Technology Switch Option and the Market Value of the Firm: A Model and an Empirical Test

Raffaele Oriani
Department of Management - CIEG
University of Bologna
Via Saragozza, 8, 40123, Bologna, ITALY
Tel.: +39 0512093956 – Fax: +390512093949
E mail: raffaele.oriani@mail.ing.unibo.it

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ABSTRACT

A correct assessment of the innovation activities is critical to firm performance. To this purpose, some authors have analyzed the relationship between innovation and firm's market value within a framework based on the *real options theory*. However, in these papers there is not an explicit modeling of the 'real options'. Our model of market value formally includes a *technology switch option*, which allows the firm to exchange one technology with another when it achieves a major innovation. The model also accounts for the stochastic nature of the innovation. We test the model on a panel of publicly traded British firms operating in different manufacturing industries. The results provide support to the claim that the stock market recognizes and evaluates a technology switch option.

Introduction

Different actors within the economic system need nowadays more accurate methods to assess the value of the firm's intangible assets (Lev, 2001). In particular, the evaluation of innovation-related activities is critical to firm's performance and even survival. However, assessing and financing R&D investments pose still several specific and unresolved questions (Hall, 2002). A stream of empirical studies has addressed these problems analyzing the relationship between different measures of technological knowledge and the market value of the firm (see Hall, 1999, for a review). Although this issue has been extensively investigated, the empirical and theoretical debate on the factors affecting the market valuation of R&D investments and other innovation-related assets is still open (Hall, 1999; Oriani and Sobrero, 2003). Moreover, the discussion on short-termism has been recently nurtured by empirical studies suggesting the existence of a systematic underestimation of firms' R&D investments by the stock market (Lev and Sougiannis, 1996; Chan et al., 1999).

In response to these questions, some authors have tried to re-analyze the relationship between innovation and market value within a different framework based on the emerging issues of the *real options theory* (Bloom and Van Reenen, 2002; Oriani and Sobrero, 2002). However, in these papers there is not an explicit modeling of the options embedded in the firm's capital of technological knowledge. On the other side, several authors have tried to model with increasing sophistication the management of R&D programs within a real options perspective (Grenadier and Weiss, 1997; Childs and Triantis, 1999; Weeds, 2002). While providing interesting insights on the timing of R&D investment or innovation adoption and value maximization in R&D portfolio decisions, these works have not produced empirically testable models, mainly because of their complexity. Indeed, we are still lacking an empirical validation of evaluation models based on real options theory, with the exception of very specific fields, such as petroleum leases (Paddock et al., 1988) or real estate contracts (Quigg, 1993). This shortcoming is mainly due to the difficulty of defining reliable option valuation parameters being able to reflect the complexity of the 'real' investment domain (Copeland and Keenan, 1998; Lander and Pinches, 1998; Luehrman, 1998; Fernandez, 2001).

The aim of this paper is then to move towards a reconciliation of theoretical and empirical works on R&D investments and real options through the formulation and the test of a model of the firm's market value in which a real option is explicitly formalized and evaluated. In particular, in our model the market value of the firm embeds a *technology switch option*, which is the option to exchange one technology with another when the firm achieves a major process or product innovation. In order to evaluate this option, we referred to the models already available in the financial literature. The switch option has been originally defined and evaluated for financial assets by Margrabe (1978), extended by Carr (1988, 1995) and recently applied to R&D valuation by Lee and Paxson (2001).

The model also accounts for the stochastic nature of the innovation at the firm level, following previous contributions on R&D competition (see Reinganum, 1989, for a review). This literature, which is primarily game theoretic in nature, has modeled a stochastic innovation race among firms, providing interesting results on the timing of innovation, the patterns of R&D investments and the identity of the innovator, but the scarcity of empirical data has left these insights relatively untested, with the exception of the work of Cockburn and Henderson (1994).

We test our model on a panel of publicly traded British firms operating in different manufacturing industries. We gathered data from analyst estimates and patent databases in order to define the the parameters needed for the valuation of the technology switch option. The results show that the financial market positively evaluates the technology switch option held by a firm and recognizes that firm-specific R&D investment increases the likelihood to innovate. Moreover, the regression fit notably improves when the technology switch option is included in the analysis, suggesting that the model built and tested in this paper better explains the factors affecting a firm's market value.

In this paper we offer several contributions to previous literature and practitioners. First, we build a model of the firm's market value explicitly including a real option, which is accurately defined and evaluated. Second, we provide support for the claim that the market valuation reflects the value of an option created by the firm trough its R&D activity. Third, we use data from different sources to estimate the parameters for the option valuation formula. Fourth, we validate a valuation tool for R&D investments that can find useful applications inside and outside corporate boundaries.

The rest of the paper is organized as follows. In the next section, the theoretical and empirical works on technology and real options, with a focus on the switch option, will be reviewed. In section 3, the model to be tested will be defined moving from the existing literature on innovation and market value and building on the main contributions on financial and real options, whereas in section 4 the variables, the option valuation model and the option parameters will be described in detail. In section 5 the results of the empirical analysis will be presented and in the final section the main conclusions reached in the paper and the most significant implications for practitioners will be discussed.

Technology investments, real options and firm's value

The effect of technological innovation on firm performance is hardly predictable, mainly because it is affected by a high degree of uncertainty related to both the technical success of the R&D projects and the evolution of market demand and technology within the industry. The application of valuation methods based on discounted cash flows, assuming investors' risk-aversion and the non changeability of the firms' actions once planned, normally fails to fully capture the economic effects of technological innovation and can push the management towards a general preference for the short term (Kogut and Kulatilaka, 1994). Indeed, an emerging group of scholars has proposed a new theoretical framework to analyze the economic value of technological innovation based on the theory of *real options*, which builds on the analogy between financial options and investment opportunities in the 'real' world (Trigeorgis, 1996). In this respect, "to a much greater extent than rival techniques, real options can help companies make their way through the maze of technological and market uncertainties that face them when they make their decisions" (Copeland and Keenan, 1998: 141).

The idea that investments in technology create opportunities that are analogous to the options traded in the financial markets has been widely accepted by the literature on the management of innovation (e.g. McGrath, 1997; Huchzermeier and Loch, 2001) and the financial management of R&D investments (e.g. Boer, 2002). Several models have also been elaborated for the valuation of R&D projects (Perlitz et al., 1999; Schwartz and Moon, 2000) and patents (Pitkethly, 1999) and the management of R&D portfolios (Childs and Triantis, 1999; Benaroch, 2001; Lint and Pennings, 2001) within a real options framework. Explicit modeling of R&D investments as sequential options is found in Lee and Paxson (2001). All these studies explicitly or implicitly build on the basic assumption that research programs are structured in a series of sequential steps and can be revised at the end of each step conditional on the information gathered and the results achieved up to that moment (Dixit and Pindyck, 1994).

However, although recent theoretical contributions in real options have reached a significant level of complication and sophistication in modeling several features of technology investments (e.g. Grenadier and Weiss, 1997; Childs and Triantis, 1999), we are still lacking a strong empirical validation confirming the ability of the option-based models to assess the value of technological assets and, in the end, the value of the firm. A pioneering empirical study on patent and real options has been realized by Pakes (1986). The author used data on patent renewals in conjunction with an option-based model of patent holders' decisions to estimate patent returns. More recently, Ziedonis (2002) analyzed firms' decisions to acquire commercialization rights for University technologies within a real options framework. Yet, these studies do not relate real options to the overall firm performance.

Other authors referring to the vast body of literature on innovation and market value (Hall, 1999) tried to test the presence of an option-based logic in the stock market valuation of technology. Oriani and Sobrero (2002) adopted a real options 'lens' to analyze whether market and technological uncertainty affected the stock market valuation of firms' R&D investments. Consistently with the predictions of the real options framework, they showed a positive impact of technological uncertainty, whereas market uncertainty had a more ambiguous effect. Bloom and Van Reenen (2002), building on the previous analysis of Hall et al. (2000), showed that patents positively reflect into the market value of the firm, but market uncertainty reduces the effect of patents on productivity because firms keep the waiting option alive and do not embed new technologies in product and processes. Indeed, even adopting a real options logic, none of these studies tested an analytic model of the option value.

We could then gain new insights from a model of the firm's market value explicitly including and evaluating a 'real option'. Some recent contributions in the management field have advanced that firm's R&D activity generates new technological assets that can be placed 'on the shelves' waiting for new information on market and technology evolution (Garud and Nayyar, 1994). Miller (2002) focused on the management of knowledge inventories, which involves acquiring, deploying, idling, and abandoning technologies over time. In this perspective, "the willingness of firms to invest in idle technologies reflects their interest in maintaining flexibility to switch technologies in the future" (Miller, 2002: 690). Thus, technological assets can be considered analogous to 'options' allowing the firm to switch to an emerging technology in the future and representing hedges against technological uncertainty (McGrath, 1997). Consistently with this interpretation, Hatfield et al. (2001) showed that technology hedging is more likely in the period of technological ferment preceding the emergence of a dominant design, but also in this case an empirical validation of a closed form of switch option was not provided.

