macro geographical region rather than for country effect, given the under-representation of some countries.

We find that the partial elasticities of tangible and intangible assets (physical capital and R&D, respectively) are all positive and we report the computed elasticities⁵ at the bottom of Table 2. The R&D elasticities vary from 0.023 (column 2) to 0.065 (column 1). It is hard to compare our results with those of Lev and Sougiannis (1996), Sougiannis (1994) or Lev (2000). Although we adopt the same methodology (earnings depend on tangible and non-tangible assets),

Table 1 Summary statistics

Variable	Mean	Median	SD	N	
OP_{it}	498.45	61.54	2021.46	23,946	
$R\&D_{it}$	166.03	29.85	570.70	22,909	
$\log(R\&D)_{it}$	10.49	10.30	1.54	22,909	
$PhyCap_{it}$	358.14	38.07	1349.50	20,346	
$\log(PhyCap)_{it}$	10.49	10.55	2.31	20,346	
$risk_i$	249.18	44.16	806.64	25,478	
$\Delta risk_{jt}$	0.42	12.31	378.57	22,764	
Δamb_{it}	4.98	10.51	825.34	14,072	
	1.	2.	3.	4.	5.

Correlation matrix					
1. OP	1.00				
2. $\log(\text{R\&D})$	0.34*	1.00			
3. $\log(\text{PhyCap})$	0.41*	0.62*	1.00		
4. $risk_i$	0.56*	0.39*	0.45*	1.00	
5. $\Delta risk_j$	0.08*	-0.01	-0.02*	-0.01	1.00
6. Δamb	-0.09*	0.01	0.01	0.01	-0.05*

* Correlation significant at the 0.01 %

⁵ The elasticities of R&D and physical capital are derived as $\frac{\partial \log(OP)}{\partial \log(R\&D)}$ and $\frac{\partial \log(OP)}{\partial \log(PhyCap)}$ respectively.

Table 2 Estimation results

Dep. var.: OP_{it}	(1)	(2)	(3)	(4)	(5)	(6)
OP_{it-1}	0.872*** (0.004)	0.802*** (0.005)	0.796*** (0.006)	0.806*** (0.005)	0.780*** (0.006)	0.780*** (0.006)
$\log(R\&D)_{it-1}$	36.222*** (6.889)	12.801* (6.836)	13.629* (7.511)	13.022* (7.653)	18.743** (9.018)	19.193** (9.495)
$\log(PhyCap)_{it-1}$	32.071*** (5.447)	19.067*** (5.379)	22.587*** (5.925)	19.121*** (5.882)	21.221*** (6.914)	21.633*** (7.152)
$risk_i$		0.335*** (0.014)				
$\Delta risk_{jt}$		0.863*** (0.023)	0.903*** (0.025)	0.820*** (0.026)	0.880*** (0.030)	0.871*** (0.031)
$risk_i \times Small^a$			0.129 (0.121)	0.291** (0.127)	0.141 (0.137)	0.120 (0.138)
$risk_i \times Medium^a$			0.114** (0.056)	0.401*** (0.043)	0.183*** (0.065)	0.186*** (0.066)
$risk_i \times Big^a$			0.340*** (0.014)	0.356*** (0.014)	0.391*** (0.016)	0.394*** (0.017)
Δamb_{it}				-0.319*** (0.009)	-0.331*** (0.010)	-0.336*** (0.010)
$IE(amb)_{it}$					1.238** (0.482)	1.149** (0.509)
UAI						-0.582 (0.588)
Time fixed effects	✓	✓	✓	✓	✓	✓
Industry fixed effects	✓	✓	✓	✓	✓	✓
Macro-regional fixed effects	✓	✓	✓	✓	✓	✓
Constant	-627.241*** (80.386)	-261.770*** (80.370)	-377.031*** (86.981)	-322.838*** (85.677)	-392.590*** (101.628)	-375.031*** (104.809)
Observations	17,004	17,004	15,611	14,042	11,242	10,896
R-squared	0.816	0.822	0.823	0.849	0.839	0.836
R&D elasticity	0.065*** (0.012)	0.023** (0.012)	0.024* (0.012)	0.022*** (0.022)	0.033*** (0.016)	0.036** (0.017)
PhyCapelasticity	0.058*** (0.010)	0.030*** (0.009)	0.037*** (0.010)	0.033*** (0.010)	0.038*** (0.012)	0.039*** (0.013)

