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Dissertation

R&D Portfolio Selection Considering Risk and Project Interrelations

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Kurzfassung

Die vorliegende Arbeit beinhaltet ein Modell sowie die prototypische Referenzimplementierung eines zugehörigen Frameworks für die Evaluation von Forschungs- und Entwicklungsprojekten (F&E). Dabei wird das Risiko sowie der Nutzen solcher Projekte berücksichtigt. Der Framework ermöglicht die Auswahl eines Portfolios von F&E Projekten unter Berücksichtigung beschränkter Ressourcen, Begrenzung des Risikos und verschiedener Abhängigkeiten zwischen den Projekten.

Aufgrund des innovativen Charakters von F&E Projekten, besteht auch hohe Unsicherheit bezüglich der Ergebnisse der Projekte. Daher kann die Durchführung von F&E Projekten ein risikoreiches Unterfangen sein. Unter Verwendung des Konzeptes des Value-at-Risk wird sowohl das Risiko eines einzelnen Projektes, als auch das Risiko eines Portfolios abhängiger Projekte in den Evaluationsprozess miteinbezogen.

Der Erfolg oder Misserfolg eines F&E Projektes ist schwer zu bewerten, da viele Aspekte berücksichtigt werden müssen. Daher wird eine multi-dimensionale Bewertung herangezogen, welche, zusätzlich zu den finanziellen Aspekten, auch Wissensgewinn, Umwelt- oder soziale Folgen *etc.* der Projekte in Betracht zieht. Ein informationstheoretischer Ansatz zur Bewertung des Wissensgewinns während eines Projektes wird vorgeschlagen.

Diese multi-dimensionale Bewertung wird in einem Real Options Modell für die Bewertung von F&E Projekten verwendet. Der Bewertungsprozess berücksichtigt das Risiko der Projekte.

Mit Hilfe von Multi-Attribute Utility Analysis wird diese multi-dimensionale Bewertung zu einem skalaren Nutzenwert aggregiert. Dieser Nutzenwert dient zur Auswahl eines Projektportfolios, das den totalen erwarteten Nutzen maximiert und den Ressourcenbeschränkungen genügt. Die Auswahl des Projektportfolios wird sowohl mittels einer klassischen Lösung zum 0/1 Knapsack Problem sowie mittels dynamischer Programmierung implementiert.

Um Abhängigkeiten, Synergien und Redundanzen zwischen den Projekten in der Auswahl des Projektportfolios zu berücksichtigen, wird der Algorithmus für das Knapsack Problem erweitert, um diese verschiedene Arten von Abhängigkeiten in die Portfolio Auswahl mit einbeziehen zu können.

Abstract

In this work a model and a prototypical reference implementation of an according framework for the evaluation of research and development (R&D) projects is presented, that accounts for the risk and utility of these projects. The framework allows for the selection of a portfolio of R&D projects considering limited resources, risk limits and various interrelations between the projects.

Because of the highly innovative character of R&D projects, there is also high uncertainty about the outcomes of the projects. Consequently conducting R&D projects can be a risky venture. By using the notion of the Value-at-Risk the risk for an individual R&D project as well as for a portfolio of interrelated projects is included into the evaluation process.

The success or failure of an R&D project is difficult to measure, as there are many aspects that have to be taken into consideration. Thus a multi-dimensional measure is used that, in addition to the financial aspects, considers knowledge, environmental or social impacts *etc.* of the projects. A technique for measuring the knowledge gained within an R&D project is proposed that is based on information theory.

This multi-dimensional measure is used in a real options model for the evaluation of R&D projects. The evaluation process takes the risk of these projects into account.

With the help of multi-attribute utility analysis this multi-dimensional measure is aggregated to a scalar utility value. This utility value is used to select a portfolio of projects that maximises the total expected utility, and satisfies certain constraints concerning the resources available. The portfolio selection process is implemented using a classic and dynamic programming solution for the 0/1 Knapsack problem.

In order to consider interdependencies, synergies and redundancies between the projects within the portfolio selection, the algorithm for the Knapsack problem is extended to allow for various kinds of interrelations.

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Motivation

In order to evaluate R&D projects for the selection of an R&D project portfolio, an objective and deterministic valuation and selection process is required, that guarantees a comprehensible strategy for investment decisions.

