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RETROSPECTIVE INSIGHTS FROM REAL OPTIONS IN R&D

ABSTRACT

The concept of real options acknowledges that downside risk is limited and upward potential is maximized if management can alter the sequence of actions and investment. However, real options generally require control over the underlying asset whereas financial options typically do not. To gain more insight in this issue, we describe three option valuations in a real R&D setting throughout time. We find that the (endogenous) dynamics of strategic management and of the technologies themselves played a dominant role in the actual outcome of the cases that we studied. From an options perspective, our findings stimulate the application of advanced models, while from a wider managerial perspective, we suggest to combine option models with scoring methods in order to keep matters realistic, broadly understandable and manageable.

INTRODUCTION

The analogy between the pricing of a financial option on traded assets and the valuation of an R&D project as an option on future market introduction has strong managerial appeal. Any financial or real option can be seen as an initial investment offering the exclusive opportunity to keep open a specified follow-on (dis) investment trajectory at limited predetermined costs. R&D may therefore be considered as an initial investment opening up future market introduction of new products or technologies.

Merck is the first company that has explicitly embraced real option pricing to R&D and has incorporated an option valuation approach in its investment process (Nichols 1994). The company uses stock volatilities of representative biotechnology firms to approximate the volatility of the present value of future cash flows resulting from an R&D project in about the same pharmaceutical field. This methodology makes it possible to apply the standard models for financial option pricing to R&D option valuation. The basic assumption underlying this approach is that the risk characteristics of the single R&D project under consideration exactly replicate the risk characteristics of the representative stock. The write up about Merck has attracted a lot of attention in the business press¹ and has paved the way for many R&D managers to introduce the options approach in their companies.

¹ “Exploiting Uncertainty: The ‘Real Options’ Revolution in Decision Making”, *Business Week*, June 7, 1999; “Economics Focus: Keeping All Options Open”, *The Economist*, August 14, 1999.

In spite of the major attention in practice and the potential advantage of real option valuation over myopic approaches such as a naive² application of the net present value method, however, the options approach has barely been considered by general management (Busby and Pitts 1997)³. Concerning R&D option valuation in particular, Smith and McCardle (1998), Perlitz et al. (1999), Doctor et al. (2001), and Huchzermeier and Loch (2001) affirm that it will be necessary to put more focus on documenting real projects and presenting actual R&D options cases in order to assess the impact of real options pricing in R&D.

In this paper we address this issue. Our contribution is twofold. First, we summarize three examples of emerging technologies and demonstrate why the option approach appeared more appropriate for the valuation of these research initiatives than conventional frameworks like net present value (NPV). Second, since the three R&D projects that we have studied have been completed, we take the outcome of the R&D process into consideration. We discuss the level of realism of the assumptions made by each particular option analysis and suggest more sophisticated approaches. It should be noted that we present the discussion in a non-technical manner as the focus of the paper is on what actually happened with the R&D options rather than on the mathematics behind the option models that have been documented elsewhere.

The rest of the paper is organized as follows. Section 2 summarizes the options approach to R&D and discusses the fundamental problem of the assumption of complete markets. Section 3 gives three real life applications of option valuation

² Naive refers to a static NPV approach that does not take into account that the project will be abandoned if market conditions are unfavorable at the moment of market introduction.

studies. It explains why option valuation may lead to more deliberate conclusions than traditional capital budgeting methods. Furthermore, it gives detailed information about the actual development of the R&D cases and discusses the implications that arise from these retrospective insights. Section 4 discusses the overall implications for managing R&D options. Section 5 concludes the paper.

THE OPTIONS APPROACH TO R&D

Background

The key parameter in any real option valuation model is the uncertainty of the present value of estimated future cash flows resulting from the irreversible follow-on investment. Option analysis in R&D builds upon the flexibility that the decision on investment in worldwide marketing and in new production processes is being deferred to the moment of launching the new product. Meanwhile research, necessary for creating the option, is conducted. Hence research provides an option on future market introduction. The research costs until market introduction determine the price of the option. The final decision on market introduction is based on the project value at that moment. If this value is negative, the investment will not be made and the loss of research costs is taken. The option will not be exercised. If the project value is positive at that moment, market introduction takes place. Option analysis provides the crucial insight that market introduction is contingent and that the relating investment decision is being taken on a future date with more information and at reduced market

³ Also observed by the business press, e.g., see “Management Fashion: Fading Fads”, *The Economist*, April 22, 2000.

and technological risk. The option value is always positive because market introduction does not take place when the project value at the moment of market introduction is negative.