Standard errors in parentheses *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

^a The reported coefficients are calculated as $\frac{\partial OP}{\partial risk_i}$. The specification includes the size dummies and their interactions with risk. The coefficients for the size dummies are not reported

Lev and Sougiannis (1996) deflate all the variables by annual sales, while we deflate using the GDP deflator. Moreover, they control for additional advertising expenses, and their sample is made of 2600 manufacturing companies in the period 1975–1991. For distinct reasons, comparing our results with the

literature measuring the returns to R&D can be misleading. In fact, Doraszelski and Jaumandreu (2006), adopting a production function approach, found that the coefficients vary between 0.017 and 0.075. The correspondence of our estimates to theirs is coincidental as Doraszelski and Jaumandreu (2006)

regressed the deflated revenue on a set of factor inputs (tangible, intangible assets, and labour). In general, our results partially confirm the findings of Hall et al. (2010) who reviewed many studies on the returns to R&D: we find that the private returns to R&D are strongly positive, but not “somewhat higher than those for ordinary capital”. In fact, we do not find any statistically significant difference between the two. In the first column, the assets elasticities are statistically significantly larger than in the other five columns ($p < 0.1$ or less). We believe that in the first specification the estimated coefficients are overestimated due to the lack of control for any degree of uncertainty. In this scenario, the econometrician assumes that a company is neither aware of risk nor of ambiguity, or simply ignores them, leading to an optimistic scenario of inflated tangible and intangible asset coefficients.

The specifications in columns 2 and 3 control for risk. In line with the risk-premium hypothesis, and as Chambers et al. (2002), Pennings and Sereno (2011), and Vo (2013) we find a positive effect of the risk on the earnings of companies. Both columns report positive coefficients for firm- and industry-level risk. Controlling for size gives further insights on the role of risk in firms' earnings. Larger companies are not only better placed to hedge against the risk of falling profits (e.g. by producing a wider range of products and/or operating in more markets), but they also enjoy a higher return to risk (34–38 % higher) than their medium or small counterparts (0.340 vs 0.114 or 0.129, respectively). In particular, the coefficient for smaller firms is not statistically different from zero.

This results somehow complement those of Ghosal and Ye (2014). Larger companies are not only better equipped to resist the negative impact of uncertainty on employment growth, but they also get higher returns in presence of risk. Furthermore, Montesor and Vezzani (2015) show that smaller companies get higher returns to R&D, because they benefit from more innovative R&D projects with high technical specialisation (Acs and Audretsch 1987). This suggests that further investigation on the interplay between R&D and size-premium (Reinganum 1981) is crucial for a better understanding of the entrepreneurial process.

Column 4 presents the estimated regression equations controlling for firm-level ambiguity change. The indicator of firm-level ambiguity change, point to a

negative ambiguity-profits relationship (-0.319). This result is in part explained by Cozzi and Giordani (2011) and Mazzucato and Tancioni (2013), whose theoretical studies suggested that the higher the ambiguity (and ambiguity aversion), the more cautious the evaluation of the expected R&D and innovation returns. This gives rise to two distinct effects. On the one hand, it decreases the profits as a consequence of a more “routinised” R&D investment behaviour which slows down the innovation process and, in turn, the profits of the firm. On the other hand, generalising the mispricing hypothesis advanced by Chan et al. (2001) to ambiguity, its presence might lead to higher returns to R&D. This is due to the fact that the value generated by R&D investment is even further understated by the shareholders in an ambiguous scenario, but results in higher future excess returns. To investigate this indirect effect of ambiguity on R&D returns, we control for the mediated impact of ambiguity as discussed in Sect. 3.3. Column 5 reports the full specification as in (3), where the indirect effect of ambiguity is calculated. The coefficient (1.238) measures the fraction of R&D returns due to ambiguity. The implied R&D elasticity of the marginal effect of $IE(amb)$ is 0.2 % (s.e. 0.0009). This means that 6 % (0.2/3.3 %) of the returns to R&D are due to ambiguity. In other words, our findings suggest the presence of two distinct mechanisms. On the one hand, ambiguity lowers the company's profits as a consequence of a more cautious innovative investment decision. On the other hand, when facing an ambiguous scenario, the R&D effort yields an additional premium to the investing companies. This provides the first empirical validation of the hypothesis that the observed disproportionate assets risk-premium (Chen and Epstein 2002) is deriving from the sum of a premium for risk and a separate premium for ambiguity (Mehra and Prescott 1985; Chen and Epstein 2002; Bollerslev et al. 2009; Miao and Wang 2011).