The theory behind option pricing has proven a successful valuation method in the world of finance, and is also regarded as a promising approach for the evaluation of R&D projects. Introducing options thinking into the valuation process for R&D projects stems from the idea that there are similarities between the characteristics of real options and R&D projects, for example the uncertainty with respect to the expected return of the investment. Due to the highly innovative character of R&D projects the flexibility to react to changing situations should be incorporated into the valuation process, which is provided when regarding R&D projects as real options.

Besides monetary issues, an important aspect of research projects is that they are often undertaken with the aim to gain knowledge in a certain field that can then be used for follow-up projects, product development, patents or licences. Further success criteria for R&D projects are the creation of networks, publications *etc.* As a consequence it is mandatory that the evaluation process of R&D projects focuses not just on financial aspects, but also takes the multi-dimensional character of R&D projects into account. A project that is a loss with respect to the financial return on investment can be highly successful with respect to the knowledge gained within the project, which again can be the basis for further projects being financially successful because of the contributions of the first project.

Thus the success criteria of R&D projects are multi-dimensional and the focus is not only on the financial return of the project, which is usually the case with conventional projects. Examples for further aspects worth considering are the knowledge gained, environmental or social impacts of the underlying project.

As already mentioned, R&D projects are surrounded by high risk and uncertainty. When determining the risks and uncertainties of R&D projects, as well as R&D project portfolios, it is at first necessary to define these terms in a way that has meaning with respect to the context of R&D. As taking decisions based on the level of risk is of great importance for the decision maker when selecting a portfolio, the estimations of the projects' and resulting portfolio's risk have to be part of the whole evaluation process.

Portfolio management for R&D projects has enjoyed increased attention within the last couple of years. Companies want to evaluate their technologies from a portfolio's perspective, which means evaluation of a set, or subset, of R&D projects together and in relation to one another. An important issue is the allocation and re-allocation of resources to the projects selected for the portfolio. Decisions have to be taken concerning which projects should be continued, prioritised, de-prioritised and stopped. Typical characteristics of the portfolio decision process are uncertainty, changing information, multiple objectives and interrelations among projects. Regarding the multi-dimensionality of R&D projects a project portfolio can also aim at achieving the right balance of focus on the various project dimensions. It might for example be reasonable to select projects for the portfolio, which are likely to be a financial success, in order to support projects that focus on environmental or social aspects

In addition to the multi-dimensional success criteria, and taking into account the projects' risks, a further important aspect of the portfolio selection process is the consideration of interdependencies, synergies and redundancies between projects. Taking into account various kinds of project interrelations has been identified as an important feature of project selection models in discussions with practitioners in R&D intensive industries. Two projects are interdependent if the result of one project is a necessary precondition for undertaking the other project. The creation of knowledge networks within an organisation can cause synergies between projects that cause benefits in addition to the results of the synergistic projects. Furthermore, it can be reasonable to undertake redundant projects with the same or a similar research goal simultaneously in order to reduce the risk of achieving the expected results.

This work is supported by the Austrian Research Centers ARC [1], Austria's largest non-university research group. Management within ARC initiated the development of the presented project evaluation and portfolio selection tool. Many ideas and concepts presented in this thesis were inspired by discussions at ARC, especially within the departments Systems Research and Information Technologies.

Contents

Summary

In order to introduce the special characteristics of R&D projects in comparison to conventional projects, chapter one "R&D Projects" gives an overview of the multi-dimensionality of R&D projects and the resulting multi-dimensional success criteria. These multi-dimensional aspects have to be taken into account for the evaluation of R&D projects. Definitions of research and development activities as being part of the innovation process are presented, as well as a comparison of public and private R&D.

Definitions of the terms risk and uncertainty are presented in chapter two "Risk and Uncertainty" as they are often not clearly defined in the context of R&D management. Definitions and scopes for risk, uncertainty and related concepts are presented, which are commonly used by economic theories for decision taking under uncertainty, project management and finance.

Chapter three "Project Evaluation under Risk" starts with the introduction of various methods that can be used to determine the risk of a project. Then state-of –the-art project evaluation techniques as well as extensions to existing techniques adapting them to R&D valuation are discussed. The chapter closes with a comparison of the presented project evaluation methods with respect to the requirements of R&D.