Option Valuation Models

Two types of financial options exist: options to buy a specific asset at a future point in time against a pre-determined price (call options) and options to sell a particular asset at a future moment against a pre-determined price (put options). If we transfer the analogy of financial options to strategic management, the following types of real options can be analyzed: options to abandon a project, to alter the operating scale of an investment, to open up future growth opportunities, to postpone or stage investments, and to switch within different input or output opportunities (Trigeorgis 1996). In this paper the focus is on real options in R&D that are a precondition to open up opportunities for future growth (call options).

Option valuation can either be based on a discrete time approach or on a continuous time approach. The result of the latter is a closed-form solution (formula). Rigorous treatment of discrete time models for option valuation can be found in Cox, Ross and Rubinstein (1979) and Trigeorgis (1996). The initial continuous time approach to option valuation is developed by Samuelson (1965) for an option that does not have a fixed exercise time and that can be exercised at any moment. When options can be exercised at any moment, they are labeled American options. When these options do not have a fixed exercise date they are perpetual. The seminal continuous time approach to the valuation of options with a fixed exercise moment that can not be exercised before this moment (European options) has been developed by Black and Scholes (1973) and Merton (1973).

A final distinction to be made is between options on irreversible investment (simple options) and options on subsequent options (compound or growth options). Kester (1984) has initially pointed out that options on subsequent options to invest in a stream of future projects represent a significant part of company value. Most research projects are excellent examples of compound options where an initial R&D investment opens up a chain of interrelated options on follow on stages before a final decision on product launch. Lee and Paxson (2001) develop a framework utilizing complicated compound exchange options pricing techniques.

The Assumption of Complete Markets

We single out the assumption of complete markets that is underlying option pricing theory for a more thorough discussion because this vital assumption goes against real option pricing in R&D. The valuation of real options is based on option pricing in financial markets as opposed to real markets, and uses an arbitrage argument. The crucial insight is that by creating a suitable portfolio of a financial option, the underlying asset and a bond, this portfolio is instantaneously riskless. With financial options, the creation of this portfolio is not problematic since all instruments in the portfolio are traded. In the case of real options, the underlying asset is not traded and the portfolio can only be created in an artificial way by assuming the existence of a traded asset that is perfectly correlated with the underlying asset. More generally, when it is assumed that markets are complete, all risk can be perfectly hedged by trading securities. This makes it possible to calculate the present value of future net cash flows (the underlying value of the option) from an initial strategic investment as if the project were traded, using the firm's cost of capital as the appropriate discount

rate. Next, the option value can be calculated with an option-pricing model using the risk-free rate of interest.

The replication requirement that demands that the stochastic components of the return on an R&D project and the return on the traded asset are perfectly correlated, i.e. for every sample path of the realization of the uncertainty, will likely not hold in R&D practice. Decision analysis or dynamic programming, a mathematical technique used for optimization of sequential decisions under uncertainty, provides a solution to this issue. Unfortunately, with dynamic programming the appropriate discount rate is not readily observable and as a consequence, the approach requires an exogenously specified discount rate that reflects the decision-maker's attitude toward risk. Smith and Nau (1995) and Loch and Bode-Greuel (2001) demonstrate under the assumption of partially complete markets how decision analysis and option pricing methods can be integrated. However, this integrated analysis requires managers involved in the assessment to specify their utility functions. At the early stages of R&D that are the focus of this paper, such an analysis may be arduous. Moreover, given that decision analysis and option pricing essentially give the same answer or range of solutions (Dixit and Pindyck 1994, ch.4; Smith and Nau 1995), it seems reasonable for ease of convenience to assume complete markets when applying (financial) option pricing models to early stage R&D. So, throughout this paper we assume that a synthetic portfolio of assets can be created in such a way that perfect correlation exists between the project value of the R&D (the underlying asset) and an asset traded in the financial markets.