Building on these arguments, we advance that firms investing in R&D hold an option to switch to a new alternative technology in the future if this proves to offer higher expected returns in the new competitive environment. The exercise of this option is conditioned upon the achievement of a major product or process innovation randomly originating from the firm's R&D activity. This situation is analogous to the switch option originally defined for the financial assets (Margrabe, 1978), which is the option to exchange one financial asset with another. Accordingly, we will formulate and test a model of firm value in which a *technology switch option* is formalized and evaluated according to the contributions on the valuation of the options to exchange one asset with another.

The model

Previous models of the market value of the firm (e.g. Griliches, 1981; Hall, 1993a, 1993b) did not address two significant aspects of the relationship between technology and corporate value: the stochastic nature of the innovation and the discretional, option-like nature of the firm's decision to adopt it. Building on the emerging issues of the real options theory, the aim of the model formulated in this paper is to *include the value of the potential benefits from future stochastic innovations into the firm's market value equation*. To this purpose, we make two main assumptions. First, the value of the firm has two different components: one is deterministic and consists of the present value of the expected cash flows conditional on all the available information, whereas the other is represented by the potential benefits from future unpredictable innovation and can be modeled as an option. This approach is consistent with the seminal work of Myers (1977) and the more recent contributions of Berger et al. (1996), Berk et al. (1999) and Jagle (1999). Second, innovation has a stochastic nature and the time of its occurrence has an observable probability function, as in previous studies modeling R&D races (e.g. Loury, 1979; Lee and Wilde, 1980; Reinganum, 1983).

Traditional literature in financial economics has argued that the value of a firm at time 0 should be equal in perfectly competitive markets to the present value of its expected cash flows conditional on the set of available information at time 0 (Fama and Jensen, 1985). Assuming that the present value of expected cash flows of firm *i* at time 0, $s_{i,0}$, is a function of its tangible assets ($A_{i,0}$) and technological knowledge capital ($K_{i,0}$) at time 0, we can express the market value of the firm i at time 0 ($V_{i,0}$) as follows[1]:

$$V_{i,0} = s_{i,0} = f\left[\varphi\left(A_{i,0}, K_{i,0}\right)\right] \tag{1}$$

[1] The underlying assumption is that in the future the firm will continue to invest in *A* and *K* according to the rule of optimal profit maximization (see Hall, 1993b, Appendix A, for a formal description).

where $\varphi(A_{i,0},K_{i,0})$ is the capital aggregator function. If we choose a linear functional form for the capital aggregator, as in Hall (1993b), the [1] becomes:

$$V_{i,0} = b\left(A_{i,0} + \gamma K_{i,0}\right) \qquad [2]$$

where b is the market valuation coefficient of firm's total assets reflecting its differential risk and monopoly position, γ_K is the relative shadow value of the technological knowledge capital to tangible assets, and the product $b\gamma$ is the absolute shadow value of the technological knowledge capital. In practice, $b\gamma$ reflects the investors' expectations on the overall effect of $K_{i,0}$ on the present value of the expected earnings of the corporation, while γ expresses the differential valuation of the technological knowledge capital relative to tangible assets (Hall, 1993b). Expression [2] can be interpreted as the basic version of the model that is known in literature as a hedonic pricing model, where the good being priced is the firm and the characteristics of the good are its assets, both tangible and intangible (Griliches, 1981).

However, firm i can achieve a major unpredicted product or process innovation at an uncertain time $t^* \in (0,\infty]$ and acquire a new *alternative* technology. We assume that there is a finite time τ after which this innovation has no longer effect on the firm's expected profits. The idea is that the evolution of technology within the industry deprives innovations achieved after time τ of any economic value. Time τ depends then on the exogenous industry-specific technological pace. Consequently, *if and only if* innovation occurs before or at time τ, the alternative technology can be either adopted or not by the firm. Its eventual adoption shifts the present value of expected cash flows from s_{i,t^*} to $\hat{s}_{i,,t^*}$, so that the firm will decide to adopt the alternative technology *if and only if* the condition $\hat{s}_{i,\,t^*} > s_{i,t^*}$ strictly holds. Given the discretional, option-like nature of this choice and expression [2], the market value of the firm at time 0 can then be expressed as follows:

$$V_{i,0} = b\left\{\left(A_{i,0} + \gamma K_{i,o}\right) + \delta\left[p_{i,0}(\tau)\cdot W_{i,o}(s_i,\hat{s}_i,\tau)\right]\right\} \qquad [3]$$

where $p_{i,0}(\tau)$ is the probability at time 0 that the firm i achieves the innovation at any time $t^* \leq \tau$ and $W_{i,0}(s,\hat{s},\tau)$ is an option to exchange s_i with $\hat{s}_i$ before or at time τ. The present values of expected cash flows, s_i and $\hat{s}_i$, are random variables. In particular, s_i is equal to $s_{i,0}$ at time 0 and, according to the financial options literature (Black and Scholes, 1973) and recent models of R&D competition and real options (Weeds, 2002), is assumed to follow a Brownian geometric motion:

$$\mathrm{d}s_i = rs_i \,\mathrm{d}t + \sigma s_i \,\mathrm{d}z \qquad [4]$$

where r is the instantaneous expected percentage change of s_i per unit time, σ is the instantaneous standard deviation per unit time and dz is the variation of a standard Wiener process. The random variable $\hat{s}_i$ is assumed to be equal to $\hat{s}_{i,0} = s_{i,0}$ at time 0 and to follow a Brownian geometric motion:

$$\mathrm{d}\hat{s}_i = r'\hat{s}_i \,\mathrm{d}t + \sigma'\hat{s}_i \,\mathrm{d}z' \qquad [5]$$

where r' is the instantaneous expected percentage change of $\hat{s}_i$ per unit time, σ' is the instantaneous standard deviation per unit time and dz' is again the variation of a standard Wiener process. The degree of correlation between dz and dz' is ρ. We are then assuming that at the current status the alternative technology has the same expected value of the existing technology, but follows a different stochastic process in the future.

The probability $p_{i,0}(\tau)$ in equation [3] is assumed to be independent from the stochastic processes of s_i and $\hat{s}_i$. This implies that the stochastic processes underlying the evolution of s_i and $\hat{s}_i$ over time do not depend on the stochastic process related to the achievement of innovation by the firm. In other words, similarly to Weeds (2002), we separate the economic uncertainty concerning the future profitability of the technology from the technological uncertainty over the success of the R&D investment. The probability $p_{i,0}(\tau)$ has been modeled as an exponential distribution by previous literature on R&D races (Loury, 1979; Lee and Wilde, 1980; Reinganum, 1983). In this paper, we choose a Weibull distribution, which is a generalization of the exponential distribution. Accordingly, we can write:

$$p_{i,0}(\tau) = p\{t^* \leq \tau\} = 1 - \exp(-\lambda\tau^{\alpha}) \qquad [6]$$

where $1 - \exp(-\lambda\tau^a)$ is the Weibull cumulative density function and λ is the hazard rate. In the special case of $a = 1$, we have $p_{i,0}(\tau) = 1 - \exp(-\lambda\tau)$, which is the exponential cumulative density function. In addition, we relate the hazard rate to both the specific innovation efforts of firm *i* and the R&D competition within the industry. To this purpose, we assume that the hazard rate is a linear function of the ratio of the firm *i'*s R&D investments at time 0, $R_{i,0}$, to industry total R&D investments at time 0, R_0:[2]

$$\lambda = \lambda_1 (R_{i,0} / R_0) \tag{7}$$

Combining [3], [4], [5], [6] and [7] and writing $RD\_SHARE = R_{i,0} / R_0$, we obtain the following equation to be estimated[3]:

$$V_{i,0} = b\{(A_{i,0} + \gamma K_{i,o}) + \delta[1 - \exp(-\lambda_1 RD\_SHARE \cdot \tau^a)] \cdot W_{i,0}(s_{i,0}, \hat{s}_{i,0}, \sigma_i, \sigma_i', \rho, \tau)\} \tag{8}$$

Consistently with the arguments presented in the previous section and the stochastic processes of s_i and $\hat{s}_i$ described in expressions [4] and [5], we interpret $W_{i,0}(s_i, \hat{s}_i, \sigma_i, \sigma_i', \rho, \tau)$ as a *technology switch option*. Equation [8] can be transformed, as done by several previous studies (Cockburn and Griliches, 1988; Hall, 1993b; Blundell et al. 1999; Hall et al., 2000; Bloom and Van Reenen, 2002), dividing both members by $A_{i,0}$ and then taking the natural logs:

$$\ln(V_{i,0} / A_{i,0}) = \ln b + \ln[1 + \gamma K_{i,o} / A_{i,0} + \delta \exp(-\lambda_1 RD\_SHARE \cdot \tau^a) \cdot W_{i,0}(s_i, \hat{s}_i, \sigma_i, \sigma_i', \rho, \tau) / A_{i,0}] \tag{9}$$

Equation [9] will be estimated through *non-linear least squares* (NLLS), as done by the works of Hall et al. (2000), Bloom and Van Reenen (2002) and Oriani and Sobrero (2002) applying the hedonic methodology. These studies adopted a repeated cross-section approach. Indeed, the recent study of Hall

[2] Similarly, Darby et al. (1999) assume that the probability of innovation by firms in the biotechnology industry is a linear function of the firm's human capital, represented by the number of ties to star scientists.

and Oriani (2003) showed that the inclusion of firm-specific effects in the estimation of the hedonic method on a UK sample does not remarkably affect the results.