A detailed introduction to real options theory and how it can be applied to the valuation of R&D projects is given in chapter four "Real Options Theory". Chapter four also discusses similarities and differences of the real options model compared with decision tree analysis.

Chapter five "R&D Portfolio Management" starts with a brief introduction to the aims of portfolio management for R&D projects and presents requirements that have been identified as essential for R&D portfolio selection models. The characteristics of R&D- and financial portfolios are compared. Special attention is paid to the interrelations that can exist between projects. A hierarchy of project interrelations as well as according definitions for the various kinds of interrelations are suggested. A technique for calculating the risk of a portfolio of interrelated projects is presented. Furthermore state-of-the-art portfolio selection models are introduced and compared with respect to the identified requirements.

"An Evaluation Framework for R&D Portfolios" is presented in chapter six. The model and according implementation represents a new approach to the valuation of R&D projects, as well as to the selection of projects for a portfolio. The real options model is applied to project evaluation taking the projects' multi-dimensional aspects into account. The risks for the various dimensions of each project and the portfolio are calculated. The portfolio selection is based on the solution to the 0/1 Knapsack problem. In order to account for various kinds of interrelations between the projects the Knapsack algorithm is preceded by a topological sort of the interrelated projects. To avoid the exponential complexity of the classic 0/1 Knapsack solution the dynamic programming algorithm for the Knapsack problem was modified to consider the effects of interrelated projects.

Chapter seven presents the results of the framework´s application to selected R&D projects within the Austrian Research Centers (ARC).

Chapter eight comprises "Conclusions and Further Research".

A glossary describes the essential notions used within the presented work. The Appendix provides a manual for the implemented R&D portfolio evaluation framework.

Chapter 1 — R&D Projects

This chapter gives an introduction to the special characteristics of research and development projects, starting with a definition of research and development activities in the context of an innovation process. Due to the creation of something new the innovation process is inherently risky. Innovative products and processes however, create new scopes of utility and thus research and innovation are an essential drive for economic growth. Furthermore the implications of the characteristics of research and development for the evaluation of R&D projects are described and a comparison of R&D and conventional projects is included. The chapter closes with a comparison of public and private R&D.

1.1. Terms and Definitions

The following paragraph aims at defining the term R&D and placing it in the broader context of the innovation process. Furthermore the concept of intangible assets is introduced, which is closely related to research and development activities, and will be used throughout this thesis.

Innovation

The Frascati manual of the OECD, first published in 1963, deals with definitions and ways to measure R&D. Innovations are defined as follows [OECD - Frascati, 1993]:

> *"Scientific and technological innovation may be considered as the transformation of an idea into a new or improved product introduced on the market, into a new or improved operational process used in industry and commerce, or into a new approach to a social service.*

Technological innovations comprise new products and processes and significant technological changes in products and processes."

Brockhoff distinguishes between innovations in a narrower sense and innovations in a broader sense [Brockhoff, 1999]:

We talk about an innovation in a narrower sense, if there is an invention that promises to be an economic success and thus investments for production and marketing are made. An innovation has been implemented if the product succeeds in being introduced on the market or used within a production process; this is called a product or process innovation in a narrower sense. Understanding innovation in this context, research and development is a separate activity.

Innovation in a broader sense comprises the whole innovation process, and research and development is a part thereof. Brockhoff [Brockhoff, 1999] explains the innovation process as consisting of the following activties: Research and development leading to inventions, which are introduced to the market, leading to an innovation in a narrower sense. If the product becomes accepted on the market, the diffusion process starts. This means that the new product or process propagates itself. This encourages competitors to imitate the product or process. The innovation process therefore involves a series of scientific, technological, organisational, financial and commercial activities.

As it can be seen, R&D activities are only one part of this process and may also be spread over various stages of the innovation process, thereby not only being the original source for new ideas but also serving as a kind of problem-solving technique [OECD - Frascati, 1993].

Schumpeter [Schumpeter, 1961] clearly distinguishes inventions from innovations, where the latter *e.g.* comprise new technologies for the production of goods, which are already on the market, the coverage of new markets or the establishment of new kinds of business organisations. In many cases inventions are undertaken independently of a need to be fulfilled, whereas innovations are made in order to deal with a certain problem. Schumpeter regards innovations – the emergence of new combinations – as internal factors of the economy, as opposed to external factors.