Parameter Estimation in General

Financial (real) call option pricing models generally use six input parameters: Stock price (present value of expected future cash flows resulting from follow on investment), exercise price (present value of follow on investment cost), volatility of stock return (variability of growth in project value), time to maturity (time until the investment opportunity fades away), risk-free rate of return, and dividend payments (value lost by waiting to invest).

When option valuation techniques are applied to R&D projects some of these parameters can easily be observed or approximated. The risk free rate of interest, for example, can be set equal to a government bond with the same time to maturity as the R&D option. Under the assumption that R&D is a prerequisite to create a new product (an option on product launch), the value of waiting to invest needs not to be considered when valuing R&D options; that is, the company will not be able to launch the new product prior to the end of the R&D stage. The exercise price of an R&D option may be set equal to the present value at the moment of industrialization of the irreversible cost of the follow on investment, i.e. investment in production capacity, necessary marketing costs, and costs associated with up-scaling or learning. As these costs are made before or at the moment of industrialization, they are relatively short-term oriented, and reasonable estimates of these costs are obtainable by means of interviews with managers involved in the R&D process.

The time to maturity (time-to-go-market) may be more difficult to determine. The time to go market may be assumed fixed when two conditions hold. First, market introduction before successful completion of the R&D stages may have severe implications on market performance. This condition is in line with findings from Crawford (1992) and Griffin and Page (1993), who argue that reducing time-to-market is only advisable when this does not limit the probability of success of the

final product to be introduced to the market. Second, when waiting to introduce a new product leads to a loss of first mover or pioneering advantages. In markets where strong first-mover advantages (Lieberman and Montgomery 1988) exist, management will typically exercise R&D options just at the moment of market introduction when the NPV is positive at that moment. Since waiting is useless due to evaporating first-mover advantages, these R&D options may be considered as European.

Under competitive circumstances where delayed market introduction is beneficial, such as the existence of second-mover advantages (Urban et al., 1986; Tellis and Golder, 1996) or the fear that the new product may cannibalize existing products of the firm (Conner, 1988), a company may postpone market entry and the R&D option should be considered as an American option. As this category of options can only be analyzed by numerical analysis, the valuation of American real options is more complicated than European real options. For this reason, many applications of R&D option valuation focus on projects with a fixed time to maturity, assuming that the option will be exercised on the moment of industrialization.

The present value and the variability of expected future cash flows resulting from the irreversible follow on investment are difficult to measure since estimates are required with a long time horizon. Suppose R&D takes five years to completion and market saturation will be reached five years after introduction of the new technology. In that case, management is asked to estimate sales volume, price levels, market share and product cost levels up to ten years after the initial R&D decision. Moreover, the spread between the cash flows that result from this analysis at the moment of market introduction must be estimated. This puts the procedure of cash flow and variance estimation at the heart of R&D option valuation. Unlike with financial option valuation, historic time series concerning developed technologies are likely to be

absent, or if available, it will be questionable whether they approximate the variability of growth in the new R&D project value.

In the first case study to be presented next, we used historic time series of energy prices to estimate the variance of the underlying project value, assuming that this variance would reflect future volatility in these energy prices. In the second study, we used historic business events in a representative time frame and derived the variance as a function of the expected number of business events and the expected impact of these events. We assumed that representative historic business events over a certain period of time would mirror the number and impact of future events in the same market for a similar period of time. In the final case that we studied, the variance was based on management estimates that were gathered by means of in-depth interviews with managers involved in the R&D project.

CASE-STUDIES

Overview

The first case-study concerns applying the initial Black and Scholes (1973) continuous time option pricing model to an R&D project aimed at developing a new production technology at Corus (the merger between British Steel Corporation (BSC) in the United Kingdom and Hoogovens IJmuiden (Hoogovens) in the Netherlands). The second study relates to developing and applying a discontinuous (jump) model to value an R&D option that aimed at developing product technology for multimedia applications at Philips Electronics. The third case concerns the application of a financial option pricing model on two risky assets (Stulz 1982) to value the option of

simultaneously developing two product standards concerning product technology at Philips Electronics.