As a robustness check, in column 6 we also control for country-specific attitudes towards uncertainty. In particular, we include the Uncertainty Avoidance Indicator (UAI) developed by Hofstede (1980). The index measures the attitude of a society towards uncertainty and it is used as a measure of national uncertainty aversion.⁶ It was derived from a cross-

⁶ See Rapp et al. (2010) for a review of the studies that incorporated Hofstede's uncertainty avoidance construct.

country psychology survey of 88,000 IBM employees across more than 70 countries and constructed by considering three dimensions related to people's attitude towards uncertainty: rule orientation, employment stability, and stress.⁷ Although Hofstede claims national cultures to be extremely stable over time, a common critique to this measure of ambiguity is that the index might have lost relevance over the years. Nonetheless, the UAI has been used in some empirical applications in economics (Huang 2008; Cozzi and Giordani 2011) and in international business (see Rapp et al. 2010). The coefficient measuring the impact of country-specific ambiguity attitude (*UAI*) is not statistically significant; this could be due to the fact that it varies only across countries and not over time. Therefore, the inclusion of macro-regional fixed effects could already control for most of the country-specific ambiguity attitude. More important is the fact that the coefficients attached to the other variables remain statistically unchanged, confirming the robustness of our results. Particularly relevant from an innovation policy point of view is that the returns to R&D are higher in presence of ambiguity, but profits are lower, making firms more likely to be cash-constrained. Corporate investments in R&D and innovation have a number of characteristics that make it more difficult to finance, and this is particularly true for smaller, technology intensive firms operating in an environment characterised by uncertainty (Hall et al. 2016). Moreover, largest firms are also better placed to get higher return in presence of risk. Therefore, policies should not only target smaller firms to facilitate their access to finance, but should also help solving information asymmetries (especially in periods of high uncertainty), thus providing smaller companies with other critical resources for the entrepreneurial outcomes (Kuratko et al. 2015).

5 Conclusions

This paper proposes a first empirical framework to examine the returns to R&D investment when companies face a risky and ambiguous environment. We

⁷ The index ranges from a minimum of -150 to a maximum of $+230$, with higher UAI indicating higher national uncertainty aversion and relative scarcity of uncertainty-tolerant entrepreneurs, workers, and investors.

contribute to the literature on the returns to R&D stemming from the work of Schumpeter.

First, consistently with the Knightian theory that relates risk to profitability, we model the impact of risk and uncertainty *on profits*. We find a positive effect of risk on companies' earnings, in line with the so-called "risk-premium" hypothesis (Tobin 1958). Moreover, we show that the premium is increasing with the size of the company, suggesting that larger firms are not only better placed to hedge against the risk of falling profits, but they also enjoy a higher return to risk than their medium or small counterparts.

Second, we provide the first empirical attempt to model the effect of uncertainty *on R&D returns*. We advocate the theoretical predictions of ERP puzzle literature that shows how asset returns can be expressed as a sum of a risk premium and an ambiguity premium, i.e. the presence of both risk and ambiguity may lead to higher R&D returns. Taking stock of the info-gap theory (Ben-Haim 2006), we construct an indicator of firm-level ambiguity to assess the impact of risk and ambiguity on companies' profits and profitability of R&D. Ambiguity may have a direct impact on the firm profits, but it also can account for part of the relationship between R&D investment and operating profits. To take into account these direct and indirect (through R&D) effects, we adopt a mediated linear regression model (Pearl 2001; Imai et al. 2010a, b).