In [Schumpeter, 1961] an innovation is defined with the help of a production function describing the way in which the output changes depending on a change in factor inputs. As a result of an innovation, however, factors are combined in a new way and thus the shape of the production function changes. The new production functions caused by innovations shift the cost functions within the economic system.

- Economic evolution is defined as the implementation of new components, comprising the following [Schumpeter, 1935]:
- Production of new commodities or qualities thereof
- Introduction of new ways of production that do by no means have to be based on scientific inventions
- Coverage of new markets, that might well have existed before but not for the specific branch of industry of the country of interest.
- Obtaining a new source of supply for resources or subassemblies
- Reorganisation *e.g.* creation of a monopoly position

New combinations are successfully applied if, after having reached a local optimum with the use of existing combinations, these new combinations are used to make a wider jump away from this local optimum in order to achieve economic growth. Thus, interpreting Schumpeter, innovation is the drive of the dynamics of economic evolution [Hanappi and Hanappi-Egger, 2004]. Progress caused by innovations drives the economy out of equilibrium and is thus responsible for economic cycles. These cycles are characterised by four phases: prosperity, recession, depression and rebound. While equilibrium relations prevail among the elements of the economy during recession and rebound, prosperity and depression differ in the kinds of impulses they cause but both drive the economy away from equilibrium towards disequilibrium.

Although it is sometimes not obvious economic prosperities are based on innovations and their - often much better observable - byproducts such as increasing expenditures of producers and consumers. Furthermore it is assumed that major innovations require a certain amount of time and expenditures and consequently are risky.

Regarding innovations as the source of economic cycles there must be several cyclic movements at the same time as the periods of introduction and absorption of the innovation by the economy are obviously not the same for all innovations. Schumpeter suggests concentrating on three main cycles, named after their discoverers [Schumpeter, 1961]:

- Kondratieffcycles lasting about 60 years
- Juglarcycles lasting about 10 years
- Kitchincycles lasting about 40 months

Kline and Rosenberg [Kline and Rosenberg, 1986] define technological innovation as being absolutely central to economic growth. According to the authors "a century ago organised innovation was rare and innovation therefore much slower. The successful innovator could count on gaining significant competitive advantage. Today innovation is a cost of staying even in the marketplace" [Kline and Rosenberg, 1986, p.302]. Innovation is characterised as being "complex, uncertain, somewhat disorderly and subject to changes of many sorts. Innovation is also difficult to measure…" [Kline and Rosenberg, 1986, p.275]. In many cases benefits from innovations are not only generated in the industries, that instigated the innovation, but various completely different sectors profit from the new technologies, processes *etc.*, which makes it difficult to allocate the costs and benefits of innovations. Another important characteristic of innovations is that they are based on scientific achievements, but sometimes also force the creation of science and feedback. Thus no linear model is suitable to represent the innovative process [Kline and Rosenberg, 1986].

Research and Development

The following definition is given by the OECD Frascati Manual, [OECD - Frascati, 1993]:

> *"Research and experimental development (R&D) comprise creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications."*

Research and development are defined as activities, which are embedded in an innovation process [Kline and Rosenberg, 1986], [Brockhoff, 1999]. These activities can be spread over various institutions. The success of these R&D activities is a necessary but not a sufficient condition for the new developments' success on the market. The developments are strongly influenced by real or assumed needs.

Research and development is usually classified into basic research, applied research and development. In many cases the order of this classification also applies to the timing of the activities, but this does not necessarily have to be the case, and the activities can overlap. According to the OECD 1992 definitions, (refer to [OECD - Frascati, 1993]):

- Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view.
- Applied research is also original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective.
- Development or experimental development is systematic work, drawing on existing knowledge gained from research and/or practical experience, that is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed.

R&D is closely related to other scientific and technological activites, such as scientific and technical education and training and the scientific and technological services [OECD - Frascati, 1993], regarding the exchange of information and considering the operations, institutions, networks and personnel. Whether these activities are excluded when measuring R&D or explicitly taken into account for the evaluation of R&D and related activities, is at the disposal of the decision maker.