R&D as an Option on Renovating a Production Process

Background

Our first study borrowed directly from financial theory by applying a continuous probability distribution of future cash flows resulting from an irreversible follow on investment in a new production technology while this investment was contingent on the development of an R&D option. The R&D option concerned investment in coal-based iron making, a new and energy-sensitive production process studied by Hoogovens IJmuiden, in co-operation with BSC at the beginning of the 1990s. Development of the new production technology offered an alternative for the conventional blast furnace process route. The process used fine ores and coal directly, and coking and agglomeration processes would no longer be required. Based on traditional criteria, uncertain energy conditions made it questionable whether the management should invest in R&D (a pilot plant) to develop this advanced production process. The NPV of the project appeared negative, and the NPV of the pilot plant as a stand-alone project was negative too. Based upon this unfavorable outcome, management would not consider investment in R&D.

Option Modeling

The first step in the investment process, the development of a power plant, could be framed and valued as buying an option on the total conversion of the existing process,

dependent on fluctuations of the energy price (Lint 1992). Consequently, the seminal Black and Scholes Model (1973) was applied with the present value of the energy-dependent cash flows resulting from the irreversible follow on investment as the underlying value. The variance of historic time series in the coal price and the oil price was used as an approximation of the variance of the underlying value. Geometric Brownian motion modeling⁴ of spot prices is extensively discussed and standard in the real options literature. Brennan and Schwartz (1985), Dixit and Pindyck (1994), and Smith and McCardle (1998) provide detailed studies in this field. Our –simplified- option analysis provided a balanced method for the problem concerning investment in the pilot plant. It appeared that it was worthwhile to create the opportunity of a total conversion of the production process not in spite of, but just because of volatile energy prices.

Retrospection

In retrospection it appeared that the assumptions behind our option analysis did not match reality. First, it seemed that the exercise time of the option was not fixed. There appeared no necessity to shut down the coking plants or to reconstruct or replace the existing blast furnaces as assumed when analyzing the R&D option at the beginning of the decade. By optimizing the *existing* production process and running efficiency programs, coking plants were kept in good operational condition and cost price advantages of the new versus the conventional production process were minimized during the 1990s.

⁴ Characteristics with respect to the assumption of a geometric Brownian motion are that percentage fluctuations in the expected market value per time interval are uncorrelated and that the standard deviation of the fluctuations is proportional to the time interval (for a treatise see Dixit and Pindyck 1994, p.71-73).

Second, the technology under consideration changed during the lifetime of the option (the characteristics of the technology were not a constant). R&D efforts were redirected to the engineering of a so-called Cyclone Converter Furnace (CCF) plant. The CCF iron making process extended knowledge obtained during the research stage of the previous R&D project.

Third, an unforeseen alliance with a United States of America-based steel company created the opportunity to reduce development risk. The CCF development resulted from research and pilot plant experiments carried out in Europe and the USA during the 1990s. During this period, different corporate laboratories, research institutes and universities studied elements of the process. However, the main part of development, i.e. the large scale pilot plant work, was carried out by Hoogovens as an extension of studying the former R&D project, and by a Direct Iron-making team in Pittsburgh. Hoogovens studied the pre-reduction and pre-smelting of fine ore in a melting cyclone, whereas the USA project team studied the in-bath melting process. In 1995 both parties agreed on a full technological exchange and decided to jointly carry out further development of the CCF technology in order to expand the potential of the new technology and to share development risk.

Fourth, exposure to technical up-scaling problems was considered more important by the management than exposure to the movement of the underlying energy prices of the technology option. Management put much more weight on technological uncertainty in the R&D stages as opposed to the exogenous uncertainty reflected in energy price movements. In particular the up-scaling problem was explicitly considered. Although the initial technology was proven under laboratory conditions, minor chemical and/or physical reactions that would not influence the process at small scale might play a major role at large scale operations.