The fundamental idea is that *if the stock market recognizes and evaluates accordingly the technology switch option, we should observe a positive sign of the coefficient* δ. Moreover, if the likelihood that firm i innovates before time τ depends on its R&D investments compared to competitors' R&D investments, we expect the coefficient λ_1 to be positive.

Data and Methods

Sample

The initial sample we created consisted of a panel of about 250 R&D-doing manufacturing companies publicly traded in the United Kingdom from 1989 to 1998. The choice of this country was due to several reasons: the relatively large size of the stock market; the R&D accounting regime, requiring the firm to disclose R&D investments in their financial statements, differently from other European countries (such as France, Germany and Italy)[4]; the very recent attention to the issues related to the market valuation of R&D investments as compared to the United States[5]; and the claim of short-termism of the UK stock market made by several empirical contributions (e.g. Miles, 1993; Cuthbertson et al., 1997; Black and Fraser, 2000). All these aspects, while assuring wide data availability, raised great interest on the question of whether the British stock market evaluated the real options created through a company's R&D activity.

In the original database we retained only those companies for which data were available for at least three continuous years. We then classified the firms into 24 different industries by SIC 1992 code, based on the classifications defined and used in previous studies (Hall and Vopel, 1996; Oriani and Sobrero, 2002; Hall and Oriani, 2003). The source for accounting figures and market capitalization at the firm level was Datastream International, which has a full coverage of publicly traded British firms (including information for dead stocks).

[3] Here we are implicitly assuming that *RD_SHARE* is constant over time. This assumption is supported by the empirical evidence on the stability of the firm-specific time patterns of R&D expenditures (Hall et al. 1987).

[4] See Belcher (1996) on this point.

[5] Recent remarkable exceptions are: Green et al. (1996); Blundell et al. (1999); Toivanen et al. (2002); Oriani and Sobrero (2002); Hall and Oriani (2003).

However, in order to calculate the present value of the expected cash flows ($s_{i,0}$), which represents the underlying asset of the technology switch option, we had to integrate this database with the data on the financial analysts' forecasts, as we shall explain in detail later in this section. In particular, following Berger et al. (1996), we referred to the data on analysts' consensus estimates provided by IBES, which includes analyst data on over 18,000 companies in 60 different countries. IBES summary history consists of chronological snapshots of consensus level data taken on a monthly basis. Forecast measures include items such as earnings per share, cash flow per share, net income, EBITDA, long-term growth. Nevertheless, IBES forecast data availability for the companies traded in the UK was limited in several ways as compared to the data originally gathered from Datastream. In fact, earnings per share and cash flow per share forecasts were reported only from 1993 and just for a part of the companies included in the original sample. Moreover, we retained only those observations for which cash flow forecasts were available for at least the three following years and for which LTG was estimated. In the end, we were able to create an unbalanced panel of 90 firms and 336 observations in 16 different industries from 1993 to 1998.

Firm-level variables

The total market value (V) should be calculated as the sum of the market capitalization of the firm and the market value of its debt. However, the data on the market value of debt are often not available. Some of the studies on US samples tried to define proxies for the market value of debt using data on corporate bond market (Hall, 1990). This solution was not feasible for European samples because of very limited development of corporate bond markets. Therefore, according to previous similar analyses on UK data (Blundell et al., 1992, 1999), we calculated the market value of the firm adding the value of outstanding debt to the market capitalization observed the last trading day of the year.

The capital of technological knowledge (K) was computed as a perpetual inventory of the past R&D expenditures with a constant 15% depreciation rate, as done by several previous analyses applying hedonic method (e.g. Jaffe, 1986; Cockburn and Grilches, 1988; Hall, 1993a, 1993b) and as described in detail by Griliches and Mairesse (1984) and Hall (1990). The capitalization of R&D investments was needed because annual R&D costs are not capitalized in the balance sheet, but they are normally expensed in the P&L accounts when they occur[6].

[6] These conditions are consistent with the prescription of GAAP accounting standards that allow some costs related to R&D activities to be appropriately capitalized and carried forward as assets only if they have alternative future uses (Lev and Sougiannis, 1996).

The firm's R&D share (*RD_SHARE*) was computed for each year as the ratio of the firm's annual R&D expenditures drawn from Datastream to the industry total R&D expenditures reported by the ANBERD database, released by OECD. We had to exclude those observations presenting a value of *RD_SHARE* larger than one. This situation was due to the presence of multinational companies (Marconi, Unilever, TI Group and Pilkington) performing most of their R&D activity outside the UK.

In our regression model we also included some variables to account for specific effects that could affect the corporate value. At the firm level, we considered the capital of other intangible assets of the firm (I), mainly consisting of trademarks and goodwill, scaled by the book value of total tangible assets (A). The inclusion of this variable was necessary to explain that part of the market value related to non-R&D intangibles. Furthermore, in order to control the size effects due to economies of scale and scope and learning curves, we included the natural log of the firm's total tangible assets (A). Finally, we introduced a full set of year dummies to account for eventual time-specific effects.

The valuation of the technology switch option

In order to estimate equation [9], we needed a closed form valuation formula for $W_{i,0}(s_i, \hat{s}_i, \sigma_i, \sigma_i', \rho, \tau)$. In this respect, we calculated the value $W_{i,0}$ using the model originally proposed by Margrabe (1978). This is a generalization of the Black and Scholes (1973) formula that evaluates the European option to exchange one asset with another. This model presents the limit to evaluate a European option, which implies that, differently from an American option, the option cannot be exercised before its maturity. Some more recent models combined the switch option with the compound option to evaluate a European sequential exchange option (Carr, 1988) and even an American sequential exchange option (Carr, 1995; Lee and Paxson, 2001), which more realistically represent the technology switch option when R&D programs are organized in stages and provide the firm with sequential investment opportunities that can be exercised at the end of each stage. However, we decided to rely on Margrabe (1978) formula because this is more parsimonious in terms of the number of parameters required for the estimation. This is a relevant aspect, since one of the main limitations for the practical applications of the real options theory is the difficulty of calculating reliable input parameters for the valuation formulas (Lander and Pinches, 1998; Luehrman, 1998; Fernandez, 2001). This problem can become particularly severe when the option values are simultaneously computed for firms operating in different industries, as we shall do later in this paper. Therefore, in this context the use of a more simple valuation formula reduced the possible biases arising from parameter estimation. According to the valuation formula defined by Margrabe (1978), the value of the switch option, $W_{i,0}$ can be expressed as follows:

$$W_{i,0} = \hat{s}_{i,0} N(d_1) - s_{i,0} N(d_2)$$

$$d_1 = \frac{\ln(\hat{s}_{i,0} / s_{i,0}) + 1/2\, \nu^2 \tau}{\nu \sqrt{\tau}}$$

$$d_2 = d_1 - \nu \sqrt{\tau}$$

[10]

where $N(\bullet)$ is the normal cumulative density function, $\nu^2 = \sigma'^2 - 2\sigma'\sigma\rho + \sigma^2$ is the variance of $d(\hat{s}_i/s_i)/(\hat{s}_i/s_i)$ and τ is the time to maturity. Indeed, as remarked above, one of the most complicate tasks in testing real options is the definition and the assessment of the option parameters. According to [10], in order to calculate $W_{i,0}$, we needed measures for $s_{i,0}$, which in the previous session was assumed to be equal to $\hat{s}_{i,0}$, ν^2 and τ.