Human Capital and Intangible Assets

Research activities and the first attempts to develop a new product or process are based on researchers, *i.e.* human capital, gaining new information and creating knowledge.

Human capital is defined by the OECD [OECD, 1999] as:

„The knowledge, skills, competences and other attributes embodied in individuals that are relevant to economic activity".

In order to evaluate R&D projects one has to attach values to the knowledge gained, as will be discussed later and therefore the terms "intangible assets" and "intangible capital" will also briefly be defined here:

Davidson, Stickney and Weil [Davidson, Stickney and Weil, 1988] define intangible assets in an accounting textbook as assets that can provide future benefits without having physical form. These assets are called intangibles and can for example include research costs, advertising costs, patents, trade secrets, know-how, trademarks and copyrights. Since then the term has been extended, now including the knowledge of an organisation and its employees, and their ability to learn. A combination of the concepts of economic value with intellectual and human capital is provided by [Aboody and Lev, 1999]. According to the definition of Aboody and Lev intangible (knowledge) capital represents the present value of the future stream of knowledge earnings.

Among other Austrian economists Hayek and Machlup discuss the distinction between information and knowledge, refer to [Hayek, 1937], [Hayek, 1945] [Machlup, 1962]. Their emphasis is on the active interpretation of existing information instead of passive reaction, as well as on the creation of new knowledge, that is gained through the individual contexts of the decision makers [Boettke, 2002]. In the 1950s Machlup [Machlup, 1962] started to conduct studies on innovation and the knowledge industry, where knowledge is defined as a commodity. Machlup tries to quantify the production and distribution of knowledge in an economy. For a summary of attempts to quantify intellectual capital refer to chapter six, 6.1.2.

As discussed in 1.2.1. there are also social aspects of economic development, that are strongly related to the accumulation of human capital. Schultz was one of the first who emphasised the importance of education as a pre-requisite for economic growth [Schultz, 1961].

1.2. Characteristics of Research Projects

According to Kanter [Kanter, 1989], the three most important characteristics of R&D projects are:

- High uncertainty
- High intensity
- High autonomy

These characteristics require capital investment for long-term projects that will not give financial return in the near future and flexibility concerning planning and project management.

One of the main characteristics distinguishing R&D projects from conventional projects is the high uncertainty concerning the output of the project. First of all there is the general uncertainty if research results will be generated. Then the output of the project is highly unpredictable because the results of the project can be quite different from the ones originally expected. However, in addition to being qualitatively worse, they can also be qualitatively better. In order to be innovative, one has to take the risk that the project might not turn out as expected or that the focus might change while undertaking the project.

The cost and time needed to undertake innovation projects also strongly depend on the state of knowledge in the underlying science. The need to learn is inherent to radical, major innovations and fundamental research is a learning process [Kline and Rosenberg, 1986].

The research and development process is characteristically knowledge intensive. Combining experience and interactive learning creates new knowledge, because the research is often done in teams and networks are created during the research process [Kanter, 1989].

Concerning the project management of R&D projects, there are often non-linear relationships and no clear-cut sequences between the projects' phases. Non-linear dynamical systems can exhibit a completely unpredictable behaviour. Making small changes in a non-linear system with respect to the intial input variables can have unforseeable effects on the final outcome of the system. Changes in non-linear systems happen discontinuously and represent transformations.

R&D projects are characterised by a usually high autonomy of the team members and participants. In order to achieve high performance, free sharing of knowledge between the project members is necessary. The results of R&D projects are presented in the form of new knowledge codified into *e.g.* scientific papers, reports, articles, technologies or technological processes and are characterised by a high degree of knowledge intensity [Ernø-Kjølhede, 2000]. These results can also have a strategic dimension. From a general perspective a company´s strategic success dimension depends on factors and conditions that have a long-term, significant and lasting effect on the company´s success and competitive advantage [Haedrich, Tomczak and Kaetzke, 2003]. If the strategic objective of a company is to capture a new market, there are several subgoals that have to be attained in order to achieve the overall objective. Such subgoals can *e.g.* be gaining knowledge about the new technology or features of the product to be developed or finding a way to meet environmental or legal regulations.

