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Theory and Methodology

The option value of advanced R&D

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Abstract

Existing tools for making R&D investment decisions cannot properly capture the option value in R&D. Since many new products are identified as failures during the R&D stages, the possibility of refraining from market introduction may add a significant value to the NPV of the R&D project. This paper presents new theoretical insight by developing a stochastic jump amplitude model in a real setting. The option value of the proposed model depends on the expected number of jumps and the expected size of the jumps in a particular business. The model is verified with empirical knowledge of current research in the field of multimedia at Philips Corporate Research. This way, the gap between real option theory and the practice of decision making with respect to investments in R&D is diminished. © 1997 Elsevier Science B.V.

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1. Introduction

Major international companies with large research departments time and time again face the difficulty of selecting an appropriate portfolio of research projects. The net present value (NPV) rule and other discounted cash flow techniques for capital budgeting seem to be inapt to build a portfolio of research projects as they favor short term projects in relatively certain markets over long term and relatively uncertain projects. Without turning risks to develop products with uncertain future payoffs into opportunities to gain competitive advantage, companies cannot survive in the long run. The costs of developing these new products in uncertain markets are low in comparison to the investment costs which are necessary for a global market introduction. Therefore R&D investments can be thought of as the price of an option on major follow-on investments. Accordingly, the theory of real options can be applied to R&D investments as we will discuss next.

Up to the moment of market introduction, management has the flexibility to react on unexpected events which change the NPV of the research project and hence to revise the decision to continue with research on the new product and eventually market this product. The theory of real options, introduced by Kester (1984) and Myers (1984), takes market uncertainty and managerial flexibility to abandon projects that appear not to be fruitful into account. From a real option perspective, it might be worthwhile to undertake R&D investments with a negative NPV when early investment can provide information about future benefits or losses of a project, a notion that is consistent with the analysis by Roberts and Weitzman (1981). Since R&D projects are characterised by a long planning horizon and high uncertainty, the value of managerial flexibility can be substantial. Only when market and technology uncer-

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tainty tend to zero and the investment that is required for market introduction of the newly developed product is reversible – i.e. the investment can be undone and expenditures can be recovered – the conventional NPV-rule for capital budgeting yields the same results as real option analysis. Mitchell (1990) outlined in this journal a real option framework for developing a strategy for technology and argues that it could be a major tool for new business assessment since senior business management in successful corporations is constantly probing the R&D organisations for quantifiable impact or potential benefit from technical programs. We will extend his strategic view with a quantitative model for the option value of R&D, which can be used for managerial decision making.

The aim of this paper is to present a model for estimating the uncertainty of the underlying asset of R&D options and to diminish the gap between theory and empiricism in real options analysis, concerning R&D investments. Almost all theoretical contributions on real option analysis end with the conclusion that theory has run ahead without empirical support; see for example the recent review of investment under uncertainty in Dixit and Pindyck (1994). In co-ordination with Philips we developed and implemented an easy model to value their research projects and to get the finance department involved in research at an early stage. A study by Szakonyi (1994) shows that on average there does not exist any discussion between finance and R&D departments. This stems from traditional product development processes in which R&D, finance and marketing appear sequentially. In order to develop an appropriate framework, we will briefly discuss major issues in options assessment. We will respectively give attention to the exercise moment (European versus American option), risk-neutral valuation, non-tradability, biases in estimates and discontinuous arrival of information due to business shifts.

Real options investment analysis mainly uses the Black and Scholes (1973) formula for pricing European options. These options cannot be exercised prior to maturity in contrast to American options which can be exercised at any moment up to maturity. R&D options are typically European since market introduction before successful completion of the R&D stages may have severe implications on future market share. On the other hand, by waiting to introduce the new product, a company may lose first mover or pioneering advantages, see for example Urban et al. (1986). Especially in markets which are characterised by decreasing product-life cycles and growing competition, competitive advantage primarily exists in the early stages of the product-life cycle. Therefore management will exercise R&D options just at the industrialisation moment when the NPV is positive at that moment. For an overview of the current status of real option theory and applications, see Trigeorgis (1993).

The Black and Scholes formula was originally derived for options in financial markets, where it has become a major tool for valuing contingent claims. For the derivation of their formula Black and Scholes assumed that the asset, on which the option is contingent (the underlying asset) is traded and constructed a hedge portfolio with a long position in the asset and a short position in the option. They used a no-arbitrage argument to argue that this portfolio is riskless. This argument enables us to use risk-neutral valuation. With real options however, the underlying asset is non-traded and hence we need the assumption of complete markets in order to use risk-neutral valuation; see for example Majd and Pindyck (1987). When markets are complete, all risk can be hedged by trading securities. Complete markets are assumed throughout the literature on capital budgeting including this article. It allows us to derive the strongest results.