With respect to $s_{i,0}$, we followed an approach similar to that used by Berger et al. (1996), referring, as mentioned above, to financial analysts' estimates. The use of analysts' data to assess a firm's value had been validated by Kaplan and Ruback (1995). In this paper, we gathered the information on analysts' forecasts from the IBES consensus estimates data file. Similarly to Kaplan and Ruback (1995), we adopted the Adjusted Present Value (APV) method, which discounts expected operating cash flows after corporate tax, including the tax benefits of deductible financial interest payments, at the discount rate for an all-equity firm (for details on the APV method see Brealey and Myers, 2003: 555-564). The APV method simplifies the evaluation of firms' cash flows as compared to the widely used weighted average cost of capital (WACC) approach because the estimation of the weighted cost of capital would require assumptions on the changing level of firm-specific leverage over time (Kaplan and Ruback, 1995).

In particular, for any company in our original sample we picked, when available, the estimation made at the end of year 0 of the operating cash flow per share (*CPS*) for year 1 (*CPS1*), year 2 (*CPS2*) and year 3 (*CPS3*) and the long-term growth rate (*LTG*). The measure of *CPS* calculated by IBES is the cash flow from operations, before investing and financing activities divided by the weighted average number of common shares outstanding in the year of the estimation. Note that interest payments are included in this definition of *CPS*, so that it results consistent with the APV method. *LTG* represents the expected annual increase in operating earnings over the company's next full business cycle. In general, *LTG* forecasts refer to a period of three to five years. Due to the variance in methodologies for *LTG* calculations, as recommended by IBES, we used the median value as opposed to the mean value, because the former is less affected by outlier forecasts. We completed this information with the number of outstanding shares (*NS*) that the selected companies had at the end of each year in the sample. Finally, as mentioned above, we retained only those observations for which *CPS1*, *CPS2*, *CPS3*, *LTG* and *NS* were reported in the IBES consensus estimates data file.

Then, we calculated for each firm and year the expected operating cash flows over a period of five years. For the first three years we had ***CF1*** = *CPS1* * *NS*, ***CF2*** = *CPS2* * *NS* and ***CF3*** = *CPS3* * *NS*, whereas we moved from *CF3* and used the *LTG* estimation to compute the expected operating cash flows for the fourth and fifth year: ***CF4*** = *CF3* * (1 + *LTG*) and ***CF5*** = *CF3* * $(1 + LTG)^2$. We also calculated the present value of the cash flows after year 5 (*PVCF*). To this purpose, we discounted *CF5* as a perpetual rent, assuming a 0% growth rate. Kaplan and Ruback (1995) repeated their estimation of the present value of the perpetuity for alternative nominal growth rates of 0%, 2% and 4%. In this paper we chose a 0% growth rate to be conservative and avoid the potential risk to overestimate the value of $s_{i,0}$.

However, our calculation of the cash flows did not include yet the outflows related to the investment in capital assets and working capital. Unfortunately, IBES does not provide forecast data on these items. One possible solution was to develop forecasts from historical figures, but the variations over time in capital expenditures and working capital can lead to overestimate these flows in some year and underestimate them in other years. Therefore, we followed the approach adopted by Berger et al. (1996), who subtracted from discounted cash flows a fixed percentage representing the expected excess capital expenditures and working capital increases. This percentage was calculated as the ratio of excess capital expenditures and working capital growth to the market value of equity. They had a median deduction of 12% for excess capital expenditures and 5.5% for working capital expenditures[7]. We used these values to calculate the present value of capital expenditures (*CAPEX*) and working capital growth (*WCG*) for all the observations in our sample. In order to be conservative and not to

[7] Berger et al. (1996) grouped the observations drawn from the Compustat database into deciles of the historical levels of both excess capital expenditures and expected earnings growth. Then, for each observation, they adjusted the present value of expected earnings by a fixed percentage accounting for future excess capital expenditures and working capital growth depending on the decile rankings of the specific observation. Our data did not allow us to define decile rankings with the precision that was allowed by Compustat. For this reason, we preferred to subtract the same percentage from all the observations.

overestimate the value of $s_{i,0}$, we multiplied the previous ratios not for the market value of the firm's equity, but for the enterprise value (V), which had been calculated in the previous sub-section.

Finally, we had to determine the cost of equity (r_E) to discount the expected cash flows. In this respect, we referred to the traditional CAPM method. The expected CAPM return is defined as follows:

$$r_E = r_f + \beta (r_m - r_f) \quad [11]$$

In expression [11], r_f is the risk-free interest rate and was assumed equal to the interest rate on 10-years UK Government Bonds[8] registered at the end of each year in the sample and retrieved from the Global Financial Databases, whereas r_m is the risk premium of the stock market and was set equal to 4.51% according to the estimation provided by Damodaran (www.damodaran.com) for the UK stock market[9]. The β was calculated for each firm and year as the slope of a straight line fitted to 156 observations of weekly relative price changes obtained from Datastream. In particular, the weekly percent price change in a particular stock was regressed on the weekly percent change of the FTSE all-share, which is the index including all the stocks traded on the London Stock Exchange, applying ordinary least squares. Resuming, the value of $s_{i,0}$ was calculated according to the following expression:

$$s_{i,0} = \sum_{t=1}^{5} \frac{CF_t}{(1+r_E)^t} + \frac{PVCF}{(1+r_E)^5} - CAPEX - WCG \quad [12]$$

According to definition provided with respect to expression [10], in order to measure ν^2, we needed measures of σ, σ' and ρ. However, the joint calculation of these parameters for a cross-industry database posed several difficulties that made the potential estimation unreliable. Thus, we decided to define a measure of ν^2 without estimating the abovementioned parameters in detail. To this purpose, we recalled that ν^2 is the variance of the percentage variation of $\hat{s}_i$ relative to s_i over time. This critically

[8] The choice of 10-years government bonds interest rate to measure the risk-free interest rate is often suggested by scholars and practitioners (see for example Copeland et al., 1994).

[9] Damodaran first estimates the market risk premium for the United States based upon a simple 2-stage dividend discount model. The estimation reflects the risk premium that would justify the current level of the index, given the dividend yield, expected growth in earnings and the level of the long-term bond rate. After that, he estimates the market risk premium for the other countries using the country ratings assigned by Standard and Poors'. The market risk premium for the UK is equal to the market risk premium estimated for the US.

depends on the uncertainty over the occurrence of a technological substitution in the future. In fact*,* the value of $\hat{s}_i$ relative to s_i depends on the diffusion pattern of the new technology as compared to the existing one. Previous literature on technological change has remarked the existence of a *technology cycle* (Abrnathy and Utterback, 1978). At industry level periods of incremental innovations along given technological trajectories are followed by radical innovations requiring major changes in the underlying technology (Anderson and Tushman, 1990). Radical innovations open periods of ferment in which the technological standard is not defined and performance requirements are uncertain (Henderson and Clark, 1990). In these periods, the uncertainty over the diffusion of a new technology is remarkably higher. Accordingly, we calculated ν^2 as a function of the uncertainty over the future technology in the industry. This approach was coherent with the model assumption that the stochastic processes of s_i and $\hat{s}_i$ are exogenous with respect to firm-specific innovation.

We created our variable of technological uncertainty similarly to Oriani and Sobrero (2002). In particular, we defined the measure of technological uncertainty building on patent data. In this respect, the main operational problem we had to deal with concerned the correspondence between firms' industrial classification and patents' technological classification. In fact, while the SIC classification is application oriented, technological classifications, such as IPC, are normally function oriented, so that technological classes do not match to industry groups. In order to overcome this problem, we selected the patents belonging to the firms that constitute the Tech-Line® sample created by CHI Research, including the worldwide top patenting firms and institutions (see Narin, 1999, for further details on on the sample constituents)[10]. We eliminated Universities and public research centers from the original sample, so to retain only private companies. We then reclassified these companies by SIC92 code, in order to have a classification consistent with our firm-level database. We eliminated those conglomerate corporations that could not be assigned to a specific industry. In the end, we attributed the patents granted from 1993 to 1998 to the companies in the Tech-Line sample to the industry of their assignee.

