The Option Approach to the New Product Development Process*

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[Abstract]

Current phase-review processes for new product development can not properly capture the economic value of managerial flexibility to continue or abandon a project at different stages of development. Due to this, the discussion whether it is fruitful to skip phases in the development process in order to create time-to-market advantage is left open. By applying insights from the valuation of real options, this article proposes a framework for the assessment of new product development at different stages. Moreover, we derive criteria to speed up the development process or not and introduce the options portfolios, which serve as a basis for assessment and as a tool for choosing an optimal set of business initiatives from a variety of feasible alternatives. We have explored the portfolio approach at Philips Electronics and illustrate the article with examples of some current R&D projects.

1. Introduction

Today's world is characterized by major changes in market and economic conditions, coupled with rapid advances in technologies. Management is often confronted with the dilemma whether or not to invest in a particular stage of the new product development (NPD) program, given market and technology uncertainties surrounding such a decision in current markets, most of all technology-driven or high-tech markets (Moriarty and Kosnik, 1989). The changing economic conditions and technologies combined with increased domestic and global competition, changing customer needs, rapid product obsolescence and the emergence of new markets, require a fast resource allocation process in NPD; see Bower and Hout (1988), Griffin (1993), Gupta and Wilemon (1990) and Rosenau (1988). At the same time, market and technology uncertainty demand for flexibility in the program; see Sanchez (1995) and Wind and Mahajan (1988).

Therefore, the trade-off between accelerating time-to-market or making pre-launch improvements in product performance has become a topical concern. On the one hand, an accelerated market introduction may lead to a substantial gain of future market share. The market share advantage that results from a rapid time to market has been explored by Urban et al. (1986), Gold (1987), Day and Wensley (1988), Liebermann and Montgomery (1988), and Brown and Lattin (1994). Millson, Raj and Wilemon (1992) and Urban and Hauser (1993) give surveys on the acceleration of the NPD process by skipping phases. On the other hand, as argued by Griffin and Page (1993), 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. Furthermore, Crawford (1992) discusses that there are substantial hidden costs in accelerating product development, such as the possibility of sacrificing information that is necessary for a successful market launch.

In this article, we apply an option approach to the NPD process and develop a framework that is fast and flexible and incorporates market and technology uncertainties in all decisions as well. For a related real option approach to product design, we refer to Baldwin and Clark (1998) who analyze the option value of modularity. Another related study is the recent contribution by Huchzermeier and Loch (1998) who use a real option approach to evaluate flexibility in R&D and introduce a distinction between financial uncertainty and stochastic variability in operations. Our option approach builds upon the classic insight that research and development (R&D) creates an option -contrary to a fixed obligation- on market launch after R&D has been completed. Subsequently, management has a timing option to launch the new product any time after R&D has been completed, opposite to market introduction at a predetermined point in time.

By treating NPD as an incremental process, our option approach gives explicit decision rules for the trade-off between validating the project or market pre-emption. We will set up a framework for NPD that can be regarded as (i) an extension of stage-wise NPD processes, (ii) an interface between marketing, finance and R&D and (iii) an amalgamation of qualitative and quantitative NPD assessment criteria. Our main contribution is to derive economic criteria for the go/no go decision before and after the R&D stages -including the decision to launch a new product- based upon the flexibility to opt out at each decision node. We will derive pre- and post-R&D option portfolios that enable an objective comparison between all feasible projects. This way, we provide a justified assessment of idiosyncratic new product initiatives at all stages of the NPD process in an uncertain environment. When economic criteria for assessing a project's flexibility in terms of the value to opt out are lacking, decision rules are invalid and a justified dynamic portfolio of feasible business initiatives can not be arrived at.

Our key parameter will be the uncertainty during the R&D stages and after the R&D stages. When uncertainty is high, there is a high probability that a high (low) project value turns out to be low (high). Since management has the flexibility to opt out the NPD process at all stages, downward risk is limited while upward potential is not. Therefore, a higher uncertainty is beneficial during the initial stages of the NPD process. However, with a high uncertainty at the final stages, the option approach induces firms to postpone market introduction as there is a high risk of failure. Thus, our option approach is consistent with Crawford's observation that delaying market introduction while gathering more information is valuable in the case of high uncertainty. Cohen, Eliashberg and Ho (1996) give a recent related study about the performance and time-to-market trade-off. While we focus on uncertainty during the NPD process, the decision to skip the validation stage in the NPD process or entirely refrain from market introduction, and an objective comparison of the firm's bundle of projects, they analyze in a deterministic setting the optimal time to market and the product performance target of a single new product.

With option analysis, R&D is not considered as necessary costs of business in terms of overhead expenses, but R&D is treated as an investment that can be analyzed with the same consistent and explicit financial criteria used for other investments within the corporation. Also, marketing and financial elements can be integrated at an early stage of the NPD process.

An incremental approach to NPD is suitable when there exist clearly defined milestones at which sunk cost decisions have to be taken. Therefore, the proposed approach is not capable of valuing NPD processes with an integrated design, manufacturing and rollout, which is current practice in the software industry (Cusumano and Selby, 1996; Iansiti, 1998). In this industry market uncertainty already resolves at the R&D stages.

This article is organized as follows. In section 2 we briefly survey the literature on improved resource allocation of R&D. Consequently, section 3 discusses investment under uncertainty and the specific conditions and assumptions that are fundamental to the option approach to the NPD process. Section 4 presents our option framework for NPD that helps to solve timing issues of sequential investments in NPD. Subsequently, section 5 analyzes the value of managerial flexibility at the R&D and launching stages, thereby creating explicit rules for the decision to conduct R&D. In section 6, we introduce the option portfolios which enable management to discriminate between different but equally feasible alternatives. Finally, section 7 concludes the article.

2. Current Decision Processes

In general, with current approaches projects continue as long as the appointed tasks are accomplished. This way, abandonment of developing new products mainly occurs due to technological failure instead of foreseeable market failure. A major contribution to the resource allocation process of R&D projects is given by Roberts and Weitzman (1981) who analyze that it might be worthwhile to undertake R&D investments with a negative Net Present Value (NPV) when R&D can provide information about future benefits or losses of a project. Consequently, Pennings and Lint (1997) develop and apply a real option approach in sequential R&D decision making. Given that financial risk assessment is important in the NPD-process (Page, 1993), standard discounted cash flow methods, such as the NPV-techniques (e.g. Haley and Goldberg, 1995) dominate the project evaluation process (Liberatore and Titus, 1983). However, only when the NPD process is treated as a fixed series of investment, the application of NPV-techniques is justified. In a sequential process for NPD with the possibility to opt out after each stage however, the use of the NPV-rule is conceptually mistaken (Dixit and Pindyck, 1995; Mitchell and Hamilton, 1988). In a phase review process the decision to continue or not at different stages in the NPD depends on the results of previous stages, whereas the outcome of previous stages is random.