A far more striking problem that arises from the observation that the underlying asset of a real option is non-traded concerns the estimation of the volatility of the underlying asset. In contrast with financial options, there are no historic time series that enable us to estimate the uncertainty of the underlying asset. However, it is a well-established fact that the option value is very sensitive to the uncertainty of the underlying asset. Reasonable estimates of the volatility are therefore required. Often, the value of the underlying asset depends on price movements of natural resources. Brennan and Schwartz (1985), for example, value the option to mothball and later reactivate a copper mine. With a time series of copper prices, an estimate of the variance can be obtained. Another example is given in Quigg (1993). She values the option to wait to develop land and uses data on land transactions to get an estimate of the variance. Options in R&D require another estimation approach. At Merck, they take stock volatility in order to approximate the volatility of the NPV of future cash flows resulting from pharmaceutical R&D; see Nichols (1994). Using judgements of senior management to attain reasonable values for the uncertainty provides another approach. Unfortunately, no convincing heuristics have been proposed so far.

Another interesting difference with financial options is imbedded in the underlying value of the option. While the current value of the underlying asset of financial options is known, the underlying value of real options is stochastic at present, as it hinges on estimates of future profits. However, uncertainty in the estimate of the underlying value will not change the option value at present nor the investment rule at maturity of the option. This result follows from the irreversibility of the investment. When the option is in the money at maturity, the investment rule is to invest. In fact, the usual NPV-rule applies. By the stochastic nature of the underlying value, the option may appear to be out of the money after the product has been introduced as well as deeper in the money. However, when the underlying value is an unbiased estimator, the expected value of the project value outcome equals the estimated underlying value. Since at maturity the investment rule only depends on the underlying value and hence the spread around this value is irrelevant, estimation errors in the underlying value do not affect the option value and can hence be assumed to equal zero.

In this article we assume that unbiased estimates of net cash flows that are generated by the irreversible investment are provided to management. Clearly, this assumption is used in all discounted cash flow studies. We also assume that the costs associated with the irreversible investment, required for market introduction, and the necessary time for completing R&D can be given with reasonable accuracy. In order to focus on uncertainty and the arrival of information over time, we will abstain from dividends.

The approach we propose in this paper builds upon discontinuous arrival of information that affects the present value of future net cash flows. Black and Scholes analysis assumes that the underlying asset follows a geometric Brownian motion, which is highly questionable for the value of innovative research projects. It implies a continuous arrival of information that changes the underlying variable. In financial markets the underlying assets are traded and new information will directly be reflected in the prices of the assets. Information that affects future net cash flows of research projects will however arrive at discrete points in time. So in real markets managers will not continuously adjust the present value of future cash flows, but will only adjust it when information with strategic impact arrives. Moreover, from interviews with senior management we found that currently the financial status of research projects, once undertaken, will only sporadically be revised in the case of arrival of new information. Examples of adjustments in the present value of future net cash flows include the discovery of new production technologies resulting in cost reduction, or the fast entrance of competitors with a market penetrating strategy so that future prices erode. In the first example cash outflows drop and accordingly the present value of future cash flows increases. The second example induces a reduction in cash inflows and hence in the net present value of future cash flows. A Poisson (jump) process would be able to describe these movements in the underlying variable. This way, the variance of the underlying asset can be decomposed in three parameters, respectively reflecting the expected number of information arrivals and the expected jump sizes of both upward and downward shifts.

When a business shift has occurred, management can revise the business plan, recalculate the option value and rebalance the R&D portfolio. Positive shifts might result in a higher budget and more R&D efforts while negative shifts might have an opposite effect. Investment decisions with a positive probability that the present value of future cash flows jumps to zero have been examined by McDonald and Siegel (1986). Jumps in financial assets in general were first introduced by Cox and Ross (1975). In their paper, the jump process follows a deterministic movement upon which are superimposed discrete jumps. Merton (1976) suggests a model in which the stock price has stochastic jumps superimposed upon geometric Brownian motion. From our experience that information arrives discontinuous in time we present a model in which the present value of future cash flows follows a deterministic movement upon which are superimposed stochastic jumps. Baldwin and Meyer (1979) also consider Poisson jump processes and irreversible investments in real assets. Their model differs from our approach in that the arrival rate of investment opportunities – instead of the arrival rate of information that changes a single project value – is Poisson distributed, though the arrival of a new investment opportunity might be information that affects the value of an existing project.

Strebel (1992) argues that business discontinuities are often accompanied by sharp shifts in competitive behaviour. Competitive shifts consist of standardisation shifts and rejuvenation shifts. Successive examples of these shifts include standardisation of technique and introduction of differentiated products, designed to increase perceived value. With the shrinking product and technology life cycles in today's markets, he asserts that standardisation shifts often follow closely on rejuvenation shifts. We found that such competitive breakpoints frequently occur in the product development process and have a large impact on the decision whether to industrialise the new product at the end of the R&D stage or not.