We then decided to use patent citations to build our indicator. Each patent normally cites previous patents that represent the prior state of art. Data on patent citations have been used in a series of empirical works (Jaffe and Trajtenberg, 2002). In particular, the measure we calculated is based on the Technology Cycle Time (*TCT*) indicator, defined and calculated by CHI Research. This is computed as the median age in years of the US patent references cited on the front page of the patent. When

[10] Patent assignees are consolidated at corporate level by CHI Research. Moreover, when M&A operations occur, the patents are automatically reassigned to the acquiring company.

calculated at industry level, it captures some elements of the *rapidity of the technology cycle* in that industry since it measures the time between the previous patents upon which current patents are improving and the current patents (Narin, 1999). Accordingly, companies operating in an industry with a shorter technology cycle have to switch more rapidly from prior to new technology and consequently face a greater uncertainty about the future technological design than companies in industries with a longer technology cycle. This implies that industries with a lower *TCT* are characterized by a higher degree of technological uncertainty. Therefore, for each industry and year in our sample we calculated ν^2 as the inverse of the average *TCT* indicator calculated at the industry level. In practice, we had $\nu^2 = (TCT_0)^{-1}$. In Figure 1 we plot the estimated values of ν^2 by industry and year. It is possible to see that these values are comprised between .07 and .17 and are rather constant over time within the industry (except for th utility industry). In the electronics, scientific instruments and pharmaceutical industries the values of ν^2 are much higher than in all the other industries.

Finally, we had to assess the time to maturity (τ) of the technology switch option. In the model described in the previous section it had been defined as the time after which this innovation had no longer effect on the firm's expected profits. It had also been considered exogenous with respect to firm-specific innovation. Consistently with these assumptions, for each industry and year in the sample we set τ equal to the average *TCT* calculated at the industry level. In fact, as discussed above, this indicator represents a proxy of the length of the technology cycle within the industry. The idea is that an innovation occurring after the current technology cycle has no economic value because the technological progress has made it obsolete. Clearly, the *TCT* was also used to calculate the time τ appearing in the Weibull distribution in equation [6], which, according to the model specification, coincides with the time to maturity of the technology switch option[11].

The use of the *TCT* indicator to calculate both the standard deviation and the time to maturity of the technology switch option allows us to address empirically the ambiguity of the effect that the length of the technology cycle has on the value of the option value. In fact, a greater length of the technological cycle increases the time to maturity of the option, which is a positive element of the option value, but, negatively impacting on technological uncertainty, decreases the variance of the expected returns of the underlying asset, which instead should reduce the option value. Using the *TCT* indicator to determine both the time to maturity and the variance, we can observe the prevalence of either the maturity or the variance effect related to the technology cycle.

[11] In fact, τ has been defined as the time after which the potential innovation has no longer economic value and consequently represents also the maturity for the exercise of the technology switch option.

Having defined $s_{i,0}$, ν and τ, we could use expression [10] to calculate $W_{i,0}$ for any observation remaining in the sample. We excluded the observations presenting a negative value of $s_{i,0}$. The average value *W* scaled by total tangible assets (*A*) by industry is shown in Figure 2. The average ratio *W/A* is larger than .3 in the electronics, scientific instruments and pharmaceuticals industries and larger than .1 in the chemical, primary metals and motor vehicles industries, whereas it is lower than .1 in all the other industries.

Descriptive statistics and correlations

After excluding the observations with *RD_SHARE*>1 and $s_{i,0}$<0, we were left with a sample of 318 observations, whose distribution across industries is reported in Table 1. The descriptive statistics of the variables, including mean, standard deviation, median, minimum and maximum values, are shown in Table 2. Finally, in Table 3 we report the correlations between the variables. *W/A* is positively correlated to both *K/A* (.33) and *I/A* (.33), and negatively correlated to TCT (-.65). There also exists a high positive correlation between *RD_SHARE* and *ln A* (.62). However, these correlation coefficients should not raise serious concerns about multicollinearity.

Results

We estimated equation [9] through NLLS. The results are reported in Table 4. We first estimated the basic version of the hedonic model, without including the technology switch option (Model 1). The coefficients of *K/A* (.59) and *I/A* (.36) are both positive and statistically significant at 1% level, but they are lower than one, suggesting that both *K* and *I* are evaluated less than *A* by the financial market. Moreover, these results are very close to those obtained by Hall and Oriani (2003) for a broader UK sample. The size variable (*ln A*) has instead a negative (-.039) and significant effect on *ln (V/A)*.

In model 2 we include the technology switch option scaled by total tangible assets (*W/A*) according to equation [9]. The coefficient of *W/A* is positive (4.74) and statistically significant at 5% level, supporting the idea that the financial market recognizes the value of the technology switch option. Note also the increase in the *adjusted* R^2, passing from .37 in model 1 to .53 in model 2. This means that the inclusion of the technology switch option in the regression equation considerably improves the fit of the regression. The ratios *K/A* and *I/A* still have positive (.76 and .78 respectively) and significant coefficients (at 5% level), which however in this model are closer to one. Thus, the results of model 2 confirm that considering the technology switch option within a market value equation adds information on the determinants of the firm's expected performance.

In model 3 we introduce the probability to innovate before τ, as defined in equation [9]. We initially set $a = 1$, so that we have an exponential probability distribution. The coefficient of *RD_SHARE* is positive (19.48) and statistically significant at 5% level, suggesting that a higher R&D share improves the expected probability to innovate before time τ, consistently with the theoretical studies on R&D races (Loury, 1979; Lee and Wilde, 1980; Reinganum, 1983). The coefficient of *W/A* is still positive (2.90) and now significant at the 1% level, confirming a positive valuation of the technology switch option by the financial market. The coefficients of *K/A* and *I/A* remain positive (.34 and .49 respectively) and statistically significant (at the 5% and 1% respectively), whereas *ln A* has again a negative (-.035) and significant (1% level) coefficient.

In models 4 and 5 we choose different values of *a* (respectively .5 and 2) for the Weibull distribution function specified in equation [6], in order to test the robustness of the results of model 3 with respect to the parametric form imposed to the probability to innovate. We obtain results very similar to those reported for model 3. The coefficients of *K/A*, *I/A*, *W/A* and *ln A* only show slight changes and the coefficients of *RD_SHARE* remain positive (57.61 in model 4 and 2.66 in model 5) and statistical significant at the 5% level. Moreover, when we plot the values of the probability function with respect to *RD_SHARE* for $\tau = 9.5$ (which is the sample mean of *TCT*) in Figure 3, we observe that there is a very little difference between the alternative parametric forms (exponential; Weibull with $a = .5$; Weibull with $a = 2$). This evidence indicates that our results are robust to the value of *a* that we choose for a generic Weibull distribution. We also plot the exponential distribution for several different industries in Figure 4, setting τ equal to the specific value of *TCT* registered in those industries in 1998. As we could expect, in the industries with a shorter technology cycle, such as electronics or pharmaceuticals, firms need a higher R&D share than in industries with a longer technology cycle, such as food and primary metal, to have the same expected probability to innovate.

Discussion and conclusions

Methods for a better evaluation of innovation-related assets are progressively more necessary as these assets become critical for the competition among firms. The real options theory has provided very useful insights to this respect, but its practical application has been hindered by several problems

(Lander and Pinches, 1998; Luehrman, 1998; Fernandez, 2001). First, it is hard to define the valuation parameters because the real projects to be evaluated are not traded assets. Second, the theory still lacks of a robust empirical validation. Some studies (Bloom and Van Reenen, 2002; Oriani and Sobrero, 2002) have adopted a real options perspective in the analysis of the stock market valuation of firms' technological knowledge, but they do not formalize the real options associated with the firm's R&D activity.

This paper addressed this shortcoming through the modeling of a technology switch option and its inclusion within a testable market value equation. It also defined new measures of the option parameters needed for the valuation. To this purpose, indicators of technology uncertainty were built on industry-level patent data. Moreover, differently from previous models, this paper also tried to account for the stochastic nature of innovation, linking the firm's probability to innovate to its R&D investments.

The results of the empirical analysis support the claim that the stock market recognizes and evaluates accordingly a technology switch option. The remarkable improvement in the regression fit after including the switch option strongly suggests that the explicit valuation of this option adds relevant information on the determinants of a firm's market value. Moreover, the market valuation seems to implicitly acknowledge that a greater R&D share increases the firm's probability to innovate. This latter result is in line with the theoretical works on R&D competition, which, however, with the exception of the study of Henderson and Cockburn (1994), has received scarce empirical validation.

We believe that the analysis conducted in this paper can offer several useful contributions to the existing literature on innovation and real options, as well to managers and financial analysts. First, it formalizes the value of the technology options that had already been intuitively individuated by previous contributions on the management of innovation (e.g. McGrath, 1997; Miller, 2002). Furthermore, the validation of a closed form of the option embedded in the firm's technological capital within a cross-industry empirical setting can provide financial analysts with the basis for more sophisticated models to assess the firm's market value. In addition, our analysis empirically supports the effectiveness of an option-based valuation method, defining and testing at the same time new valuation parameters. In this way it proposes to managers a new tool for the assessment of R&D strategies.