It should be noted that with NPV-analysis all go/no go decisions are made with all information that is currently available. The NPV can be modified so as to assign probabilities ex ante to all go/no go decision nodes in order to model the possibility to opt out. This way a decision tree can be built. Seminal contributions on decision trees for decision making stem from Magee (1964) and Schlaiffer (1969). Although uncertainty of continuation is modelled with decision trees, the uncertainty of the project value outcomes, on which future go/no go decisions are taken, is not encompassed in decision trees. With an NPV approach, differing management forecasts of project values are weighted in order to get a single forecast of the *average* project value, thereby neglecting the extra information in the entire data set (i.e. the NPV-rule assumes a fixed scenario without any contingencies). With the option approach, however, we will consider the spread around project value outcomes. This enables the calculation of the flexibility that arises at each go/no go decision, since the flexibility value depends on the ex ante possibility to opt out when project value outcomes develop unfavorably.

The traditional process for new product development is the sequential approach, see Kotler and Armstrong (1989, p. 273-299). Projects proceed sequentially through the development tasks, which must be accomplished prior to commercialization. Different functions are responsible for completing each phase, so projects are handed over from one functional area to another during the development cycle. Management reviews each phase before the process proceeds to the next phase. Several refinements to this approach have been proposed, mainly because of the lack of speed and flexibility in the sequential approach.

Takeuchi and Nonaka (1986) set up a holistic approach. This approach is in correspondence with the growing literature on the importance of integration between functions such as marketing, R&D and manufacturing, see, among others, Crawford (1980), Gupta, Raj and Wilemon (1986), Wilemon (1988), Hauser and Clausing (1988), Souder (1988), Clark (1989), Gomory (1989), Gupta and Hise, O'Neal, Parasuraman and McNeal (1990), and Narver and Slater (1990). Although Takeuchi and Nonaka acknowledge that the NPD process involves different stages, they stress that these stages interact with each other. Their approach to NPD builds upon the iterative communication between the functional specialists and the parallel processing of tasks. Since the process does not delay when one functional department is lagging behind, this NPD process is flexible and effective. The holistic approach is improving the sequential approach, but lacks criteria how much integration is to be achieved and this may hamper its use in practice; see Gupta, Raj and Wilemon (1986). Also, the approach does not explicitly capture market and technology uncertainty, nor gives it guidelines for the optimal time to abandon the project or to go market with the project. Since development already starts when research is still in its embryonic stage, projects are liable to continue once research is finished.

Quality Function Deployment (QFD) provides another approach that aims at simultaneous development across functions, see Griffin (1992), Griffin and Hauser (1992) and Hauser and Clausing (1988). QFD uses customer's perceptions of several physical product characteristics and requirements of a new product in order to arrive at the final new product. However, the proposed framework is less suited for the whole NPD process, but particularly useful in the design phase of the NPD process.

An attempt to redesign the whole NPD process in such a way that management can better deal with market and technology uncertainty is made by the phase review process, see Cooper (1990) and Urban and Hauser (1993). Phase review processes divide NPD into a predetermined set of stages, between which checkpoints are built. Cooper refers to these checkpoints as gates. Each gate is characterized by a set of deliverables or inputs, a set of criteria and an output. The inputs of the functional area at each stage are the deliverables from the functional area at the preceding stage. The criteria are the hurdles that the project must pass at the gate to have it opened to the next stage. At these stages management can perform different kinds of assessment such as market, technical, financial and legal. The outputs are the go/no go decisions at the gate to get to the next stage. The stages of the stage-gate system are multidisciplinary and multifunctional: no ‘one’ stage is owned by any ‘one’ function. Functional activities occur in parallel rather than in serial activities. A multidisciplinary team in which marketing, financial, R&D, engineering and manufacturing forces are combined undertakes the project. By dividing the NPD process into different stages at which a go/no go decision is made, this new approach is better able to deal with market and technology uncertainty, surrounding the new product. The phase review approach will therefore be the basis underlying our option approach to the NPD process and will be extended with resource allocation rules in the appropriate stage. Liberatore and Stylianou (1995) also discuss the need for extensions of current decision processes in a recent critical examination of current approaches.

3. Background and Assumptions

For a proper background of the consequences from making irreversible commitments to investments in the product development process, we first briefly discuss the real option approach (McDonald and Siegel; 1986, Dixit and Pindyck, 1994; Trigeorgis, 1996). These authors state that firms should only make an irreversible investment when the value of the investment opportunity, V, exceeds some critical value, V*, which in turn exceeds the required fixed investment sum, I, market uncertainty, and a value that is lost by keeping the option alive. This theory is applicable to the NPD process. NPD can be considered as an incremental process in which incremental investments provide options to proceed in the process. Moreover, when the R&D stages are completed, the option of market launching the new product is created. The value of introducing the new product into the market is V-I: the present value of future net cash flows, generated by the new product minus the irreversible capital and marketing expenditures that are required for successful market launch.

The threshold can be written formally as $g(\sigma_2,\delta)\cdot I$ with $g(\sigma_2,\delta)\geq 1$ defined in the appendix. The parameter σ_2 denotes the standard deviation per unit time of the growth in V after the R&D stages and δ is the so-called dividend yield of the underlying assets. The dividend yield accounts for the value that is lost by not exercising the market introduction option. Let T_L denote the time when R&D is finished and market launching could take place. Product launch prior to this lowerbound to the optimal timing of market introduction entails substantial technology risks and may have severe consequences for future market share. The standard deviation can be considered as a measure of the uncertainty surrounding the project value. As uncertainty increases, the probability that V ex ante appears to be lower than the value expected at the moment of market introduction increases. At the same time, as uncertainty increases, the chances of attaining a higher project value by waiting increase. Therefore management will require a higher V* in an environment with a higher uncertainty. When there is no uncertainty at all, market introduction will take place when the non-random value of the investment opportunity exceeds the investment sum. The outcome of the value of the project, once installed, will exactly equal the project value at the moment of market launching in a business environment that is assumed to be deterministic. This investment rule is just the traditional net present value (NPV) rule, put forward by finance theory. The NPV rule is encompassed in this micro economic framework since $g(\sigma_2,\delta) = 1$ in the case of $\sigma_2 = 0$.

After describing the background of the option approach in general, we define the following five specific assumptions with respect to the option approach to the NPD process:

A1. The capital and marketing expenditures that are required for market introduction are significantly larger than the development costs, while the development costs in turn exceed the research costs to a great extent.

When capital and marketing expenditures are relatively small, but development costs are high, the investment decision is not about creating the launching opportunity, but about conducting research or not. In case major investments in development have been made while the investments required for market launch are relatively low, there is no managerial flexibility left and the market launch decision is straightforward. When the value of the project turns out to be so low that management will refrain from market introduction, major losses have been made. The same line of reasoning holds for research costs. When research costs are considerably higher than the development costs, research has to be regarded as an option on market launching. Consequently, when management chooses to conduct research, development will always be imbedded in the NPD process because of its relatively low costs. For empirical examples supporting assumption A1, see Urban and Hauser, 1993, Ch 3, p60.

A2. The market launch investments, consisting of the capital and marketing expenditures that are required for successful market introduction, such as plants, advertizing, etc., are assumed to be irreversible.

The expenditures cannot be undone or in some way be recovered. Without this (reasonable) assumption, there is no final go/no go decision as a project can be stopped after market launch of the new product without major financial consequences.

A3. The length of the R&D stages is fixed.