On the one hand, we find that ambiguity lowers the company's profits as a consequence of a more cautious innovative investment decision. On the other hand, when facing an ambiguous scenario, the R&D effort yields an additional premium to the investing companies. Thus, we confirm the hypothesis that the observed disproportionate assets risk-premium is deriving from the sum of a premium for risk and a separate premium for ambiguity. This ambiguity premium is mediated by the innovative effort of companies.

R&D investment is crucial when uncertainty and turbulence are high. In this context, R&D policies could be particularly effective by preventing firms to lower their R&D efforts (as a consequence of ambiguity) especially when returns to R&D are expected to be higher.

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References

- Abdellaoui, M., Baillon, A., Placido, L., & Wakker, P. P. (2011). The rich domain of uncertainty: Source functions and their experimental implementation. *American Economic Review*, *101*(2), 695–723.
- Acs, Z. J., & Audretsch, D. B. (1987). Innovation in large and small firms. *Economics Letters*, *23*(1), 109–112.
- Alvarez, S. A., & Barney, J. B. (2007). Discovery and creation: Alternative theories of entrepreneurial action. *Strategic Entrepreneurship Journal*, *1*(1–2), 11–26.
- Arthur, W. (2009). *The nature of technology: What it is and how it evolves*. Ujjain: Free Press.
- Becker, M. C. (2004). Organizational routines: A review of the literature. *Industrial and Corporate Change*, *13*(4), 643–678.
- Ben-Haim, Y. (2006). *Info-gap decision theory: Decisions under severe uncertainty*. Cambridge: Academic Press.
- Bloom, N., & Reenen, J. V. (2002). Patents, real options and firm performance. *The Economic Journal*, *112*(478), C97–C116.
- Bogliacino, F., & Pianta, M. (2013). Profits, R&D, and innovation—A model and a test. *Industrial and Corporate Change*, *22*(3), 649–678.
- Bollerslev, T., Tauchen, G., & Zhou, H. (2009). Expected stock returns and variance risk premia. *Review of Financial Studies*, *22*(11), 4463–4492.
- Bronk, R. (2011). Uncertainty, modelling monocultures and the financial crisis. *Business Economist*, *42*(2), 5.
- Chambers, D., Jennings, R., & Thompson, R. B. (2002). Excess returns to R&D-intensive firms. *Review of Accounting Studies*, *7*(2–3), 133–158.
- Chan, L. K., Lakonishok, J., & Sougiannis, T. (2001). The stock market valuation of research and development expenditures. *The Journal of Finance*, *56*(6), 2431–2456.
- Chen, Z., & Epstein, L. (2002). Ambiguity, risk, and asset returns in continuous time. *Econometrica*, *70*(4), 1403–1443.
- Coad, A., & Rao, R. (2010). Firm growth and R&D expenditure. *Economics of Innovation and New Technology*, *19*(2), 127–145.
- Cozzi, G., & Giordani, P. E. (2011). Ambiguity attitude, R&D investments and economic growth. *Journal of Evolutionary Economics*, *21*(2), 303–319.
- Czarnitzki, D., & Toole, A. A. (2011). Patent protection, market uncertainty, and R&D investment. *The Review of Economics and Statistics*, *93*(1), 147–159.