Implications from an options perspective

From an options based framework it might have been a closer match to reality to model the R&D option as a compound option (an option on CCF offering an option on a full conversion of the Hoogovens steel works). However, it remains questionable whether the development of CCF technology as an extension of the development of the previous research, or the alliance with USA steel companies to jointly develop CCF could reasonably have been foreseen when the initial R&D option was evaluated. Another observation is that the exercise time of the R&D option apparently was not fixed. This means that any European option-pricing model falls short to value the R&D option appropriately. Chi et al. (1997) propose a model that relaxes the assumption of a fixed time to project completion and take into account that a development project that requires an uncertain time to build can still provide some payoff if terminated without achieving the initially envisioned performance objectives.

A final approach that might have been considered would have been to model the R&D option as a forward start (Hull, 1996) American perpetual option. The R&D option was forward since the R&D was necessary to create the option on future conversion of the production process. The option was American since after the R&D stages, technological uncertainty would be resolved and the option could be exercised at the moment at which the project value would pass a certain threshold (McDonald and Siegel 1986), with uncertainty based on the movement of the energy prices related to the underlying value. The option was perpetual since in principle it would last forever once created. Modeling the R&D option in this perspective might have

been more realistic. However, a fixed time to completion of the R&D stages would still be a necessary condition.

R&D as an Option on Market Introduction

Background

At Philips Corporate Research an innovative technology was developed in the mid-1990s: optical recording with the use of tape. The best of both worlds was combined: an optical (laser) system (hence no decay) and an enormous storage capacity (tape) of 75 GByte (with extension opportunities up to 1 Terrabyte). This was a hundred times the capacity of the compact disc (CD) and seven times more than the double layered digital versatile disc (DVD). Optical tape was a major research opportunity because market segments with multi-billion dollar turnovers annually (data storage in audio, video and PC) were at stake. Optical tape was expected to suffice future demand for large data storage as the technology provided an attractive way to store and distribute very large amounts of data. From a technological point, the project was in the research stage during the mid-nineties and important uncertainties existed concerning the feasibility as a consumer product.

Option Modeling

R&D projects in the field of multimedia were characterized by a number of exogenous events that might substantially change the underlying value during subsequent stages of development. The application of a jump option pricing model enables management to capture business and technology events that change the

underlying project value discontinuously. Jump models are widely discussed in real option theory. Baldwin and Meyer (1979) considered Poisson jump processes and irreversible investments in real assets. McDonald and Siegel (1986) examined investment decisions with a positive probability that the present value of future cash flows jumps to zero in general. Schwartz and Moon (1999) provided a model for the pharmaceutical industry in which the value of the project may jump to zero at any moment. Brach and Paxson (2001) provide a jump option model for a gene-to-drug venture.

It was shown (Lint and Pennings 1998), that the option value of the R&D project on optical tape recording could be approximated with the initial Black and Scholes (1973) formula where the variance of the underlying was replaced by the product of a parameter representing the number of annual expected business shifts and the square of a parameter that is a yardstick for the expected absolute change in the underlying value at every business shift. The option value calculated this way appeared to exceed the cost of creating the option (the research cost). So, the decision to start with the research on optical tape was justified.

Retrospection

It appeared at the end of the 1990s that the optical tape recording project was actually overhauled by the development of the digital versatile disc (DVD). In particular development and market introduction of the recordable CD and the subsequent introduction of the recordable DVD in combination with advanced data compression techniques took the wind out of the sails of optical tape recording. Furthermore, the data storage capacity of DVD appeared sufficient for the consumer electronics and personal computer businesses in the foreseeable future. Moreover, after a prototype of

the optical tape recording mechanism had been built and demonstrated successfully, unforeseen technical constraints emerged during the next steps of development. These technical problems could have been resolved, but would result in higher cost and, consequently, a much higher anticipated consumer price of the equipment. So, it was decided to abandon the optical tape project.

Implications from an options perspective

Although the jump diffusion model cogently captured exogenous shifts, it did not capture endogenous technological uncertainty, such as the simultaneous development of a competing technology *within* the firm and the high risk of a technical failure. This type of uncertainty might be difficult to capture in a practical option-pricing model, but it should have had more emphasis in the option valuation framework. This notion is consistent with theoretical results by Huchzermeier and Loch (2001) who find that in developing a radical technology improvement under high technical uncertainty, the option value of managerial flexibility (that is analogous to financial option value) may substantially be reduced. Furthermore, the observation that the optical tape project was surpassed by the DVD implies that a better way to model the option might have been a simultaneous development perspective.