When the R&D stages are completed, management holds the option to introduce the newly developed product to the market. In order to calculate the value of the R&D, the option value must be discounted to get the present value. For reasons of tractability, we assume that the length of the R&D stages is fixed. Note that although the length of the R&D stages is fixed, the outcome of the project value is random. The length of the R&D stages is given by T_L-t_{RD}. Treating T_L as an optimalization parameter requires a separate analysis. We refer to Granot and Zuckerman (1991) for an interesting multi-period model in which the stopping time of the R&D process is introduced as a decision variable to be determined endogenously.

A4. The capital and marketing expenditures, required for a successful market introduction, are non-random.

When the possibility of market introduction is created and market launch appears to be fruitful, the option approach considers future profits as stochastic. Capital and marketing expenditures are assumed to be fixed, though stochastic investments can easily be implemented in the model.

A5. The project value follows a geometric Brownian motion[1] *with drift* μ *and standard deviation* σ_1 *for* $t \leq T_L$ *and a geometric Brownian motion with zero drift and standard deviation* σ_2 *for* $t > T_L$*. So,* $dV = \mu V dt + \sigma_1 V dz$ *for* $t < T_L$ *and* $dV = \sigma_2 V dz$ *for* $t \geq T_L$*.*

Once the R&D stages are successfully completed, the uncertainty surrounding technology is resolved. Also, part of the market uncertainty is resolved. Since product specifications are set and scans of targeted markets are conducted, product-market combinations become clear. Therefore, σ_1 will drop to a lower value σ_2 after T_L. In our model, σ_2 represents the amount to which the project value is exposed to market uncertainty, while σ_1 represents the amount to which the project value is exposed to both market and technology uncertainty. Bernanke (1983) and Cukierman (1980) provide a more general proof that potential investors can improve their chances of making the correct irreversible investment decision by waiting for new information relevant to assessing project returns. Nelson (1961) proves the validity of a model in which uncertainty decreases during the R&D stages.

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[1]The described decision rules are based on specific assumptions about the diffusion process of V. More specific, it is assumed that V follows a geometric Brownian motion after time T_L.

The expected project value will increase during the R&D stages since the current value of V, V(t), can be regarded as the product of all probabilities, p_i, that the product will successfully go through the R&D stages in the product development process, multiplied with the value V at the moment of market introduction, V(T). The probabilities of success at each stage are conditional on reaching that particular stage. So, $V(t) = V(T)\prod_i p_i(\tau_i)$ with $0<p_i<1$ and $t<\tau_i<T$. Therefore V is a non-decreasing function of time for $t \leq T_L$. Mansfield and Wagner (1975) studied the probabilities of success with regard to new products. They found that the probability of technical completion was equal to 57%, while the probability of commercialization given technical completion and the probability of economic success given commercialization respectively equalled 65% and 74%. By taking a growth rate of zero for the expected project value after the R&D stages we assume that there are no significant possibilities to increase the expected market value after these stages.

4. An Improved Investment Approach to the NPD Process

The current phase-review processes are not capable of valuing the flexibility at the different stages to continue or abandon the project. As a result, managers using the traditional phase-review process, favor short-term oriented projects with a relatively low risk over highly uncertain projects with a long-term strategic impact. In their suggested guidelines for changing the NPD process, Wind and Mahajan (1988) point out that too much of the new product-development effort is focused on low-risk options, on expected short-term results and on non synergetic projects. The option approach also incorporates another suggested guideline to an improved NPD process, which says that ‘commercialization is too much viewed as separate from the development process and there is a dangerous shift of resources away from commercialization'. With the option approach commercialization aspects are integrated in an early stage of the NPD process.

Our option approach to the NPD process takes financial elements into account within the NPD process as to capture the flexibility value and extend the R&D-marketing interface to a cross functional interaction between R&D, marketing and finance. At each stage of the NPD process, management has the possibility, but not the obligation to step into the next stage. In the last part of the product development cycle this turns into the possibility of market launching the new product. From the possibility to stop the NPD process at each stage, including the possibility of refraining from market launch when market and technology conditions turn out to be unfavorable, downward risk is limited while upward potential is maximized. Flexibility, though it does not offer benefits in an environment known with certainty, is advantageous under uncertainty. At each stage this flexibility stems from different options. First, there exists the option to conduct R&D without the obligation of market launching. Second, when R&D is completed, management has the option of validation or market introduction.

Since Cooper's stage-gate system treats NPD as an incremental process, this system will serve as the basis for our investment approach. This approach is graphically presented in figure 1. Urban and Hauser provide a phase review process for NPD of a similar kind. The utilized framework is composed of four stages: (i) idea generation, initial screen, (ii) research and development, (iii) validation and (iv) market launch. Between all stages, option assessment will take place of each individual project. We will explain the specific contribution of the option approach at each of these stages.

4.1 Idea Generation and Initial Screen

At the initial screen, the product idea is evaluated and a go/no go decision whether to embark on large-scale R&D is made. All involved functional departments -marketing, finance, R&D and engineering- will contribute to and evaluate to the input parameters for option decision making. This way, the potential value of the project (V) as well as the aggregate market and technology uncertainty (σ_1) surrounding the project value can be analyzed. With managerial judgment, the fraction of market uncertainty (σ_2) within the aggregate uncertainty must be captured. Also, the capital and marketing expenditures that are required for market introduction, as well as the length of the R&D stages are determined. At the same time a concept business plan is written with the vision, scope, strategic fit, unique selling points, entry barriers, challenges, competencies and a suited marketing mix. The interaction between the qualitative strategic assessment and the quantitative option assessment will lead to realistic business plans, as well as to realistic input parameters as inaccurate financial, marketing or R&D assessments will be detected and changed to meet reality. Finally, the expenditures that are required for successful R&D are determined. When all information is gathered and the tasks are completed, the value of the option to launch (O_L) can -as we will analyze in the next section- be calculated and compared to the costs of the option (C). These costs denote the minimum R&D effort that is required for successful completion of the research stage. When $C>O_L$, the product should move back to the initial screen. Consequently, the vision, scope and unique selling points of the new product have to be redefined in order to attain a project value that sufficiently increases the option value.

4.2 Research and Development

At this stage, R&D is completed and business plans with detailed financial, marketing and manufacturing plans are worked out. The option portfolio will be created on an ongoing basis, thereby tracking the dynamics in the value during the R&D stages that result from new information about the market and technology. A discussion of the R&D options portfolio is presented in section 5. At the end of this stage all technology uncertainty is resolved and all involved functional departments will recalculate the project value. The spread between all estimates will have narrowed in comparison to the previous spread, indicating that uncertainty only consists of market uncertainty after the R&D stages. Previous estimates of the required irreversible investments and market uncertainty can be recalculated and evaluated.