This article is organised as follows. In Section 2 we develop a model for valuing options on R&D projects. From approximating the distribution of the present value of future net cash flows by a lognormal distribution, we can deduce the standard deviation of the lognormal distribution from the parameters in the jump diffusion model. Subsequently, the option value of advanced R&D is calculated. Section 3 deals with a case on the option value of R&D on optical tape that we studied at Philips. From a sample of jumps during the R&D process in the field of multimedia, an estimate of the uncertainty of the underlying asset will be derived. Finally, Section 4 concludes.

2. A real option model for valuing R&D projects

In the introduction we argued that a geometric Brownian motion does not seem to fit with a managerial decision making process. It seems that uncertainty about the NPV of the new product at the moment of industrialisation arises due to unforeseen events. A manager will only exercise a real option – market the new product – at the moment of industrialisation (T) when the expected present value of future net cash flows (S) exceeds the investment sum (I). The expected present value of future profits will be adjusted a random number of times between the present time (t) and the moment of industrialisation. We will assume that the waiting time until new information arrives, w, that has such strategic impact that future cash flows will be revised, is exponentially distributed with parameter θ:

$$W_i \sim \exp(\theta). \tag{1}$$

During this waiting time, no random shocks occur. A major advantage of the exponential distribution is the no-memory property. This implies that the probability of arrival of new strategic information does not depend on the arrival of past strategic information. The exponential distribution also implies that the number of strategic information arrivals, n, follows a homogeneous Poisson process with intensity parameter $\lambda = 1/\theta$. Hence the expected number of arrivals of strategic information during the research period $[t,T]$ is equal to $\lambda[T-t]$. The parameter λ will typically depend on the kind of business of the research projects.

Philips acts in technology-based markets which are characterised by a large number of events as there exists both technology and market uncertainty; see Moriarty and Kosnik (1989). Technological improvements are rapidly expanding and it is crucial which standard will be accepted in the market. At the same time consumer preferences rapidly change and product life cycles are shrinking. Both stylised facts have a positive impact on the number of business events during the R&D stage. During this stage standardisation of new products is the most important goal, since only one technology standard can survive. Well-known examples include the analog video market in which Philips (V2000), Sony (Betamax) and Matsushita (VHS) competed for an analog video standard and recently the digital video standard for which Philips and Sony jointly competed with Toshiba and Time Warner.

From a financial perspective, market introduction of a new product depends on the NPV at time T. The NPV in turn depends on the preferences of software producers who will eventually choose the new standard. Issues on standardisation can be considered as events as they positively affect market uncertainty. So in technology based markets λ will be large. On the other hand irreversible investments in, for example, infrastructure will not yield very much strategic information during the research period, and hence λ will be lower in these markets.

The market value of future net cash flows conditional on industrialisation, based upon all information at time t, $\Omega(t)$, with $\Omega(t) \subseteq \Omega(s)$ for $t < s \leq T$, is equal to

$$S(t) = \sum_{i=0}^{\infty} \exp(-(T+i)\mu) E[\mathrm{CF}_{T+i} | \Omega(t)], \quad (2)$$

where μ denotes the firm's cost of capital and CF_{T+i} the net cash flow, i years after the irreversible investment. We assume that all cash flows have equal risk characteristics and hence that μ is constant for all cash flows. The option value, F, at the moment of industrialisation is defined as

$$F(S(T)) = \max[0, S(T) - I]. \quad (3)$$

Since T is fixed and the option cannot be exercised prior to the moment of industrialisation as industrialising the new product requires full completion of the R&D stage, the option is European.

Under some conditions, Black and Scholes (1973) show that it is possible to create a riskless hedge portfolio and the resulting differential equation is free of risk preferences. Consequentially, they can take any growth rate for the underlying asset and calculate the expected value of the underlying asset at maturity. Risk neutral valuation, which uses the risk-free rate as a growth rate of the underlying asset, is most common in financial markets to value contingent claims. When the underlying asset follows a jump diffusion process, Merton (1976) argues that it is not possible to construct a riskless hedge portfolio, consisting of stocks and options. He also shows that the expected return on these securities should equal the riskless rate, when it is assumed that the Capital Asset Pricing Model holds and the jump component will be uncorrelated with the world economy. In that case the CAPM β is zero and the jump components only represent non-systematic risk. When the underlying variable is traded, the non-systematic risk can be diversified and Merton (1976) derives an option pricing formula, but unfortunately it is not a closed form solution.

Jump components in R&D projects will in general be uncorrelated with the aggregate market, as most of these jumps occur due to innovations in technology, actions of competitors, changes in strategy or shifts in demand of particular lines of business. Hence, assuming complete markets, we can apply risk-neutral valuation and take the risk-free rate, r, as growth rate of the underlying asset.