Finally, it is noteworthy to remark the limitations of this paper. The main problem is that firms simultaneously develop several product and process technologies. Thus, a more precise formalization of the switch option would require an analysis at the level of the single R&D project. However, this is extremely difficult within a cross-industry setting. This suggests at least two possible fruitful research avenues. Without loss of generality, building on previous studies on the relationship between patents and firm's market value (e.g. Hall et al., 2000), it is possible to model a portfolio of options using firm-level patent data. Alternatively, limiting the focus on a specific industry, it can be insightful to study more in depth the determinants of the value of the technology switch option embedded in the firm's market value. Further steps into these directions could shed new light on the innovation-related value creation processes and provide practitioners with more refined valuation methods of a firm's technology investments.

References

Abernathy W. J., Utterback J. M., (1978), "Patterns of Industrial Innovation", *Technology Review*, **80**(7): 40-47

Anderson P., Tushman M. L., (1990), "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change", *Administrative Science Quarterly*, **35**(4): 604-633

Belcher A., (1996), "R&D Disclosure: Theory and Practice", in Belcher A., Hassard J., Procter S. (Eds.), *R&D Decisions: Strategy, Policy and Disclosure*, Routledge, London

Benaroch M., (2001), "Option-based Management of Technology Investment Risk", *IEEE Transactions on Engineering Management*, **48**: 428-444

Berger P. G., Ofek E., Swary I., (1996), "Investor Valuation of the Abandonment Option", *Journal of Financial Economics*, **42**, pp. 257-287.

Berk J., Green R. C., Naik V.,(1998), "Optimal Investment, Growth Options, and Security Returns", *Journal of Finance*, **54**(5): 1553-1607

Black A. J., Fraser P., (2000), "International Comparisons on Stock Market Short-Termism: How Different Is the UK Experience?" *Manchester School*, **68**: 38-50

Black F., Scholes M., (1973), "The Pricing of Options and Corporate Liabilities", *Journal of Political Economy*, **81**(3), pp. 637-654

Bloom N., Van Reenen J., (2002), "Patents, Real Options and Firm Performance", *Economic Journal*, **112**: 97-116

Blundell R., Bond S., Devereux M., Schiantarelli F., (1992), "Investment and Tobin's Q", *Journal of Econometrics*, **51**(1-2): 233-257

Blundell R., Griffith R., Van Reenen J., (1999), "Market Share, Market Value and Innovation in a Panel of British Manufacturing Firms", *Review of Economic Studies*, **66**(3): 529-554

Boer F. P., (2002), "Financial Management of R&D 2002", *Research-Technology Management*, July-August: 23-35

Brealey R. A. , Myers S. C., (2003), *Principles of corporate finance*. McGraw-Hill, New York.

Carr P., (1988), "The Valuation of Sequential Exchange Opportunities", *Journal of Finance*, **43**(5): 1235-1256.

Carr P., (1995), "The Valuation of American Exchange Options with Application to Real Options", in Trigeorgis L. (ed.), *Real Options in Capital Investment: Models, Strategies and Applications*, Praeger, Westport, CT

Chan L. K. C., Lakonishok J., Sougiannis T., (1999), "The Stock Market Valuation of Research and Development Expenditures", National Bureau of Economic Research Working Paper 7223, Cambridge, MA

Childs P. D., Triantis A. J., (1999), "Dynamic R&D Investment Policies", *Management Science*, **45**(10): 1359-1377

Cockburn I., Griliches Z., (1988), "Industry Effects and Appropriability Measures in the Stock Market's Valuation of R&D and Patents", *American Economic Review*, **78**(2): 419-423

Cockburn I., Henderson R., (1994), "Racing to Invest? The Dynamics of Competition in Ethical Drug Discovery", *Journal of Economics and Management Strategy*, **3**(3): 481-519

Copeland T. E., Keenan P. T., (1998), "Making Real Options Real", *The McKinsey Quarterly Review*, n.3: 129-141

Copeland T. E., Koller T., Murrin J., (1994), *Valuation. Measuring and Managing the Value of Companies*, Wiley, New York

Cuthbertson K., Hayes S., Nitzsche D., (1997), "The Behaviour of UK Stock Prices and Returns: Is the Market Efficient?", *Economic Journal*, **107**(443): 986-1008

Darby M. R., Liu Q., Zucker L. G., (1999), "Stakes and Stars: The Effect of Intellectual Human Capital on the Level and Variability of High-Tech Firms' Market Value", NBER Working Paper #7201, Cambridge, MA.

Dixit A. K., Pindyck R. S., (1994), *Investment under Uncertainty*, Princeton University Press, Princeton, N.J.

Fama E. F., Jensen M. C., (1985), "Organizational Forms and Investment Decisions", *Journal of Financial Economics*, **14**(1), pp. 101-119.

Fernandez P., (2001), "Valuing Real Options: Frequently Made Errors", Working Paper, IESE Business School, Madrid

Garud R., Nayyar P. R., (1994), "Transformative Capacity: Continual Structuring by Intertemporal Technology Transfer", *Strategic Management Journal*, **15**(5): 365-385

Green J. P., Stark A. W., Thomas H. M., (1996), "UK Evidence on the Market Valuation of Research and Development Expenditures", *Journal of Business Finance & Accounting*, **23**(2): 191-216

Grenadier S. R., Weiss A. M., (1997), "Investment in Technological Innovations: An Option Pricing Approach", *Journal of Financial Economics*, **44**(3): 397-416

Griliches Z., (1981), "Market Value, R&D and Patents", *Economics Letters*, **7**, pp. 183-187

Griliches Z., Mairesse J., (1984), "Productivity and R&D at the Firm Level", in Griliches Z. (ed.), *R&D, Patents, and Productivity*, The University of Chicago Press, Chicago

Hall B. H., (1990), "The Manufacturing Sector Master File: 1959-1987", NBER Working Paper # 3366, Cambridge, MA

Hall B. H., (1993a), "The Stock Market's Valuation of R&D Investment During the 1980's", *American Economic Review*, **83**(2): 259-264

Hall B. H., (1993b), "Industrial Research During the 1980s: Did the Rate of Return Fall?" *Brookings Papers on Economic Activity. Microeconomics*, 2: 289-343

Hall B. H., (1999), "Innovation and Market Value", National Bureau of Economic Research Working Paper 6984, Cambridge, MA

Hall B. H., (2002), "The Financing of Research and Development", *Oxford Review of Economic Policy*, **18**(1): 35-51

Hall B.H, Griliches Z., Hausman J. A., (1987), "Patents and R&D: Is There a Lag?", *International Economic Review*, **27**: 65-83

Hall B. H., Jaffe A. B., Trajtenberg M., (2000), "Market Value and Patent Citations: A First Look", National Bureau of Economic Research Working Paper #7741, Cambridge, MA

Hall B. H., Oriani R., (2003), "Does the Market Value R&D Investment by European Firms? Evidence from a Panel of Manufacturing Firms in France, Germany and Italy", Conference Paper for DRUID's Knowledge Conference, June, Helsingor

Hall B. H., Vopel K., (1996), "Innovation, Market Share and Market Value", Working Paper, University of California at Berkeley, Berkeley, CA

Hatfield D. E., Tegarden L. F., Echols A. E., (2001), "Facing the Uncertain Environment from Technological Discontinuities: Hedging as a Technology Strategy", *Journal of High Technology Management Research*, **12**(1): 63-76

Henderson R. M., Clark K. B., (1990), "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms", *Administrative Science Quarterly*, **35**(1): 9-30

Huchzermeier A., Loch C. H., (2001), "Project Management under Risk: Using the Real Options Approach to Evaluate Flexibility in R&D", *Management Science*, **47**(1): 85-101

Jaffe A. B., (1986), "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value", *American Economic Review*, **76**(5): 984-1001

Jaffe A. B., Trajtenberg M., (2002), *Patents, Citations and Innovations: A Window on the Knowledge Economy*. MIT Press, Cambridge, MA

Jagle A. J., (1999), "Shareholder Value, Real Options, and Innovation in Technology-Intensive Companies", *R&D Management*, **29**(3): 271-287

Kaplan S. N., Ruback R. S., (1995), "The Valuation of Cash Flow Forecasts: An Empirical Analysis", *Journal of Finance*, **50**(4): 1059-1093

Kogut B., Kulatilaka N., (1994), "Options Thinking and Platform Investments: Investing in Opportunity", *California Management Review*, **36**(2): 52-71

Lander D. M., Pinches G. E., (1998), "Challenges to the Practical Implementation of Modeling and Valuing Real Options", *Quarterly Review of Economics and Finance*, **38**(Supplement): 537-567

Lee J., Paxson D. A., (2001), "Valuation of R&D Real American Sequential Exchange Options", *R&D Management*, **31**(2): 191-201

Lee T., Wilde L. L., (1980), "Market Structure and Innovation: A Reformulation", *Quarterly Journal of Economics*, **94**, pp. 429-436.