In case of successful development, the option approach provides a decision tool for accelerating new product development. In section 2, we reviewed that a company invests in a project when, first, the project passed the minimal required time to create the investment opportunity and, second, the project value has crossed the investment hurdle. When the R&D stages are successfully completed with the development of a prototype, marketing and manufacturing plans contain all elements for successful market launch, and hence the company meets the condition of the minimal required time for market launch. When project uncertainty has decreased so that the project value, implied by the sales projections in the business plan, exceeds the investment hurdle -the irreversible market launch investments multiplied with the factor representing the uncertainty- market introduction is supported. Waiting for market launch by means of entering the validation stage might cause a substantial loss of future market share in these circumstances and pioneering advantages will be foregone. With the market introduction rule, launch whenever $V>V^*$, the option approach provides a clear solution to the dilemma of early entry or not. With market launch just after the R&D stages, one phase in the NPD process, the validation stage, is skipped. As argued in the introduction, skipping a phase in the NPD process is one of the possible ways to accelerating NPD.

When a satisfying prototype has been built, but the uncertainty surrounding the new product is still very high and expected future sales do not sufficiently exceed the required capital and marketing expenditures, the required additional resolution of uncertainty can be achieved in the validation stage.

4.3 Validation

The validation stage reviews the R&D stages of the projects that are not suitable for early market introduction. In the validation stage, the company will test market the new product, trial sell the new product by means of a phased roll-out or use simulated test markets in order to get more insight in the market. The purpose of these procedures is to attain solid forecasts of volume and profitability and to obtain diagnostic information about market conditions for refining the business plan. When prototype development failed on technological grounds, product definitions have to be re-examined and a renewed option assessment must be conducted. When development of the new product has failed within the context of engineering or production, the product design concept has to be altered and an initial screen is required for the new design concept.

In the case that $V<V^*$, additional information about the value of the project will be pulled from the market by means of validation. The outcome can be that the project value is higher than predicted just after the R&D stages, resulting in either support for market entry or postponing market launch once more. In the latter case, the

product strategy can be revised -for example by market introduction in targeted markets only (regional, professional etc.)- and the conditions for market launching can subsequently be re-evaluated, thereby preserving the speed and flexibility in the NPD process. The procedure of strategy reformulation can in principle be repeated up to the moment that the new product's time window of opportunity (T_U) has been reached. When it appears that V<<V*, so that the probability that the threshold will be crossed is nearly zero resulting from marketing and financial shortcomings, either the project strategy has to be entirely revised, or, in very unfavorable circumstances, the project should be abandoned.

4.4 Market Launch

once the option approach supports market introduction, the product has a high probability of success. The product that enters a market characterized by high uncertainty is expected to yield high benefits since otherwise the option approach will repress the decision to go market. This way, the option approach prevents a company from commercializing failures arising from high market and technology uncertainties.

5. The Option Value at Each Stage

By combining microeconomic theory with an NPD perspective, we can derive and apply a model for assessing the value of the options in the NPD process as described. When the R&D stages are completed and the possibility of market introduction is thus created, the option value of launching can be calculated as

$$F(V(T_L)) = E\left[\max_{T \geq T_L}\left(e^{-\rho(T-t_D)}\left(V(T)-I\right)\right)\right]$$

where E[.] denotes the mathematical expectation operator, ρ is the appropriate discount factor and T is the ex ante optimal time to market. The option value reflects the expected net value of the launching opportunity. This value is always non-negative since the product will not be launched into the market as long as the investments required for a proper market launch (I) exceed the value of market introduction (V). When it is expected that V will never surmount I, the optimal time to market (T) will tend to infinity and, by discounting, the option value will tend to zero.

Market and technology uncertainty have a positive effect on the option value since downward risk is limited by the possibility to postpone market launch when this appears to be unfavorable. Upward potential however is maximized since market launch only takes place when conditions appear to be favorable. An increase in uncertainty enables management to profit from higher unexpected upward swings while it can ignore augmented unexpected downward swings in the value of the project. Therefore the optimal time to market and the value of the timing option increase with σ_2.

Finance management should assess the market uncertainty associated with the project and the opportunities, while R&D management can best rate the technology uncertainty surrounding the project. The costs of creating the option to step into the next stage consist of the costs that the present stage entails. The costs of the option to develop the new product, for instance, mainly consist of the research costs. With the option value and the option costs of each new product initiative, management has guidelines on how much to spend on each initiative and a balanced non-myopic portfolio can be built.

Samuelson (1965) and Dixit and Pindyck (1994) argue that product launching can be regarded as an American perpetual call option. The option is American since it can be exercised any moment after completion of the R&D stage while it is perpetual since there are in principle no limitations to the length of the exercise time. When

$V(T_L)>V^*$, the investment threshold has been crossed at T_L and there is no value in waiting to invest. Economic theory suggests that the option should be exercized immediately and market introduction should take place. Hence, the net value of the market introduction possibility, $F(V(T_L))$, equals $V(T_L)-I$. When it appears that the investment threshold has not been crossed after the R&D stages, continuing the NPD process is valuable. Dixit and Pindyck (1994) show that the option value in this case can be calculated as

$$F\left(V\left(T_L\right)\right) = AV^{\beta}\left(T_L\right)$$

with A>0 and $\beta>1$ defined in the appendix. Although uncertainty is advantageous during the R&D stages, it limits market introduction afterwards. Projects with an everlasting high uncertainty will tend to be promising forever but will never be introduced to the marketplace because of the high threshold. In the meantime, a competitor can develop a competing product innovation and thereby increase the market uncertainty for both product innovations. This leads to a higher threshold for market entry. Consequently, later entrants can do better than pioneers in the long run if there are uncertainties about which technology will eventually dominate the industry (Ali, 1994, and Rosenbloom and Cusumano, 1987, for empirical evidence in the VCR-industry). When T_L is passed, project uncertainty has to be resolved in order to lower the threshold and make an improved go/no go decision. Management must proactively handle the relevant information content and resolve uncertainty by increasing research efforts and team capabilities, by enhanced customer orientation, by product tests, (pre) test marketing, by setting up appropriate distribution channels and by managerial decision making. When the threshold becomes lower, crossing the threshold will get more likely. Since the growth rate of V is zero, it can be shown that market introduction will never take place when the required investments exceed the expected project value.

In order to create the option on product launching, a firm has to successfully fulfil the R&D stages. Prior to these stages -after idea generation- a firm has in fact a European option on an American perpetual option, i.e. a compound option. In the case that the present value of the costs of R&D, denoted by C, exceed the value of the compound option, the firm will abandon the research project. The product launch option can be written as

$$O_L(t_{RD}) = \exp(-\rho(T_L - t_{RD}))E_{t_{RD}}\left[F(V(T_L))\right]$$

In the appendix, the value of the product launch option is derived as

$$\begin{aligned} O_L(t_{RD}) = {} & AV^{\beta}(t_{RD})\exp\left(\beta w_{\mu} + \tfrac{1}{2}\beta^2 w_{\sigma}^2\right)\Phi(\kappa_1) \\ & + V(t_{RD})\exp(\mu(T_L - t_{RD}))\Phi(\kappa_2) - I\Phi(\kappa_3) \end{aligned}$$

where k_1, k_2 and k_3 are parameters that are defined in the appendix.