1.2.1. Multi-dimensional Success Criteria

Regarding R&D as part of an innovative process Kline and Rosenberg [Kline and Rosenberg, 1986, p.304] emphasise that "it is necessary to view the process of innovation as changes in a complete system of not only hardware, but also market environment, production facilities, knowledge and the social contexts of the innovating organisation." New technologies have much wider impacts than just improved technical performance and have to be conceived within the context of their potential economic and social significance. New technologies are unrealised potentials and can be regarded as building blocks, whose impacts depend on what will be constructed with them. [Rosenberg, 1986].

Similar to conventional projects, success criteria for the outcomes of R&D projects are economic and financial criteria such as expected cash flows, return on investment or cost savings. Further quantitative criteria are fitness-for-market, time-to-market and performance concerning the project being on time, on budget respectively. More specific to R&D projects are outputs like new products and processes or improvements in products and processes.

R&D projects also generate qualitative outputs. Undertaking a highly innovative project contributes to the capabilities and skills of the team members. New knowledge is generated and exchanged, which often leads to the establishment of networks. The creation of networks while conducting a research project obviously has got a strategic dimension as well, *e.g.* the exchange of know-how and further collaboration within future projects Furthermore the pool of innovations is extended. Another aim of an R&D project can be to enhance the social situation or to fulfil environmental concerns by undertaking the project. Thus ethical values can also be criteria for success.

Some R&D projects are only accomplished in order to gain knowledge that can then be used for follow-up projects. Together these kinds of success criteria distinguish R&D projects from conventional projects, which in most cases focus on financial and economic issues [Geisler, 1999]. Consequently the multi-dimensional aspects of R&D projects should also be taken into account in the evaluation process.

The multi-dimensional success criteria of R&D projects can be mapped to a hierarchy of multi-dimensional goals. This hierarchy of goals consists of an overall goal and a number of subgoals which result in the overall goal. Obviously one can distinguish between quantitative and qualitative goals [Eyer and Haussmann, 2001]. Quantitative goals can be represented by measurable indices, which express the level of realisation of the goal. Many goals however can only be measured by indirect and often non quantifiable factors. Therefore indicators have to be defined in order to measure these qualitative goals. The level of transfer of knowledge can for example be put in concrete terms by the frequency of contacts between the collaborating teams.

If the relation between the various goals of an R&D project can be structured in means and purposes there is a goal hierarchy consisting of sub-, intermediate and overall goals [Heinen, 1985]. Another way of structuring goals is to group the various goals into different dimensions, such as social, economic and ecological goals.

The goals of an R&D project can also be conflicting. High quality and high security for example usually are in conflict with low costs and fast results. Taking into account goals concerning environmental care, these alter the goal relation between the environmental goal and the profitability goal.

1.2.2. Success Measurement

A traditional approach to measure a project's success is to compare how well the results meet the aims originally set for the project. When evaluating the results of a research project one must take into account that the conditions may have changed considerably while undertaking the project. This can be a result of gaining knowledge and new insights during the project period [Ernø-Kjølhede, 2000]. Therefore the evaluation method has to account for flexibility concerning the implementation and the results of the project.

R&D investments are crucial for the long-term strategic position of a company and a company's strategy can be changed entirely because of an innovation. Due to limited resources usually not all ideas for research projects result in an innovation project. A selection of projects financed for further development has to be made with the aim of creating a portfolio of projects that enhance the company's strategic ability to carry out future projects [Clark and Wheelwright, 1993]. Also strategic advantages resulting from economies of recombination can be realised by selecting a portfolio of related projects, after having undertaken an initial innovation project [Davies and Brady, 2000].

By making an early strategic investment commitment a company can improve its strategic position and increase the value of its future growth opportunities. This early strategic investment decision may also have an effect on the strategic reactions of the competitors and consequently sometimes even result in a change of the market structure [Smit and Trigeorgis, 2001].

Patents can be regarded as a strategic instrument, because the decision to apply for a patent can depend on the behaviour of competitors. Applying for a patent can have signalling reasons

[Crampes and Langinier, 1998] and strenghten a company's bargaining position in the case of patent litigation threats [Hall and Ziedonis, 2001]. Crampes and Langinier [Crampes and Langinier, 1998] examine the strategic dimension of patents resulting from the information asymmetry between the innovator and potential competitors. Given perfect information an innovator will renew a patent if the expected profits compensate for the renewal costs. Under imperfect information however, by renewing the patent the innovator signals that the market for the innovation remains profitable and may thus encourage a potential competitor to enter the market as well.