- de Palma, A., Ben-Akiva, M., Brownstone, D., Holt, C., Magnac, T., McFadden, D., et al. (2008). Risk, uncertainty and discrete choice models. *Marketing Letters*, *19*(3–4), 269–285.
- Dernis, H., Dosso, M., Hervás, F., Millot, V., Squicciarini, M., & Vezzani, A. (2015). World corporate top R&D investors: Innovation and IP bundles. A JRC and OECD common report. Luxembourg: Publications Office of the European Union.
- Dixit, A. K., & Pindyck, R. S. (2012). *Investment under uncertainty*. Princeton: Princeton University Press.
- Dobbelaere, S., Lutgens, R. I., & Peters, B. (2008). Starting an R&D project under uncertainty. DRUID Working Papers 08-09, DRUID. Copenhagen Business School, Department of Industrial Economics and Strategy/Aalborg University, Department of Business Studies.
- Doraszelski, U., & Jaumandreu, J. (2006). *R&D and productivity: The knowledge capital model revisited*. Cambridge, MA: Harvard University.
- Doraszelski, U., & Jaumandreu, J. (2013). R&D and productivity: Estimating endogenous productivity. *Review of Economic Studies*, *80*(4), 1338–1383.
- Dosi, G., & Egidi, M. (1991). Substantive and procedural uncertainty. *Journal of Evolutionary Economics*, *1*(2), 145–168.
- Ellsberg, D. (1961). Risk, ambiguity, and the savage axioms. *The Quarterly Journal of Economics*, *75*(4), 643–669.
- European Commission. (2013). The 2013 EU industrial R&D investment scoreboard.
- Freytag, A., & Thurik, R. (2007). Entrepreneurship and its determinants in a cross-country setting. *Journal of Evolutionary Economics*, *17*(2), 117–131.
- Gajdos, T., Tallon, J.-M., & Vergnaud, J.-C. (2008). Representation and aggregation of preferences under uncertainty. *Journal of Economic Theory*, *141*(1), 68–99.
- Ghosal, V., & Ye, Y. (2014). Uncertainty and the employment dynamics of small and large businesses. *Small Business Economics*, *44*(3), 529–558.
- Gilboa, I., & Schmeidler, D. (1989). Maxmin expected utility with non-unique prior. *Journal of Mathematical Economics*, *18*(2), 141–153.
- Griliches, Z. (1979). Issues in assessing the contribution of research and development to productivity growth. *The Bell Journal of Economics*, *10*(1), 92–116.
- Hall, B. H., Mairesse, J., & Mohnen, P. (2010). Measuring the returns to R&D. Working Paper 15622, National Bureau of Economic Research.
- Hall, B. H., Moncada-Paternò-Castello, P., Montresor, S., & Vezzani, A. (2016). Financing constraints, R&D investments and innovative performances: New empirical evidence at the firm level for Europe. *Economics of Innovation and New Technology*, *25*(3), 183–196.
- Hodgson, G. (2011). The eclipse of the uncertainty concept in mainstream economics. *Journal of Economic Issues*, *45*(1), 159–175. Original article can be found at <http://mesharpe.metapress.com/> Copyright Newfound Press.
- Hofstede, G. (1980). Culture and organizations. *International Studies of Management & Organization*, *10*(4), 15–41.