6. Management of R&D Investments: The Options Portfolios

Management typically encounters a myriad of funding opportunities. Yet, in general resources are limited and an evaluation of which opportunities are most profitable must be made. Decisions are also needed concerning the level of resources allocated to competing projects. We will develop two option portfolios. The first one consists of projects on which management has to decide whether R&D will be abandoned or continued. The other one consists of projects after the R&D stages on which management has to decide whether to introduce these directly to the market (pre-empting), to wait with market introduction or to abandon market introduction. The options portfolios support allocation of resources to a collection of appropriate R&D projects by explicit decision rules.

6.1 The R&D Options Portfolio

Considering the first portfolio, projects can be classified at the R&D stages in four categories, depending on two variables. First, the level of joint market and technology uncertainty (σ_1). We will distinguish between projects with a low σ_1 and projects with a high σ_1. Second, the expected value at present of the difference between the expected project value and the investment threshold and the R&D costs: PV[E (V(T_L))-V*]-C. When it turns out that this variable is positive for a specific project, the option approach supports continuation of R&D while market launching should be postponed for negative values of this variable. Therefore we cut the sample of projects into projects with a positive value and a negative value. The four categories are illustrated in figure 2 and can be described as follows.

- A: Projects, which are so valuable that their market introduction is expected as soon as R&D is completed. These projects have a low market and technology uncertainty. This implies that the investment threshold is close to the investment. Also, E (V (T_L))-V* will still be positive. Because of the low uncertainty surrounding the project outcomes, the traditional NPV-rule can be applied. The option content of these projects will be low since there is no reason to stop them. The option approach to NPD will also confirm continuation of these projects during the R&D stages.

- B: These projects are liable to be market failures. Since these projects have a low market and technology uncertainty, the threshold is close to the required amount of investments and traditional NPV-rules, put forward from finance theory, can be applied. The NPV-rule tells not to invest in these projects because of the negative

NPV. In a low uncertainty area the option content can be neglected, so that there is no economic argument for stepping into the next stage. The option approach will therefore not support continuation of these projects.

- C: These projects are exposed to a high market and technology uncertainty. The threshold can be relatively low in the case of low market uncertainty or relatively high in the case of large market uncertainty. Nevertheless it is ex ante expected that the threshold will be crossed at the first moment of potential market launching. This means that there are two kinds of projects in this cell. On the one hand there are projects, which are surrounded by a relatively large market uncertainty, but with expected sales that compensate the uncertainty to a great extent. On the other hand, cell C includes projects with a relatively low market uncertainty, but relatively high technology uncertainty. Development of the required technology is a bottleneck, but market demand forecasts are accurate. The option value during the R&D stages will be relatively high for both projects in this cell and will likely exceed the up-front investments that are required in the R&D stages. Regardless of the kind of project, the option approach supports rapid completion of R&D for these projects in order to create possible first mover and pioneering advantages.

- D: Like projects in cell C, these projects are surrounded by a relatively high market and technology uncertainty. Market uncertainty can be relatively high or relatively low. In each case however, the investment threshold will ex ante exceed the expected project value, so that there is a high probability that market introduction will be postponed after the R&D stages and validation is recommended. Since these projects can be stopped at the end of the R&D stages, the relatively high market and technology uncertainty during these stages will provide an option value that may exceed the R&D costs. At the end of the R&D stages management can determine whether the investment threshold has been crossed and market introduction can take place. When market uncertainty can be decreased, marketing theory advocates embarkment upon a validation stage. Otherwise, microeconomic principles suggest that waiting for the optimal time to market is advisable. Ultimately, management can decide on a revision of strategy.

The portfolio consists of all projects in the R&D stages. At each moment on which new information that affects the project values arrives, the portfolio can be revised. Consequently, a dynamic portfolio is built and management can fine-tune the allocation of R&D resources. We made a first step at Philips Electronics Corporate Research to build a portfolio along the lines outlined above. Typical A-projects with a high expected payoff and relatively low uncertainty appear in the field of lighting. The option approach does not support B-projects. As a consequence, they are abandoned and are not part of the actual option portfolio. The Philips' R&D pipeline is well fueled with C-projects. Typical C-projects are multimedia applications, such as optical tape recording, and speech recognition systems. D-projects appeared to involve new technologies with an application base that is dominated by mature product-market combinations. A representative example is polymer Light Emitting Diodes (LEDs) which could replace existing Liquid Crystal Displays (LCDs) in existing products.

6.2 The Market Launch Options Portfolio

The second portfolio deals with projects of which the R&D stages are fulfilled. We can distinguish between projects that just depart from the R&D stages and enter the portfolio on the one hand and projects that are already included in the portfolio for a certain period since the option of market launch embedded in these projects has not been exercised yet. Like the R&D options portfolio, the market launch portfolio can be divided as follows.

- AA: These projects are characterized by a low market uncertainty and hence the traditional NPV-rule applies. The investment hurdle of these projects has been crossed, or, alternatively, these projects have a positive NPV. Consequently, these options should be exercised immediately. Therefore, this cell is likely to consist only of projects that recently completed the R&D stages.

- BB: Like the investment projects in cell AA, these projects are subject to a low market uncertainty, but in contrast to the projects in cell AA, the investment hurdle has not been crossed. These projects typically have a negative NPV and will be abandoned. Like cell AA, this cell is likely to contain projects that just left the R&D stages.

- CC: Projects in cell CC can be identified as projects with a high market uncertainty surrounding the project value. Hence, the investment hurdle is relatively high, but despite this high hurdle the project value exceeds the investment hurdle. Because of this high project value, the options in cell CC can be exercised immediately.

- DD: Like the projects in cell CC, the value of the projects in cell DD is subject to a high market uncertainty, but contrary to the projects in cell CC, it has not crossed the investment hurdle yet. Since market uncertainty is high, the investment hurdle in this cell exceeds the project value and immediate exercise of these options is not optimal. It might be true that the project value exceeds the irreversible costs and thus, that the NPV-rule -neglecting the high market-uncertainty- would support immediate investment. However, the option approach shows that postponement of market introduction and waiting until the project value has crossed the investment hurdle is optimal for these projects. This cell may include a lot of projects, since projects can stay within this cell for an unknown period.

7. Discussion

Although the option approach establishes a foundation for a holistic phase-review NPD system, its limitations should also be considered. The limitations can be divided in imperfections of the phase-review system, flaws inherent to assumptions A1 to A4, and shortcomings in managerial practice. Cooper (1994) discusses the main disadvantages of the formal 'stage-gate' systems for NPD and concludes that they are too time consuming and that they have no provision for focus. Inevitably, it will take time to implement the option approach to NPD and results will not immediately be available. Instead of increasing the speed of NPD with the option approach, it may initially slow down NPD. Millson, Raj and Wilemon (1992), however, state that initial problems should not deter management from changing the NPD process.

The statement that phase review processes have no provision for focus does not hold with the option approach. By incorporating an option approach into phase review processes, the R&D portfolio contains projects that generate short-term cash flow, required for the liquidity of the company, as well as projects that meet long term strategic objectives. Also, the launching portfolio provides criteria for pre-empting the market, for validating the project by test marketing or market tests, or for mothballing newly developed products.