From the previous analysis we suggest that the process for $S(t)$ in a risk-neutral world follows a jump process with drift r:

$$\mathrm{d}S(t) = rS(t)\mathrm{d}t + S(t)\mathrm{d}n, \quad (4)$$

where $\mathrm{d}n$ equals 0 with probability $1 - \lambda \mathrm{d}t$ and a jump of size Ξ_i with probability $\lambda \mathrm{d}t$. When the jump amplitude, measured as a proportional increase in the underlying variable, is deterministic and positive, the process for S boils down to the pure jump model, suggested by Cox and Ross (1975). The idea of stochastic jump amplitudes closely matches our perception of management's decision making process, as the impact of new information is random. From the observation that the underlying variable does not change when no new information arrives, a geometric Brownian motion that captures continuous changes in the value of the underlying asset can be disregarded. So our basic model is less complicated than Merton's (1976) jump diffusion model. Our analysis rather focuses on a model for the stochastic jump amplitude and the consequences of the use of the stochastic jump amplitude model in a real setting.

An important issue is that we can only observe jumps with amplitudes that will be different from zero. This results from the definition that jumps only occur when strategic information arrives which alters future cash inflows or cash outflows. There is a probability that the strategic information affects the cash inflows and cash outflows in the same way, such that their joint impact on the underlying variable will be close to zero. Since this will seldom occur in practice, we will assume a probability density function which will take the value of zero when the jump amplitude is zero. In our analysis we will treat the jump amplitude as a product of two random variables, one variable describing the direction of the jump and one variable describing the absolute size of the jump. The Weibull distribution with shape parameter 2, known as the Rayleigh distribution, seems to fit the absolute jump size best. The jump amplitude, Ξ_i, is therefore given by

$$\Xi_i = X_i \Gamma_i, \tag{5}$$

where

$$X_i = \begin{cases} 1 & \text{with probability } p, \\ -1 & \text{with probability } 1-p, \end{cases} \tag{6}$$

$$\Gamma_i | X_i \sim \text{Wei}(\gamma_{X_i}, 2). \tag{7}$$

When $p = 0.5$ and $\gamma_{-1} = \gamma_1$ the distribution is symmetric. The model however allows for non-symmetric jumps, so that up-side jumps may be more likely than down-side jumps. Illustrations of a symmetric density and an asymmetric density of Ξ_i are respectively given in Fig. 1a and Fig. 1b.

Of particular interest is that it must hold that the expected jump size is larger for down-side jumps than for up-side jumps when upward jumps are more likely than downward jumps. This results from the observation that the unconditional distribution of the jump amplitude always has to equal zero. Otherwise the expected future cash flows should be changed since these cash flows reflect the mean of the expected jump sizes. For empirical purposes it seems that it is more convenient to assume a symmetric stochastic jump amplitude. The mean and variance of $\Xi_i | X_i$ are given by

$$E[\Xi_i | X_i] = \tfrac{1}{2}\sqrt{\pi}\, X_i \gamma_{X_i} \tag{8}$$

and

$$VAR[\Xi_i | X_i] = \left(1 - \tfrac{1}{4}\pi\right)\gamma_{X_i}^2. \tag{9}$$

Hence, the unconditional mean of Ξ_i is zero when the following equation holds:

$$p\gamma_1 = (1-p)\gamma_{-1}. \tag{10}$$

It is straightforward that $\gamma_1 = \gamma_{-1}$ when the probability of positive and negative jumps is equal. In that case we will refer to these parameters as γ. Following the lines of Merton (1976), the resulting sample path for $S(t)$ will show finite jumps with stochastic amplitude at discrete points in time. A realisation of such a sample path, with $(T-t)$ is 3 years, an expected waiting time for strategic information of half a year and an expected absolute jump amplitude