- Huang, R. R. (2008). Tolerance for uncertainty and the growth of informationally opaque industries. *Journal of Development Economics*, 87(2), 333–353.
- Hurdle, G. J. (1974). Leverage, risk, market structure and profitability. *The Review of Economics and Statistics*, 56(4), 478–85.
- Imai, K., Keele, L., & Tingley, D. (2010a). A general approach to causal mediation analysis. *Psychological Methods*, 15(4), 309–34.
- Imai, K., Keele, L., & Yamamoto, T. (2010b). Identification, inference and sensitivity analysis for causal mediation effects. *Statistical Science*, 51–71.
- Ireland, R. D., Covin, J. G., & Kuratko, D. F. (2009). Conceptualizing corporate entrepreneurship strategy. *Entrepreneurship Theory and Practice*, 33(1), 19–46.
- Keynes, J. M. (1936). *The general theory of interest, employment and money* (Vol. 156). London: Macmillan.
- Knight, F. (1921). *Risk, uncertainty and profit*. Boston, MA: Hart, Schaffner & Marx.
- Kuratko, D. F., Morris, M. H., & Schindehutte, M. (2015). Understanding the dynamics of entrepreneurship through framework approaches. *Small Business Economics*, 45(1), 1–13.
- Lane, D. A., & Maxfield, R. R. (2005). Ontological uncertainty and innovation. *Journal of Evolutionary Economics*, 15(1), 3–50.
- Lev, B. (2000). *Intangibles: Management, measurement, and reporting*. Washington: Brookings Institution Press.
- Lev, B., & Sougiannis, T. (1996). The capitalization, amortization, and value-relevance of R&D. *Journal of Accounting and Economics*, 21(1), 107–138.
- Loomes, G., Moffatt, P. G., & Sugden, R. (2002). A microeconomic test of alternative stochastic theories of risky choice. *Journal of Risk and Uncertainty*, 24(2), 103–130.
- Markowitz, H. (1952). Portfolio selection*. *The Journal of Finance*, 7(1), 77–91.
- Mazzucato, M., & Tancioni, M. (2013). R&D, patents and stock return volatility. In A. Pyka & E. S. Andersen (Eds.), *Long term economic development, economic complexity and evolution* (pp. 341–362). Berlin: Springer.
- McFadden, D. (2001). Economic choices. *American Economic Review*, 91(3), 351–378.
- Mehra, R., & Prescott, E. C. (1985). The equity premium: A puzzle. *Journal of Monetary Economics*, 15(2), 145–161.
- Miao, J., & Wang, N. (2011). Risk, uncertainty, and option exercise. *Journal of Economic Dynamics and Control*, 35(4), 442–461.
- Montresor, S., & Vezzani, A. (2015). The production function of top R&D investors: Accounting for size and sector heterogeneity with quantile estimations. *Research Policy*, 44(2), 381–393.
- Morris, M., Kuratko, D., & Covin, J. (2011). *Corporate entrepreneurship & innovation*. Boston: Cengage Learning.
- Noorderhaven, N. (2003). Uncertainty avoidance and the rate of business ownership across 21 oecd countries, 1976–2004. *Journal of Evolutionary Economics*, 17(2), 133–160.
- Pastor, L., & Pietro, V. (2003). Stock valuation and learning about profitability. *The Journal of Finance*, 58(5), 1749–1790.
- Pearl, J. (2001). Direct and indirect effects. In Proceedings of the seventeenth conference on uncertainty in artificial intelligence (pp. 411–420) San Francisco, CA: Morgan Kaufmann Publishers Inc.
- Pennings, E., & Sereno, L. (2011). Evaluating pharmaceutical R&D under technical and economic uncertainty. *European Journal of Operational Research*, 212(2), 374–385.
- Rapp, J. K., Bernardi, R. A., & Bosco, S. M. (2010). Examining the use of Hofstede’s uncertainty avoidance construct in international research: A 25-year review. *International Business Research*, 4(1), 3.
- Reinganum, M. R. (1981). Misspecification of capital asset pricing: Empirical anomalies based on earnings’ yields and market values. *Journal of Financial Economics*, 9(1), 19–46.
- Schrödinger, E. (1935). Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften*, 23(49), 823–828.
- Sobel, M. E. (1982). Asymptotic confidence intervals for indirect effects in structural equation models. *Sociological Methodology*, 13(1982), 290–312.
- Sougiannis, T. (1994). The accounting based valuation of corporate R&D. *Accounting review*, 69(1), 44–68.
- Sutton, J. (2006). Flexibility, profitability and survival in an (objective) model of knightian uncertainty. Technical report, Working paper, London School of Economics.
- Tassey, G. (1997). *The economics of R&D policy*. Westport: Greenwood Publishing Group.
- Tobin, J. (1958). Liquidity preference as behavior towards risk. *The Review of Economic Studies*, 25(2), 65–86.
- Train, K. (2003). *Discrete Choice methods with simulation*. Online economics textbooks. SUNY-Oswego, Department of Economics.
- Tübke, A., Hervás, F., Grassano, N., & Gkotsis, P. (2015). *The 2015 EU survey on industrial R&D investment trends*. Technical report, Institute for Prospective and Technological Studies, Joint Research Centre.
- Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and uncertainty*, 5(4), 297–323.
- Vo, L. V. (2013). R&D investments, profitability uncertainty and firm’s valuation. SSRN 2287593.