The implementation of the option approach may also entail initial obstacles. In particular the estimation of uncertainty, the key variable in the option approach, will challenge management. Sales predictions from senior managers can be substantially different and, hence, are subject to uncertainty. By a first step in implementing options-based approaches to NPD at Philips Electronics we found that sales predictions and business events serve well to estimate the uncertainties described (Lint and Pennings, 1998; 1999). Second, managerial experience can help determining the uncertainty of a project by judging the uncertainty of analogous projects in the past (Pennings and Lint, 2000). Finally, at Merck, average stock volatility of companies in the same business as intended for the new product serves as a proxy for project uncertainty (Nichols, 1994).

Although the option approach to NPD eliminates major drawbacks of the traditional phase review processes, the approach simultaneously may introduce new pitfalls. Assumption A1 may hold for several new products (for example consumer goods and high-tech products), but industrial chemicals require high R&D costs relative to the investment needed for successful market launch; see Mansfield and Rapoport (1975). Also, assumption A2 may not always hold. For example, when a company works with advertizing agencies on a 'no cure no pay' basis, the advertizing costs can be recovered when market introduction appears to be unsuccessful. Also, when machines and equipment can be used for manufacturing of alternative products, the capital expenditures may be recovered. The assumption that the length of the R&D stages is fixed (A3) may not always hold as R&D breakthroughs or failures may occur randomly over the R&D stages. Moreover, fixing the R&D stages may result in relatively long periods, since researchers will likely want to minimize the risk of technical failures at the end of the R&D stages. Assumption A4 will be violated in the case of uncertain market launch investments. This, however, can easily be overcome by implementing stochastic market launch investments. Finally, a major drawback is the exclusion of explicit actions by competitors in the model. Though competitive action is implicitly built into the model by the dividend yield δ, explicit modeling is an interesting but complex avenue for further research, e.g. see Lambrecht and Perraudin (1997) and Kulatilaka and Perotti (1998).

In conclusion, using the same decision tool for different projects in different stages of NPD, an objective comparison between all involved projects will be possible. This way, a balanced portfolio of projects can be built. With the option approach, the portfolio can be balanced at each time new information arrives with substantial impact on the value of the investment proposal.

References

Ali, A. (1994), “Pioneering Versus Incremental Innovation: Review and Research Propositions”, *Journal of Product Innovation Management*, 11 (1): 46-61.

Baldwin, C. and K. Clark (1998), "Modularity in Design: An Analysis Based on the Theory of Real Options", Working Paper, Harvard Business School.

Bernanke, B.S. (1983), “Irreversibility, Uncertainty and Cyclical Investment”, *Quarterly Journal of Economics*, 98 (February), 85-106.

Bower, J.L. and T.M. Hout (1988), “Fast Cycle Capability for Competitive Power”, *Harvard Business Review*, 66 (November-December), 110-118.

Brown, C.L. and J.M. Lattin (1994), “Investigating the Relationship Between Time in Market and Pioneering Advantage”, *Management Science*, 40 (October), 1361-1369.

Clark, K. (1989), “What Strategy Can Do For Technology”, *Harvard Business Review*, 67 (November-December), 94-98.

Cohen, M.A., J. Eliashberg and T.H. Ho (1996), “New Product Development: The Performance and Time-to-Market Tradeoff”, *Management Science* 42 (February), 173-186.

Cooper, R.G. (1990), "Stage-Gate Systems for Managing New Products", *Business Horizons*, (May-June), 44-54.

Cooper, R.G. (1994), "Perspective: Third-Generation New Product Processes", *Journal of Product Innovation Management*, 11 (January), 3-14.

Crawford, C.M. (1980), "Defining the Charter for Product Innovation", *Sloan Management Review*, 22 (Fall), 3-12.

Crawford, C.M. (1992), "The Hidden Costs of Accelerated Product Development", *Journal of Product Innovation Management*, 9 (September),188-199.

Cukierman, A. (1980), "The Effects of Uncertainty on Investment under Risk Neutrality with Endogenous Information", *Journal of Political Economy*, 88 (June), 462-475.

Cusumano, M and R. Selby (1996), *Microsoft Secrets: How the World's Most Powerful Software Company CreatesTtechnology, Shapes Markets, and Manages People*, London: HarperCollins.

Day, G.S. and R. Wensley (1988), "Assessing Advantage: A Framework for Diagnosing Competitive Superiority", *Journal of Marketing*, 52 (April), 1-20.

Dixit, A.K. and R.S. Pindyck (1994), *Investment under Uncertainty*, Princeton, NJ: Princeton University Press.

Dixit, A.K. and R.S. Pindyck (1995), "The Option Approach to Capital Investment", *Harvard Business Review*, 73 (May-June), 105-115.

Gold, B. (1987), "Approaches to Accelerating Product and Process Development", *Journal of Product Innovation Management*, 4 (March), 81-88.

Gomory (1989), "From the 'Ladder of Science' to the Product Development Cycle", *Harvard Business Review*, 67 (November-December), 99-105.

Granot, D. and D. Zuckerman (1991), "Optimal Sequencing and Resource Allocation in Research and Development Projects", *Management Science* 37 (February), 140-56.

Griffin, A.J. (1992), "Evaluating QFDs Use in U.S. Firms as a Process for Developing Products", *Journal of Product Innovation Management* 9 (3), 171-187.

Griffin, A.J. and J.R. Hauser (1992), "Patterns of Communication among Marketing, Engineering, and Manufacturing: A Comparison between Two New Product Teams", *Management Science* 38 (3), 360-373.

Griffin, A.J. and A. Page (1993), "Metrics for Measuring New Product Development Cycle Time", *Journal of Product Innovation Management*, 10 (March), 112-25.

Gupta, A.K., S.P. Raj and D. Wilemon (1986), "A Model for Studying the R&D Interface in the Product Innovation Race", *Journal of Marketing*, 50 (April), 7-17.

Gupta, A.K. and D. Wilemon (1988), "The Credibility-Cooperation Connection at the R&D Marketing Interface", *Journal of Product Innovation Management*, 5 (March), 20-31.

Gupta, A.K. and D. Wilemon (1990), "Accelerating the Development of Technology-Based New Products", *California Management Review*, 32 (Winter), 24-67.

Haley, G.T. and S.M. Goldberg (1995), "Net Present Value Techniques and their Effects on New Product Research", *Industrial Marketing Management* 24, 177-190.

Hauser, J.R. and D.P. Clausing (1988), "The House of Quality", *Harvard Business Review*, 66 (May-June), 63-73.

Hise, R.T., L. O'Neal, A. Parasuraman and J.U. McNeal (1990), “Marketing/R&D Interaction in New Product Development: Implications for New Product Success Rate”, *Journal of Product Innovation Management*, 7 (2), 142-55.

Huchzermeier, A. and C. H. Loch (1998), "Project Management under Risk: Using the Real Option Approach to Evaluate Flexibility in R&D, Working Paper, Insead.

Iansiti, M. (1998), *Technology Integration*, Boston, MA: Harvard Business School Press.

Kotler, P. and G. Armstrong (1989), *Principles of Marketing*, 4th ed., Englewood Cliffs, NJ:Prentice Hall, Inc.

Kulatilaka, N. and E.C. Perotti (1998), "Strategic Growth Options", *Management Science*, forthcoming.

Lambrecht, B. and W. Perraudin (1997), "Real Options and Preemption", working paper, University of Cambridge.