Facilitating learning and the transfer of knowledge, especially across projects over time, can improve a company's long-term capabilities specifically for incremental innovations and is thus an important strategic dimension, compare [Ettlie, Bridges and O'Keefe, 1984], [Dewar and Dutton, 1986] and [Henderson and Clark, 1990].

Obviously, it is difficult to measure the success of a research project that depends on qualitative success criteria. A rather easy approach is to count the number of publications, citations, presentations or prizes and honours that result from the R&D project's outcomes. The number of patents, follow-ups, and customer projects can serve as a measure for the success or failure of a research project. One can also observe the establishment of partnership and creation of networks that is initiated by the project, and whether new research has resulted from having undertaken the R&D project. Whether scientific or technical benchmarks and standards have been developed is a further possibility [Geisler, 1999].

Another important issue is whether the project has allowed for learning. With respect to the process of thinking and remembering, individuals are usually regarded as the learning entities. However they appear to think in conjunction or partnership with other individuals. Salomon [Salomon, 1993] points out that the social and artifactual surrounding stimulates and guides the thinking process and also is a vehicle of thought. Therefore not only the individual learns but the whole system of interrelated factors. Considering this aspect one can distinguish between individual and organisational learning, for an introduction to organisational learning refer *e.g.* to [Cohen and Sproull, 1996] and [Kogut and Zander, 1996].

According to Easterby-Smith and Araujo [Easterby-Smith and Araujo, 1999] there is a technical view on organisational learning referring to explicit quantitative or qualitative information, its effective processing, interpretation and response to this information in and outside of the learning organisation. The social view on organisational learning relates to people making sense of their work experiences, derived from explicit information but also implicit and tacit sources. Accordingly learning can emerge from social interactions. Referring to Argyris and Schön [Argyris and Schön, 1996] members of an organisation individually construct a representation of the theory-in-use of the whole. As their pictures always remain incomplete the individuals are constantly trying to get a view of the whole and to get to know themselves within the context of the organisation. Regarding a company from a resource based perspective knowledge has been increasingly seen as the critical resource. For a more detailed discussion of intellectual capital and according measurement techniques refer to 6.1.2.

The effects of an R&D project's outcomes on the economy, jobs, the rate of innovation, as well as social or environmental impacts, are in most cases more difficult to measure and even more difficult to estimate in advance. This is because these long-term effects are not so easy to track. Furthermore one has to distinguish between quantitative, measurable factors as output of an R&D project and the according qualitative effects. Questionnaires and interviews are a means to record factors that cannot be measured, with the usual drawback of the subjectiveness of the data gained.

Another way to gain probabilities concerning the occurrence of the potential effects of innovations is to use so-called prediction or information markets. These are virtual, speculative markets consisting of assets whose final value–measured in play money units–depends on a parameter or the occurrence or non-occurrence of a particular event. The asset´s current market price provides information about the predictions of the probability of the event occurring or the expected value of the parameter. By buying low and selling high traders are rewarded for improving the market prediction and the other way round. The method was used by CERN, the European laboratory for particle physics, in order to find out whether the probability of discovering a Higgs boson particle was high enough to justify extending the operation of its collider [Pennock et al., 2001]. The estimates are based on a large sample of participants and thus the method compensates for the subjectiveness of the individual estimates. Gjerstad shows that under the assumption that the distribution of beliefs is smooth, *e.g.* beliefs are normally distributed, prediction market prices resulting from information markets usually are very close to the mean belief of market participants, refer to [Wolfers and Zitzewitz, 2004]. Empirical studies by Pennock [Pennock et al., 2001] and Servan-Schreiber *et alii* [Servan-Schreiber et al., 2004] indicate that there is a strong correlation between prices of binary prediction markets and actual event frequencies. Similar to real markets prediction markets are subject to manipulation attempts. Hanson, Oprea and Porter [Hanson, Oprea and Porter, 2006] however show that such attempts usually do not last very long and eventually increase the market´s accuracy due to an increased profit incentive by betting against the manipulator.