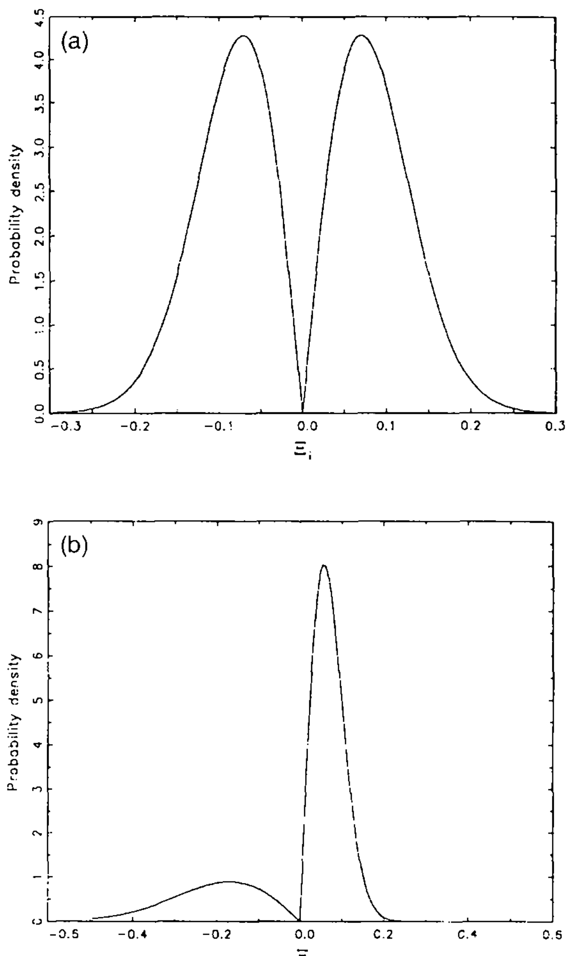

Fig. 1. (a) Density of jump amplitude Ξ_i with $p = 0.5$, $\gamma = 0.1$; (b) density of jump amplitude Ξ_i with $p = 0.75$, $\gamma_1 = 0.08$, $\gamma_{-1} = 0.24$.

of $0.05\sqrt{\pi}$ is given in Fig. 2. This parameter choice implies that the expected number of jumps is equal to 6.

In order to calculate the option value, we need the distribution of $S(T)$. Observe that $S(T)$ can be written as

$$S(T) = S(t)[\Xi(N) + 1], \tag{11}$$

with for $N \geq 0$,

$$[\Xi(N) + 1] = \prod_{i=0}^{N} [\Xi_i + 1], \tag{12}$$

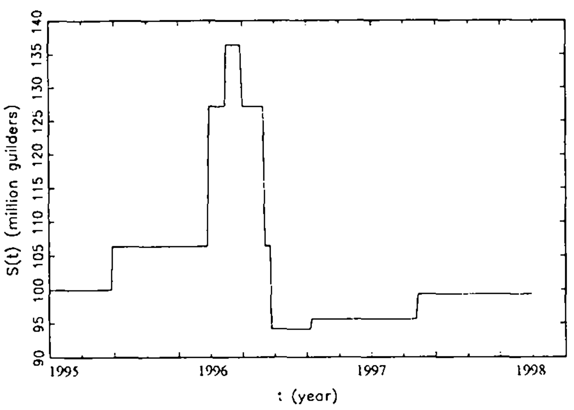

Fig. 2. Process of $S(t)$ up to the moment of industrialisation with $\gamma = 0.1$, $\theta = 0.5$, $T - t = 3$, $r = 0$, $S(1995) = f$ 100m.

where $\Xi_0 = 0$ by definition and hence $\Xi(0) = 0$. The Ξ_i are independent, while N is Poisson distributed with parameter $\lambda[T - t]$. Note that the model in (11) allows a small probability that the underlying asset becomes negative, due to a large down-side jump. Sick (1989) recognises that there is nothing preventing the 'price' of an underlying real asset from being negative. In rapidly changing technology markets, for instance, a technology can be outdated during the research period, since competitors may develop another technology standard. When the value of the underlying asset becomes negative, it is questionable whether the assumption that the research option is European still holds. In the case of a substantial negative jump in the underlying value, R&D management may decide to precipitate abandonment of the research project. Consequently, the option has to be considered as American. However, when the probability that the option will end up in the money after such a firm jump in a downward direction is very small, the option value will be zero in both the European and the American case. In practice, R&D resources are to a large extent committed to a research project for a fixed period of time. Only actions of competitors or other circumstances that make continuation of the research project futile appear to coerce R&D management to stop the project. Therefore, considering the option as European instead of American will not significantly harm the overall results.

It is obvious that the mean of $[\Xi(N) + 1]$ is equal to one. In the remaining part of this section we will assume that $p = 0.5$. Under this assumption, the variance of $[\Xi_i + 1]$ is equal to γ^2, $\forall$i; see Appendix A. The appendix also proves that the variance of $[\Xi(N) + 1]$ equals $\exp(\lambda\gamma^2[T - t]) - 1$. When the value of the underlying asset is assumed to follow a geometric Brownian motion with zero drift, standard deviation σ and a unit initial value, the variance of S_T is given by $\exp(\sigma^2[T - t]) - 1$ and the resulting distribution at the moment of industrialisation is lognormal.

The Central Limit Theorem (e.g. Feller, 1968) states that the sum of logarithmic changes in $S(t)$, i.e. the returns of the underlying asset, converges to a normal distribution when time intervals become arbitrarily small. This result is also found in financial markets. Though it is common that a normal distribution does not adequately fit the observed asset returns as they exhibit fatter tails than implied by a normal distribution, alternative stochastic processes for these returns can only provide better approximations of the true asset price distribution than a lognormal distribution when forecast horizons are relatively short. When forecast intervals get larger, alternative stochastic models for asset returns will yield the same results as the assumption of a normal distribution for these returns. Since R&D projects usually last for several years, the information that is lost when we assume a geometric Brownian motion for the underlying asset with variance $\lambda\gamma^2$ might be negligible. We will test the validity of this approximation by comparing simulation results with the results obtained by the approximating analytical formula for the option value.