R&D Option Value in Simultaneous Product Development

Background

The third study originated in an R&D investment decision at Philips Electronics concerning simultaneous development of analog and digital video tape recording at the beginning of the 1990s. The analysis concerned the flexibility value of a

standardization issue in the VCR market. Philips had the choice between developing two new standards, analog and digital, for new 8-mm tape products for the video recorder market, with the same amount of follow-on investment, but with different expected cash flows and risk where (exogenous) uncertainty existed which product standard would eventually prevail in the market.

Option Modeling

The option value of exchanging risky assets is well documented in option theory. The option of exchanging one risky asset for another is examined in more detail by Margrabe (1978). Stulz (1982) provided an initial model for the value of an option on the maximum of two risky assets, while Johnson (1987) presented a complementary model for the value of an option on the maximum of several risky assets. The initial Stulz (1982) model was adapted and applied to determine the option value of simultaneously developing the two product standards in video, see Lint and Pennings (2000). It was demonstrated that this type of option analysis enriched R&D decision making on concurrent development, and that this option valuation led to a more deliberate perspective than net present value analysis.

Option analysis confirmed that creating the option on two standards might be more attractive when the correlation between the payoffs of the two standards was lower. The two video product standards appeared to have a low positive correlation. Since the extra costs of developing improved analog and digital video simultaneously were relatively low, we found that creation of the option to develop both standards was attractive for relatively low investments. As the required investment increased, development of just the digital technology yielded the highest net value. Reasonable errors in the estimated variables had some impact on decision ranges, but did not

substantially change overall results. Disregarding uncertainty and the interdependence between the payoffs of the two standards led to significantly different conclusions based on NPV-analysis. Option analysis showed that keeping options open by developing both product standards simultaneously was optimal for an investment level up to 60% higher than the optimal investment level to develop both standards as determined by NPV analysis.

Retrospection

Philips started research to develop both standards simultaneously. In the mid-1990s it appeared that the conventional analog standard (VHS) with its large installed base remained a very strong technology standard. Moreover, the introduction in the audio field of Digital Compact Cassette (DCC) by Philips yielded a lower diffusion rate than initially expected. DCC had the general advantages of digital technology over analog technology; that is, excellent sound quality and large data storage capacity. Furthermore, DCC was fully compatible with the existing analog cassette technology. Unfortunately, it became clear that the major product advantages were not disruptive enough to excite customers. This observation raised the perceived risk of introducing improved analog or new digital technology in the well-established VHS market where Philips was not a dominant player. Meanwhile research had been started to develop a successive technology (DVD) for CD technology. CD technology was originally developed by Philips in co-operation with Sony and was a major commercial success. It was expected that successful development and subsequent market introduction of DVD would also generate excessive returns. Given these observations, it was decided to abandon further development of a new standard for the video tape market. The

VHS system remained the dominating standard in the 1990s and only Sony kept on marketing its 8-mm tape standard in the camcorder market niche.

Implications from an options perspective

Findings from the industrial organization perspective on excess inertia, installed base, and consumer switching costs appeared to play a major role in practice. An amalgamation of industrial organization insights (e.g., see Farrell and Saloner 1985, or Katz and Shapiro 1985) with option valuation models might have offered a better way to model this R&D option that would have been subjected to a technology standardization contest. Trigeorgis (1996) integrates insights from strategy analysis with option valuation in a discrete time context while Grenadier (1996), Lambrecht and Perraudin (1997), and Kulatilaka and Perotti (1998) have made contributions in a continuous time setting.

In particular, Kulatilaka and Perotti (1999) demonstrate that the effect of increased uncertainty increases the value of investment in a time-to-market option. Although an increase in uncertainty rises the value of the option to wait to invest, the strategic value of early investment rises even more. This establishes a first-mover advantage and prompts early exercise of the option. However, Weeds (1999) shows that two competing firms conducting R&D to get an exclusive patent will anticipate a patent race and delay investment to a greater extent than in the absence of competition. The author draws an analogy with contestants in a long-distance race where the escape for the finish typically takes place at the end of the race. She concludes that in situations where both real option value and strategic interaction arise, it will be necessary to analyze the specific conditions carefully in order to determine whether pre-emption or time-to-wait is dominant.