Liebermann, M.B. and D.B. Montgomery (1988), “First-Mover Advantages”, S*trategic Management Journal*, 9 (Summer), 41-58.

Liberatore, M.J. and A.C. Stylianou (1995), “New Product Development Decision Making”, *Management Science* 41 (August), 1296-316.

Liberatore, M.J. and G.J. Titus (1983), “The Practice of Management Science in R&D Project Management”, *Management Science*, 29, 962-74.

Lint, L.J.O and H.P.G. Pennings (1998), “R&D as an Option on Market Introduction”, *R&D Management*, 28 (October), 279-287.

Lint, L.J.O and H.P.G. Pennings (1999), "The Option Value of Developing Two Product Standards Simultaneously when the Final Standard is Uncertain", in L. Trigeorgis (Ed.), *Real Options: New Developments and Applications*, Oxford University Press, NY: New York, forthcoming.

Magee, J.F. (1964), “Decision Trees for Decision Making”, *Harvard Business Review*, 42 (July-August), 126-39.

Mansfield, E. and J. Rapoport (1975), “The Costs of Industrial Product Innovation”, *Management Science*, 21 (August), 1380-6.

Mansfield, E. and S. Wagner (1975), “Organizational and Strategic Factors Associated with Probabilities of Success in Industrial R&D”, *Journal of Business*, 48 (April), 179-98.

McDonald, R.L. and D.R. Siegel (1986), “The Value of Waiting to Invest”, *Quarterly Journal of Economics*, 101 (November), 707-27.

Millson, M.R., S.P. Raj and D. Wilemon (1992), “A Survey of Major Approaches for Accelerating New Product Development”, *Journal of Product Innovation Management*, 9 (March), 53-69.

Mitchell, G.R. and W.F. Hamilton (1988), “Managing R&D as a Strategic Option”, *Research-Technology Management*, 31 (May-June), 15-22.

Moriarty, R. and T. Kosnik (1989), “High Tech Marketing: Concept, Continuity and Change”, *Sloan Management Review*, 30 (Summer), 7-17.

Narver, J.C. and S.F. Slater (1990), “The Effect of a Market Orientation on Business Profitability”, *Journal of Marketing*, 54 (October), 20-8.

Nelson, R. (1961), “Uncertainty, Learning and the Development of Parallel Research and Development Efforts”, *Review of Economics and Statistics* 43 (November), 351-64.

Nichols, N.A. (1994), “The New Pharmaceutical Paradigm”, *Harvard Business Review*, 72 (January-February), 88-105.

Page, A.L. (1993), “Assessing New Product Development Practices and Performance: Establishing Crucial Norms”, *Journal of Product Innovation Management* 10 (4), 273-290.

Pennings, H.P.G. and L.J.O. Lint (1997), "The Option Value of Advanced R&D", *European Journal of Operational Research* 103, 83-94.

Pennings, H.P.G. and L.J.O. Lint (2000), “Market Entry, Phased Rollout or Abandonment? A Real Option Approach”, *European Journal of Operational Research*, forthcoming.

Roberts, K. and M.L. Weitzman (1981), “Funding Criteria for Research Development and Exploration Projects”, *Econometrica* 49 (5), 1261-88.

Rosenau, M.D., Jr. (1988), “From Experience Faster New Product Development”, *Journal of Product Innovation Management*, 5 (2), 150-3.

Samuelson, P.A. (1965), “Rational Theory of Warrant Pricing”, *Industrial Management Review*, 6 (Spring), 41-50.

Sanchez, R. (1995), “Strategic Flexibility in Product Competition”, *Strategic Management Journal*, 16 (Summer), 135-159.

Schlaiffer, R. (1969), *Analysis of Decisions under Uncertainty*, New York, NY: McGraw Hill.

Souder, W.E. (1988), “Managing Relations Between R&D and Marketing in New Product Development Projects”, *Journal of Product Innovation Management*, 5 (March), 6-19.

Takeuchi, H. and I. Nonaka (1986), “The New New Product Development Game”, *Harvard Business Review*, 64 (January-February), 137-46.

Trigeorgis, L. (1993), “Real Options and Interactions with Financial Flexibility”, *Financial Management*, 22 (Autumn), 202-24.

Trigeorgis, L. (1996), *Real Options*, Cambridge, MA: MIT Press.

Urban and Hauser (1993), *Design and Marketing of New Products*, 2nd ed. Englewood Cliffs, NJ: Prentice Hall, Inc.

Urban, G.L., T. Carter, S. Gaskins and Z. Mucha (1986), "Market Share Rewards to Pioneering Brands: An Empirical Analysis and Strategic Implications", *Management Science*, 32 (6), 645-59.

Wind, Y. and V. Mahajan (1988), "New Product Development Process: A Perspective for Reexamination", *Journal of Product Innovation Management*, 5 (December), 304-10.

Appendix

When the possibility of market launch has been created, the value of the timing option can be calculated analogous to Dixit and Pindyck (1994, pp140-144).

$$F\left(V\left(T_L\right)\right)=\begin{cases}AV^{\beta}\left(T_L\right) & V\left(T_L\right)<V^{*}\\ V\left(T_L\right)-I & V\left(T_L\right)\geq V^{*}\end{cases} \tag{1}$$

with $\beta=\frac{1}{2}-\frac{\rho-\delta}{\sigma_2^2}+\sqrt{\left(\frac{1}{2}-\frac{\rho-\delta}{\sigma_2^2}\right)^2+\frac{2\rho}{\sigma_2^2}}$, $A=\frac{1}{\beta}\left(\frac{\beta-1}{\beta I}\right)^{\beta-1}$, $V^{*}=g\left(\sigma_2,\delta\right)I$ and

$g\left(\sigma_2,\delta\right)=\frac{\beta}{\beta-1}$. Under assumption A5, ρ=δ, so $\beta=\frac{1}{2}+\sqrt{\frac{1}{4}+\frac{2\rho}{\sigma_2^2}}$.

Now, we can determine the value of the market launch option (O_L) as the discounted expected value of the timing option as follows. Note that

$$O_L\left(t_{RD}\right)=\exp\left(-\rho\left(T_L-t_{RD}\right)\right)E_{t_{RD}}\left[F\left(V\left(T_L\right)\right)\right] \tag{2}$$

By applying Ito's lemma, it holds that the process for ln(V) for $t<T_L$ reads

$$d\ln\left(V\right)=\left(\mu-\tfrac{1}{2}\sigma_1^2\right)dt+\sigma_1 dz \tag{3}$$

Therefore, it is true that

$$\ln\left(V\left(T_L\right)\right)-\ln\left(V\left(t_{RD}\right)\right)\sim N\left(\left(\mu-\tfrac{1}{2}\sigma_1^2\right)\left(T_L-t_{RD}\right),\sigma_1^2\left(T_L-t_{RD}\right)\right) \tag{4}$$