The option value of the research project at the moment of industrialisation will be the expected value of the maximum of zero and the net present value of industrialising the new product. The present option value therefore equals

$$F(t) = \exp(-r(T - t))\,\hat{E}[\max(0, S(T) - I)], \tag{13}$$

where the head on the expectation operator denotes expected value in a risk-neutral world. With the assumption that $S(T)$ is lognormal and by applying the usual calculus in the context of the Black and

Scholes analysis, it can be shown that this equation can be rewritten as

$$F(t) = S(t)\Phi\left(d + \sqrt{\lambda(T-t)}\,\gamma\right) - I\Phi(d)\exp(-r(T-t)), \qquad (14)$$

where

$$d = \frac{\ln(S(t)/I) + \left(r - \frac{1}{2}\lambda\gamma^2\right)(T-t)}{\sqrt{\lambda(T-t)}\,\gamma} \qquad (15)$$

and Φ denotes the cumulative density function of a standard normal distribution.

3. Case: the option value of R&D in optical tape recording

A main research topic at Philips Electronics at this moment are innovations in the field of multimedia. Research topics include a variety of differentiated and complementary items, such as blue lasers, multimedia IC's, High Density Compact Disc (HDCD), solid state data storage and optical tape. Philips spends approximately 600 million Dutch guilders (*f* 600m) on research annually, while, in total, Philips spends approximately *f* 3500m on R& D. In this article we analyze the results of the option approach to the research project on optical tape recording and focus on three main issues: technology, market and finance.

It should be noted that the data in this section are stylised and do not necessarily correspond with reality and the standpoints in this article do not represent former or current standpoints of Philips on research or product development policy. The research background of the case, however, is based on the actual situation as Philips has already disclosed the current research and technological status of the project; see Van Rosmalen et al. (1994). The case is used to offer new insight in the option value of advanced R&D and to show how the model can be used as an operational tool for managerial decision making on product development.

First, we will give a brief description of the technology that forms the basis for the optical tape. The new optical tape recording system is based on a very fast rotating polygon mirror. This system combines a high data rate with a high storage density and fast access. The recording system is compact and, apart from the polygon mirror, requires only simple mechanics. As optical storage has entered the audio, data and, now, digital-video domains, the search for higher information densities has led, for example, to lasers with shorter wavelengths. Using higher-quality optics, today's most advanced source-coding techniques (MPEG) and blue lasers, instead of current infrared lasers, will result in a major increase in the CD's capacity, which now contains 784 Mbyte. Moreover, with the latest double-layered HDCD, developed in conjunction with Sony, the CD capacity has already been increased by a factor 10 to 7.4 GByte.

However, advanced multimedia applications in the foreseeable future will require even more storage capacity. Optical tape recording offers a solution to this issue. Also, with optical tape both read and write applications are easily possible. The research on optical tape recording within Philips has been led by the idea of developing a mass storage system for a mass storage application and therefore it should be non-expensive and simple. The concept is originally based on film recording. It is a one-laser system based on beam deflection by a polygon mirror. An objective lens with a field of 1 mm and an aperture of 0.45 can resolve approximately 1600 bits per scan. The data rate is limited by the scan frequency of the polygon. If a data rate in the order of 30 Mbit/s is desirable, which is reasonable for a system with a very high storage capacity, the scanrate has to be around 18 kHz. For a six facet polygon, this results in a rotation frequency of 3 kHz which implies 180000 rotations per minute. Philips has proven that such a device can be made. This way, optical tape recording can provide an attractive way to store and – contactlessly – distribute large amounts of data and therefore provides exclusive opportunities for multimedia applications. At this moment the storage capacity of optical tape amounts to 75 Gbyte. This is a hundred times more capacity than the present CD and ten times more than the double-layered HDCD.

When we take a glance at the marketing aspects of optical tape recording, we note that market conditions for optical tape seem to be flourishing in today's information age. Multimedia and electronic highways will demand high data storage capacities for relatively low prices in the near future. Optical tape might suffice this future demand, but its marketing success will mainly depend on product strategies of competitors, the adoption of software producers and standardisation. Negotiations with other large electronic companies, like Sony, will be necessary for a successful market introduction.

Now that the technological and marketing background of optical tape recording have been described, we will discuss the financial implications of the investment project. Research on the optical tape will take about five years before a potential market introduction of the optical tape. After these five years, in 2000, irreversible capital and marketing expenditures will be required to manufacture the optical tape in large amounts. During these years a lot of events may occur that change future net cash flows. It may even be the case that market conditions change in a negative way and hence market introduction will not be fruitful in 2000 because of large downward jumps.