Lev B., (2001), *Intangibles: Management, Measurement, and Reporting*, Brookings Institution Press, Washington, D.C.

Lev B., Sougiannis T., (1996), "The Capitalization, Amortization, and Value-Relevance of R&D", *Journal of Accounting and Economics*, **21**(1): 107-138

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

Luehrman T. A., (1998), "Investment Opportunities as Real Options: Getting Started on the Numbers", *Harvard Business Review*, **76**(4): 51-67

Margrabe W., (1978), 'The Value of an Option to Exchange One Asset for Another', *Journal of Finance*, **33**, pp. 177-186.

McGrath R. G., (1997), "A Real Options Logic for Initiating Technology Positioning Investments", *Academy of Management Review*, **22**(4): 974-996

Miles D., (1993), "Testing for Short Termism in the UK Stock Market", *Economic Journal*, **103**(421): 1379-1396

Miller K. D., (2002), "Knowledge Inventories and Managerial Myopia", *Strategic Management Journal*, **8**(23): 689-706

Myers S. C., (1977), "Determinants of Corporate Borrowing", *Journal of Financial Economics*, **5**(2): 147-175

Narin F., (1999), "Tech-Line® Background Paper", Manuscript, CHI Research Inc., Haddon Heights, NJ, http://www.chiresearch.com

Oriani R., Sobrero M., (2002), "Assessing the Market Valuation of Firms' Technological Knowledge Using a Real Options Perspective", Paper presented at the International Annual Conference of the Academy of Management, Denver, August 9-13

Oriani R., Sobrero M., (2003), "A Meta-Analytic Study of the Relationship between R&D Investments and Corporate Value", in Calderini M., Garrone P., Sobrero M. (Eds), *Corporate Governance, Market Structure and Innovation*, Edward Elgar, Cheltenham

Paddock J. L., Siegel D. R., Smith J. L., (1988), "Option Valuation of Claims on Real Assets: The Case of Offshore Petroleum Leases", *Quarterly Journal of Economics*, **103**(3): 479-508

Pakes A., (1986), "Patents as Options: Some Estimates of the Value of Holding European Patent Stocks", *Econometrica*, **54**(4): 755-784

Perlitz M., Peske T., Schrank R., (1999), "Real Options Valuation: The New Frontier in R&D Project Evaluation?" *R&D Management*, **29**(3): 255-269

Pitkethly R., (1999), "The Valuation of Patents: A Review of Patent Valuation Methods with Consideration of Option Based Methods and the Potential for Further Research", Working Paper 05/99, Oxford IP Research Centre, Oxford

Quigg L., (1993), "Empirical Testing of Real Option-Pricing Models", *Journal of Finance*, **48**(2): 621-640

Reinganum J. F., (1983), "Uncertain Innovation and the Persistence of Monopoly", *American Economic Review*, **73**(4): 741-748

Reinganum J. F., (1989), "The Timing of Innovation: Research, Development and Diffusion", in Schmalansee R., Willig R. D., (eds.), *Handbook of Industrial Organization*, Volume I, North-Holland, Amsterdam

Schwartz E. S., Moon M., (2000), "Evaluating Research and Development Investment", in Brennan M., Trigeorgis L. (Eds.), *Project Flexibility, Agency and Competition. New Developments in the Theory and Application of Real Options*, Oxford University Press, Oxford

Toivanen O., Stoneman P., Bosworth D., (2002), "Innovation and Market Value of UK Firms, 1989-1995", *Oxford Bulletin of Economics and Statistics*, **64**: 39-61 ù

Trigeorgis L., (1996), *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, MIT Press, Cambridge, MA

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

Ziedonis A. A., (2002), "Real Options in Technology Acquisitions", Working Paper, University of Michigan Business School, Ann Harbor, MI

TABLE 1
Observations by industry

Industry	Freq.	Percent (%)
Food	46	14.47
Textile	6	1.89
Paper	2	0.63
Chemicals	61	19.18
Oil	18	5.66
Rubber & Plastics	15	4.72
Primary metals	10	3.14
Refined metals	13	4.09
Machinery	26	8.18
Electrical	15	4.72
Electronics	13	4.09
Aerospace	12	3.77
Motor vehicles	23	7.23
Sc. Instruments	18	5.66
Pharmaceuticals	29	9.12
Utilities	11	3.46
Total	**318**	**100.00**

TABLE 2
Observations, mean, standard deviation, median, minimum and maximum of the variables included in the regression

Variable	**Obs.**	**Mean**	**Std. Dev.**	**Min**	**Med**	**Max**
V/A	318	2.7284	2.3106	.6230	1.9408	22.5519
K/A	318	.2099	.2410	.0060	.1241	1.1682
I/A	318	.2704	.6052	.0000	.0009	5.3031
W/A	318	.1382	.1386	.0001	.0896	.8108
RD_SHARE	318	.1156	.1576	.0001	.0476	.8667
ln A	318	13.4955	1.4081	10.0513	13.5539	16.9906
TCT	318	9.5190	1.7310	5.9212	9.5398	13.6003

TABLE 3
Correlations between the variables included in the regression

	V/A	K/A	I/A	S/A	RD_SHARE	ln A	TCT
V/A	1.00						
K/A	.44	1.00					
I/A	.47	.24	1.00				
W/A	.64	.33	.33	1.00			
RD_SHARE	.04	.33	.00	-.14	1.00		
ln A	-.09	.01	.07	-.34	.62	1.00	
TCT	-.32	-.31	-.12	-.65	.07	.06	1.00

TABLE 4
Results of the NLLS estimation of equation [9]. Dependent variable: ln (V/A)

	(1)	(2)	(3)	(4)	(5)
Constant	1.16^{***}	.17	$.76^{***}$	$.76^{***}$	$.70^{***}$
	(.17)	(.40)	(.25)	(.25)	(.26)
K/A	$.59^{***}$	$.76^{**}$	$.34^{**}$	$.34^{**}$	$.37^{**}$
	(.16)	(.38)	(.16)	(.16)	(.18)
I/A	$.36^{***}$	$.78^{**}$	$.49^{***}$	$.49^{***}$	$.52^{***}$
	(.08)	(.33)	(.14)	(.14)	(.15)
ln A	$-.039^{***}$	-.011	$-.035^{***}$	$-.035^{***}$	$-.033^{***}$
	(.005)	(.022)	(.008)	(.008)	(.009)
W/A		4.74^{**}	2.90^{***}	2.83^{***}	3.08^{***}
		(2.18)	(.82)	(.80)	(.91)
RD_SHARE (Exp, *a* = 1)			19.48^{**}		
			(8.17)		
RD_SHARE (Weib, *a* =.5)				57.61^{**}	
				(24.85)	
RD_SHARE (Weib, *a* = 2)					2.66^{**}
					(1.12)
Year dummies	Yes	Yes	Yes	Yes	Yes
Obs.	318	318	318	318	318
Adjusted R^2	.36	.53	.51	.51	.51