Let $w_\mu=\left(\mu-\tfrac{1}{2}\sigma_1^2\right)\left(T_L-t_{RD}\right)$ and $w_\sigma=\sigma_1\sqrt{T_L-t_{RD}}$. Now we can write V (T_L) as

$$V\left(T_L\right)=V\left(t_{RD}\right)\exp\left(w_\mu+w_\sigma x\right) \tag{5}$$

where x is standard normal. Now,

$$\begin{aligned}O_L\left(t_{RD}\right)=\exp\left(-\rho\left(T_L-t_{RD}\right)\right)\Bigg[&\int_{x<x^{*}}AV^{\beta}\left(t_D\right)\exp\left(\beta w_\mu+\beta w_\sigma x\right)\varphi\left(x\right)dx\\ &+\int_{x\geq x^{*}}V\left(t_D\right)\exp\left(w_\mu+w_\sigma x\right)\varphi\left(x\right)dx\Bigg]\end{aligned} \tag{6}$$

where φ(.) denotes the density function of a standard normal distribution and

$$x^* = \left(\ln\left(V^*\right) - \ln\left(V\left(t_{RD}\right)\right) - w_\mu\right) \Big/ w_\sigma \tag{7}$$

Equation (6) can be written as

$$\begin{aligned} O_L\left(t_D\right) = {} & AV^\beta\left(t_D\right)\exp\left(\beta w_\mu + \tfrac{1}{2}\beta^2 w_\sigma^2\right)\Phi\left(\kappa_1\right) \\ & + V\left(t_D\right)\exp\left(\mu\left(T_L - t_D\right)\right)\Phi\left(\kappa_2\right) - I\Phi\left(\kappa_3\right) \end{aligned} \tag{8}$$

where $\Phi(.)$ denotes the cumulative probability distribution function of a standard normal variable and where $\kappa_1 = x^* - \beta w_\sigma$, $\kappa_2 = -x^* + w_\sigma$ and $\kappa_3 = -x^*$.

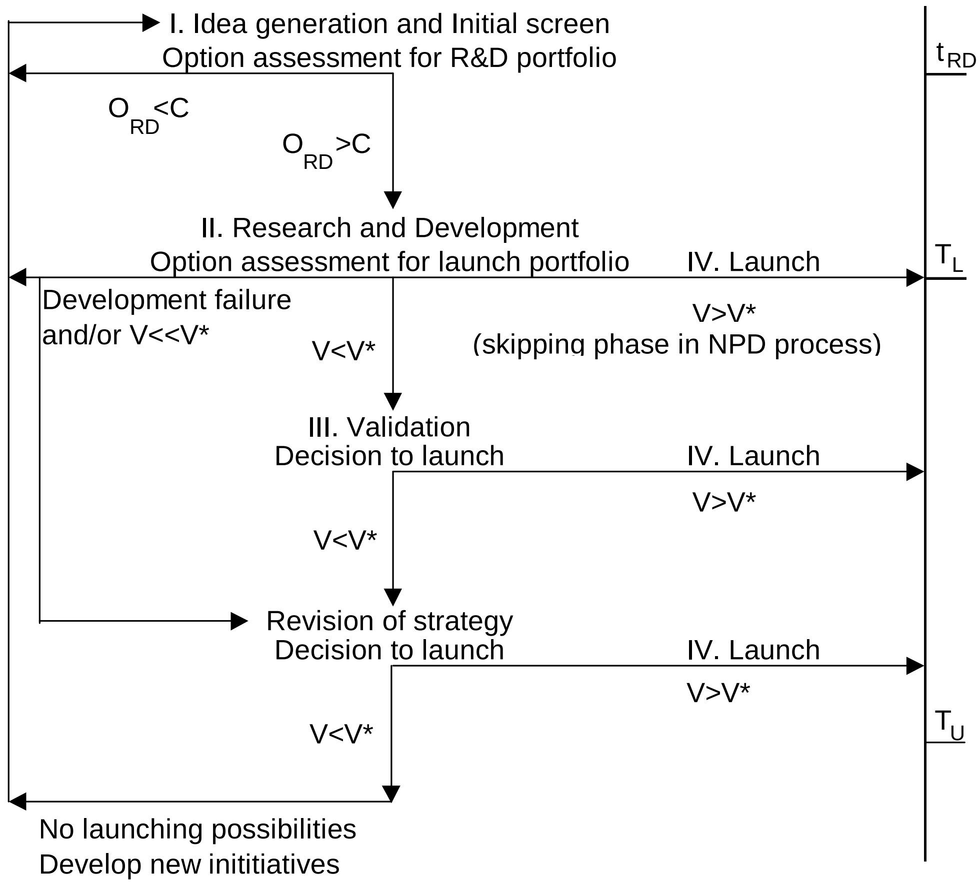
I. Idea generation and Initial screen
Option assessment for R&D portfolio
O RD<C
O RD>C
II. Research and Development
Option assessment for launch portfolio
IV. Launch
Development failure
and/or V<<V*
V<V*
V>V*
(skipping phase in NPD process)
III. Validation
Decision to launch
IV. Launch
V>V*
V<V*
Revision of strategy
Decision to launch
IV. Launch
V>V*
V<V*
No launching possibilities
Develop new inititiatives
tRD
TL
TU

figure 1

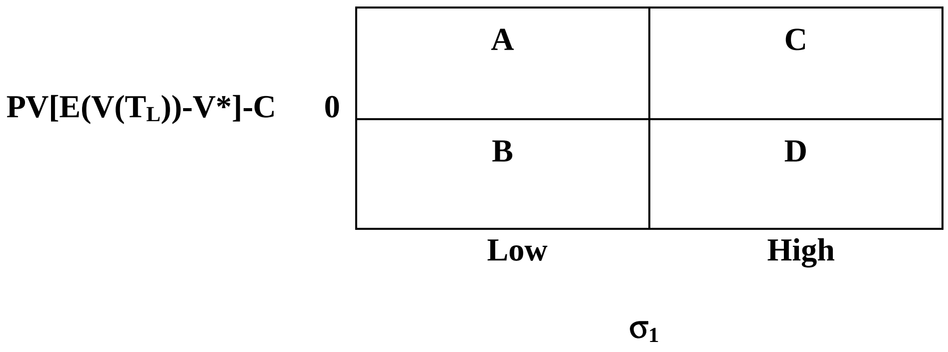

Figure 2: The R&D Options Portfolio

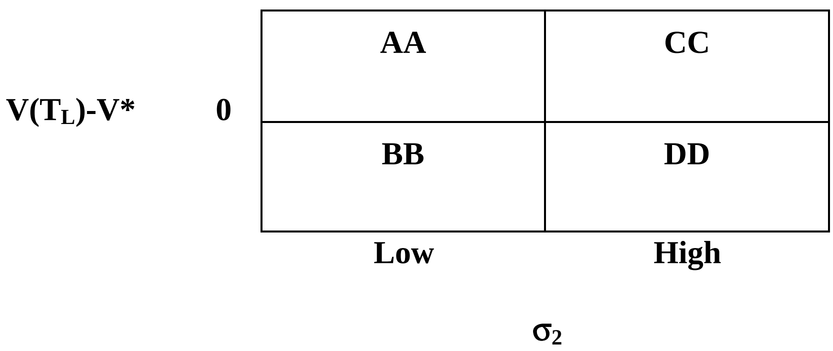

Figure 3: The Market Launch Options Portfolio