To be able to calculate the option value, which can be regarded as discounted cash flows plus a flexibility premium, we need estimates of the unknown parameters θ, γ_{-1} and γ_1. Standard textbooks on statistics show that maximum likelihood estimators of these parameters are given by

$$\hat{\theta} = \frac{1}{n} \sum_{i=1}^{n} W_i, \qquad (16)$$

$$\hat{\gamma}_X = \left(\frac{1}{N_i} \sum_{i \mid X_i = X} \Gamma_i^2 \right)^{1/2}, \quad X = -1, 1, \qquad (17)$$

with N_i denoting the number of observations for which $X_i = X$. These estimators are known to be asymptotically normal and efficient. As the number of observations for a historic unique investment project is not large, the parameter estimates may be cumbersome. Pooling data of investment projects in the same business can improve the parameter estimates. The data we obtained from our optical tape investment analysis were mingled with the data we obtained from other investment projects in multimedia. It will do no harm to the results as the risk characteristics of the optical tape project are quite similar to the characteristics of other multimedia projects. To ease computation, γ_{-1} and γ_1 are assumed to be equal. The parameter estimates we obtained are given in Table 1.

Table 1
Parameter estimates

$\hat{\theta}$	0.299
$\hat{\gamma}$	0.107

These parameter estimates are based on a number of events in multimedia that happened between January 1990 and February 1995. Hence the length of the time interval we considered is 5.08 years. In total 17 events are gathered and, by the relationship between λ and θ, it can be verified that the estimate of θ in Table 1 matches 5.08/17. Some of the events studied are company confidential, but most of them are publicly known. All events have been judged by senior management to gauge their impact on the NPV of the different research projects. Events include discussions on standardisation, strategic alliances, patent positions and technological breakthroughs. As our application of a Rayleigh distribution to the absolute jump size may look arbitrary, a chi-squared goodness-of-fit test is used to test H_0: $\Gamma_i \sim \text{Wei}(\gamma, 2)$.

Appendix A shows that we cannot reject H_0 at the $\alpha = 0.10$ level of significance and hence it appears that the Weibull distribution well fits the absolute jump sizes.

Estimates of future net cash flows from 2000 to 2007 are obtained from senior management. They are based on expected market size, the expected market share of Philips and the market profitability. The value of these future cash flows at time T, generated by market introduction of optical tape, equals ƒ 1200m. The investment at the industrialisation moment, necessary for market introduction, has been estimated at ƒ 1400m. These investment costs include building manufacturing plants and market introduction costs. It is obvious that the NPV of total future cash flows is negative and therefore conventional capital budgeting would not support investing in optical tape. The NPV calculation however denies the flexibility of not investing in optical tape at the moment of industrialisation.

To enable the determination of the option value, we need to specify the remaining parameters: μ and

r. The firm's costs of capital at Philips is fixed at 12% and the risk-free rate over the period 1995 to 2000 is set equal to the annual return on government bonds with a maturity of five years (7.0%). Hence $S(1990) = f\ 660$m. From the parameter values in Table 1, it follows that the annual volatility (the square root of $\lambda\gamma^2$) equals 0.2. With these parameters, it can be verified that the option value of the optical tape recording project amounts to f 33.1m. Monte Carlo simulation of 5000 sample paths yields an option value of f 32.3m. Despite this relatively small error, the most delicate problem that causes far more serious errors in the option value is still the estimation of future cash flows.

As we discussed in the introduction, the option value serves as a concrete instrument to research management and shows two sides of the same coin: on the one hand the overall R&D budget for optical tape recording should not exceed f 33.1m. This way, in terms of capabilities and allocation of researchers, guidelines for the optimal total number of researchers working on this project throughout the R&D phase can be derived. Moreover, a balanced and optimised R&D portfolio that is consistent with current financial thinking can be created.

On the other hand, the option value of the potential benefits of marketing optical tape recording is estimated in an appropriate way that goes far beyond conventional myopic methods like payback, NPV, ROI or percentage methods. The option value can be used in practice for transparent communication and open discussions with relevant Product Divisions or Business Groups: the optical tape recording project is of interest, not in spite of the risk characteristics and a negative NPV, but because of these risk characteristics, since they can be handled proactively by management. With proactive option management downward risk is limited while upward potential is maximised.