MANAGERIAL IMPLICATIONS FOR THE STRATEGIC MANAGEMENT OF REAL OPTIONS

With regard to strategic management, two fundamentally different approaches coexist: the position-based approach to competitive dominance (Porter 1985) and the resource-based approach to strategic thinking (Collis and Montgomery 1995). Basically, the position-based approach takes the view that the company's environment (both macro and micro) has more impact on the company's strategy than the other way around. According to this perspective, a successful strategy -a strategy that generates excess returns- is aimed at gaining a sustainable competitive advantage by creating an optimal position in the environment. This view fits quite well with an option approach based on financial option valuation as uncertainty is treated exogenously in financial markets (the holder of a financial option can not control situational factors influencing the underlying value, such as the price of a stock).

The resource-based approach emphasizes the impact that a company has on the environment with its own resources. This approach assumes that a company can develop unique and superior competences with which substantial competitive advantages can be obtained and that the microenvironment can be altered. In this approach, a successful strategy consists of using unique possibilities and means to fine-tune the microenvironment and to gain competitive advantage. By treating the microenvironment as endogenous (rather than exogenous), the resource-based approach dovetails with our study. The resource-based approach considers the optimal allocation of a company's resources, and hence implicitly the reduction of micro-

uncertainty as the most important task of strategic management (see also Bowman and Hurry, 1993). As discussed previously, we may even leverage a resource-based options approach to cooperation and competition strategies (games) that may substantially reduce endogenous uncertainty.

Our retrospective insights trigger the application of more sophisticated methods to R&D option valuation as outlined before. Unfortunately, complicated methods to R&D project selection have had little impact in practice, whereas conceptually simple models such as checklists and scoring approaches are used widely. Most of the quantitative information necessary for a detailed analysis at the R&D stages is usually absent or partly in place. Also, management generally has to judge numerous –relatively small- R&D investments simultaneously (portfolio management) rather than making one major single investment decision. Cooper et al. (1999) provide evidence that traditional financial methods (NPV and ROI) are used frequently in R&D portfolio management, but fail to generate high-value new products. Strategic approaches and scoring methods yield much better results. The authors find that the firms from their sample that stand out in new product performance tend to use multiple methods to analyze and consistently manage the R&D portfolio.

As traditional financial approaches to R&D appear to be used widely, but perform badly, we suggest to enhance conventional R&D resource allocation by the more thoughtful framework of option valuation. As scoring methods are used less frequently, but appear to perform excellently, we suggest to combine option valuation with a scoring approach. Thus, we may be better able to capture the organizational dynamics inherent in R&D option valuation. To keep matters concrete and simple, we suggest to develop a modular approach to R&D option valuation and portfolio

management. Standard (closed-form) option pricing models, ranging from simple to complex (compound with multiple uncertainties), may be amalgamated with a set of scoring elements to capture organizational and strategic matters cogently⁵. This way, the conventional financial approach to R&D project selection and portfolio management is enhanced substantially by means of an options approach that is realistic, comprehensible and manageable.

CONCLUSION

It follows from our study that R&D option valuation enhances conventional financial approaches to R&D resource allocation, but the approach must be linked closer to real life conditions. We describe the option valuation and actual outcome of three R&D options concerning production process improvement, development of a new technology standard and simultaneous product development. We find that the characteristics of the projects that we considered, were not constant. The strategic and organizational dynamics of the technologies apparently played a dominant role in the evolution of the R&D options that we studied. The study described here seems to be a first attempt to give some detailed descriptions of option valuation in a real R&D environment *throughout time*, as opposed to the usual hypothetical, static cases presented in text books or articles. Our study provides a somewhat better understanding of the pros and cons of managing and assessing R&D projects by building upon option pricing techniques. The results may stimulate R&D managers to

⁵ For example, Lint and Pennings (1999) make a preliminary step by combining the jump option model described above with scoring elements that capture organizational

take into account organizational and strategic matters more extensively when applying an options approach to R&D.

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