*** p<.01; ** p<.05

FIGURE 1
Estimated values of ν^2 by industry and year

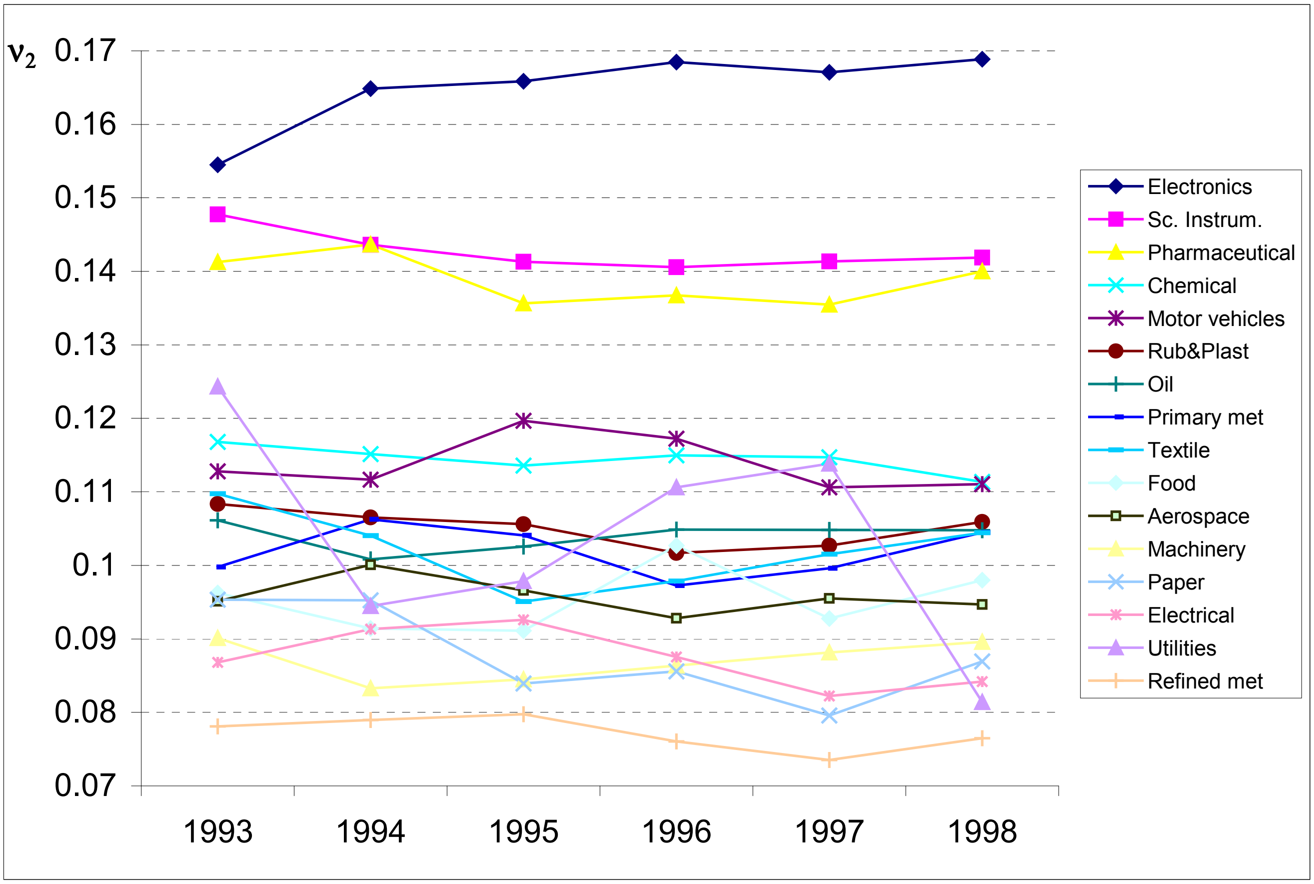

FIGURE 2
Average W/A ratio by industry

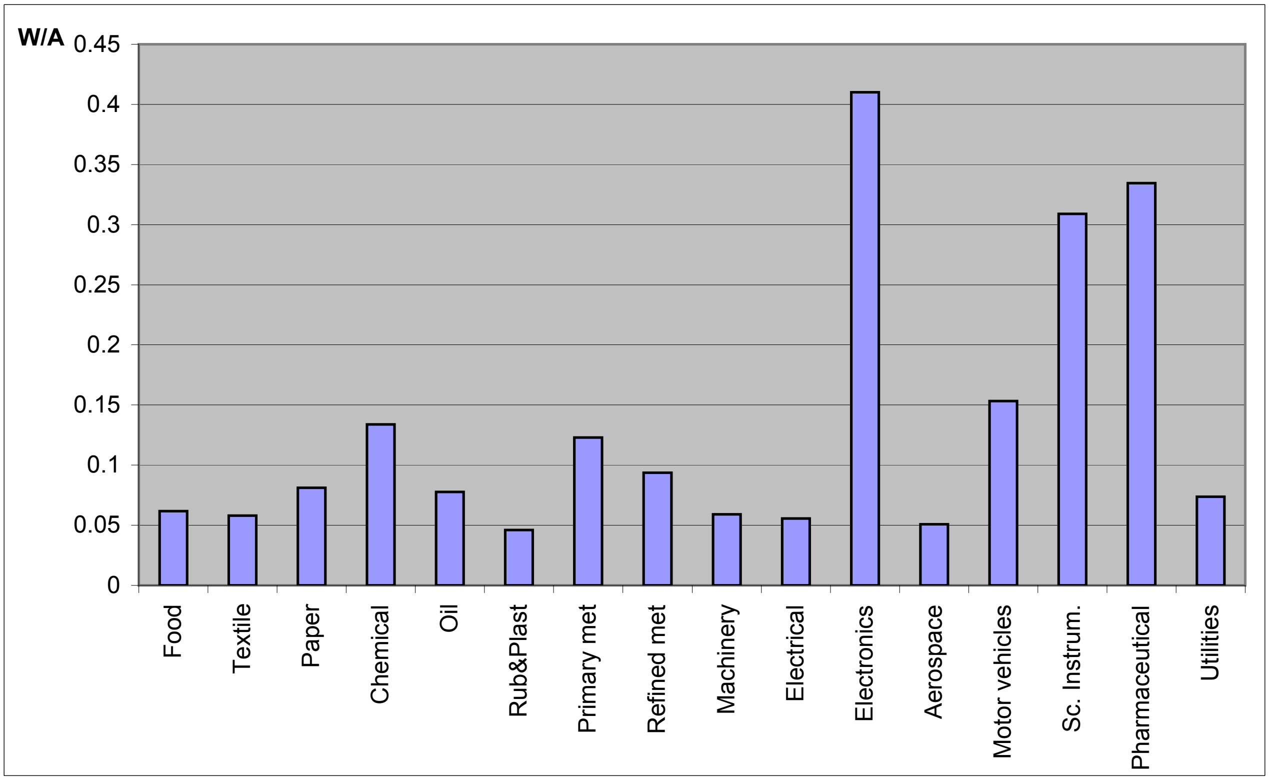

FIGURE 3

Relationship between the probability to innovate, p(τ), and *RD_SHARE* (Probability distributions: Exponential; Weibull with a =.5; Weibull with a = 2. τ = 9.5 for all the distributions)

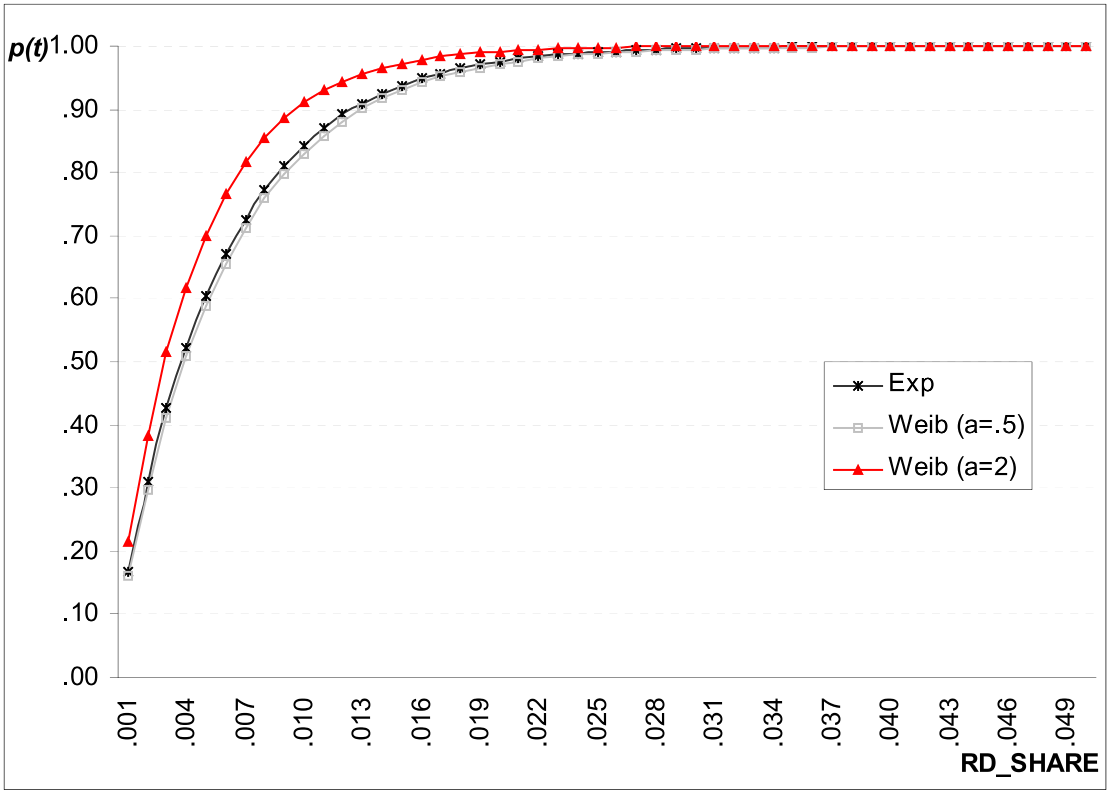

FIGURE 4
Relationship between the probability to innovate (exponential distribution), $p(\tau)$, and *RD_SHARE* for selected industries