4. Discussion and conclusion

Our first intention at Philips was to implement a kind of Black and Scholes option formula to value their research projects. Determining the standard deviation of the underlying value, however, appeared to be arduous within R&D practice and future use of this tool would therefore be limited. Accordingly, we changed our plan, and proposed a model which appeared to be a closer match to reality. It appeared that changes in the underlying variable – the NPV of future cash inflows generated by market introduction of the new product – occurred at a random number of times during the R&D period. These up- or downward changes have different impact on the underlying variable and are therefore assumed to be stochastic. To calculate the option value, stochastic processes for the events and their impact have been specified and its parameters have been estimated in the case of a specific research project in the field of multimedia. At Philips Corporate Research we were able to calculate the option value of seventeen R&D projects of which one is illustrated in this paper. Though the NPV of the whole project was negative, the large uncertainty in the field of multimedia accounted for an option value of approximately 5% of the underlying value. Besides financial grounds there are, of course, strategic reasons to invest in an R&D program. Empirically based option models provide a first step into the amalgamation of finance and strategy as they assign a higher value to long term strategic R&D projects than traditional discounted cash flow models.

Directions for future research include estimation of the jump parameters in other R&D-driven industries. Also, the assumption of a European option might be relaxed by introducing a special kind of Bermudan options or compound options. Bermudan options can only be exercised at particular moments, for instance when consumer demand for luxury products is sufficiently large. When market introduction is considered as a timing option (an American perpetual option), investment in R&D can be thought of as an option on an option, i.e. a compound option.

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Appendix A

A.1. Derivation of the variance of $[\Xi_i + 1]$

$$\begin{aligned}
\mathrm{VAR}[\Xi + 1] &= \mathrm{VAR}[X_i \Gamma_i] = E_{X_i}[\mathrm{VAR}(X_i \Gamma_i | X_i)] \\
&\quad + \mathrm{VAR}_{X_i}[E(X\Gamma_i | X_i)] \\
&= \left(1 - \tfrac{1}{4}\pi\right)\gamma^2 + \mathrm{VAR}_{X_i}\left[\tfrac{1}{2}\sqrt{\pi} X_i \gamma\right] \\
&= \left(1 - \tfrac{1}{4}\pi\right)\gamma^2 + \tfrac{1}{4}\pi\gamma^2 E_{X_i}\left[X_i^2\right] \\
&= \left(1 - \tfrac{1}{4}\pi\right)\gamma^2 + \tfrac{1}{4}\pi\gamma^2 = \gamma^2.
\end{aligned}$$

A.2. Proof that $\mathrm{VAR}(\Xi(N)) = \exp(\lambda\gamma^2(T-t)) - 1$

Proof. Let $\gamma_1 = \gamma_{-1} = \gamma$ and $p = 0.5$.

First of all we have that

$$\begin{aligned}
E\left[(\Xi(N) + 1)^2\right] &= \sum_{n=0}^{\infty} E\left[\prod_{i=0}^{n} (\Xi_i + 1)^2\right] P[N = n] \\
&= \sum_{n=0}^{\infty} \left(\prod_{i=0}^{n} E\left[(\Xi_i + 1)^2\right]\right) P[N = n] \\
&= \sum_{n=0}^{\infty} \left(\prod_{i=0}^{\infty} \left(E[\Xi_i^2] + 1\right)\right) P[N = n] \\
&= \sum_{n=0}^{\infty} (\gamma^2 + 1)^n \frac{(\lambda(T-t))^n \exp(-\lambda(T-t))}{n!} \\
&= \exp(\lambda(T-t)\gamma^2).
\end{aligned}$$

The first and second equality follow from the independence of Ξ_i, $i = 0, \dots, N$, the third from the fact that $E[\Xi_i] = 0$ and the fourth from the fact that $\mathrm{VAR}[\Xi_i] = \gamma^2$.

Because

$$E[\Xi(N) + 1] - 1,$$

we have that

$$\mathrm{VAR}[\Xi(N) + 1] = \exp(\lambda(T - t)\gamma^2) - 1. \quad \square$$

Table 2
Observed and expected frequencies of the absolute jump size

Absolute jump size	< 0.08	0.08–0.11	> 0.11
Observed (o_i)	8	5	5
Probabilities (p_i)	0.45	0.24	0.32
Expected (e_i)	7.65	3.91	5.44

A.3. A chi-squared goodness-of-fit test applied to the distribution of Ξ

Suppose we wish to test $H_0: \Gamma \sim \mathrm{Wei}(\gamma, 2)$ using a chi-squared goodness-of-fit test. First, divide the sample space into 3 cells, say $A_1, \dots, A_3$, let $p_j = P[\Gamma \in A_j]$ and let o_j denote the number of observations that fall into the j-th cell. Under H_0 the expected number in the j-th cell equals $18 p_j$.

$H_0: \Gamma \sim \mathrm{Wei}(\gamma, 2)$ is rejected at the 10% significance level if

$$\chi^2 = \sum_{j=1}^{3} \frac{(o_j - e_j)^2}{e_j} > \chi^2_{0.90}(1) = 2.71.$$

Table 2 depicts the observed and expected frequencies for the chi-squared test of a Rayleigh distribution with ω estimated at 0.103. We find that $\chi^2 = 0.70$ and hence we cannot reject H_0 at the $\alpha = 0.10$ level of significance.

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