Mansfield *et alii* [Mansfield et al. 1977] provide a method to measure the social rate of return of an innovation briefly described in the following: If the supply curve for a product is shifted downward as a result of the innovation, the area under the product's demand curve between the preinnovation and postinnovation supply curves is used as a measure of the social benefits gained due to the innovation. Given that all prices remain constant, the social value of the additional quantity of the product plus the social value of the resources saved because of the innovation, are equal to this area. Comparing the input stream of R&D necessary for the innovation with the stream of so measured social benefits provides a way to estimate the social rate of return from the investment in the innovation.

Empirical literature, compare *e.g.* [Jones and Williams, 1998] estimates the social rate of return to R&D by an explanatory variable measuring R&D input or output in an estimating equation explaining growth in total factor productivity. This estimated R&D variable indicates the productivity growth resulting from an increase in R&D activity.

Another attempt to measure the success of an R&D project is to observe the creation of new markets, market segments or new customers that emerge as a result of the R&D project [Ernø-Kjølhede, 2000]. Some research is undertaken without a specific target market for the new product or process in mind. The potential customers may belong to some market niches, *e.g.* mobile phones in Scandinavia. These market niches benefit from the development of the new product and suddenly the product is used not only by the customers of the market niches but by completely new and unexpected customers. Thus new market segments can emerge due to an innovation, as the innovation may create needs that have not existed before—or the customers were not aware of—but are now fulfilled by the product or process resulting from the innovation. Accordingly a new market emerges that could not be foreseen. The emergence of new markets or market segments can be observed by new companies, imitators and competitors, who want to benefit from the emerging market, as well as new companies going public. A higher differentiation of an existing market is an indicator of the existence of new market segments.

The following table provides a summary and comparison of conventional versus research projects.

Conventional Projects	Research Projects
Defined objectives and measurement categories for success.	Objectives may be abstract and subject to change.
Divided into distinct project phases and sub-tasks.	Non-linear and overlapping phases and tasks.
Projects are repetitive.	Research projects are highly innovative and thus particular and singular.
Normally projects are intra-organisational.	Research projects are often inter-organisational.
Project participants work (almost) full-time on the project.	Most researchers take part in a set of R&D projects and also conduct teaching, publication of results, or other supplementary activities.
There is often a standard procedure for planning and controlling-rationality.	Planning and control is difficult and may limit the success of the project-bounded rationality.
The project manager is the expert in the field and guides the project by giving advice and instructions.	The research project manager often lacks the required professional knowledge. The team members are experts in the various fields that are covered by the project and have a high degree of autonomy. Too rigid control can have a negative impact on the results.
The various work tasks are concretely defined at the beginning of the project.	Work tasks are undefined and new tasks emerge while undertaking the project.
Aims and goals are clearly defined.	Aims and goals can change completely during the project.
The aims are defined in commercial terms.	The aims are defined in both commercial and non-commercial terms.
Applied technology is developed.	Applied and non-applied technology is developed.
The product or processes are developed for customers—clearly defined by the end user's impression of the result.	There may be no defined customer at all.
Limit uncertainty—focus on safety. Need to reduce risks to ensure the delivery of the desired result on time and budget.	Uncertainty is a necessary part of research. Risks must be taken in order to be innovative and successful.
Evaluation takes place by comparing what was planned by what happened.	The purpose is learning and reaching optimum results. Planned results may prove second-best or unrealistic.

Table 1.1 "Research Projects versus Conventional Projects" – Source: [Ernø-Kjølhede, 2000]

Within the presented framework the potential success of an R&D project can be estimated according to various dimensions, such as economic, knowledge and ecological goals. The overall goal is to optimise a project's or a portfolio's utility. The utility is composed of various goal dimensions. In order to avoid conflicts between these various goal dimensions, as discussed in 1.2.1. multi-attribute utility analysis (MAUA) is used, refer to 6.5.2. In case of an additive utility function MAUA allows to specify priorities between the dimensions by attaching weights. In case of a general utility function the various dimensions are not necessarily mutually independent and thus they do not form a hierarchy.

1.3. Public and Private R&D

Blank and Stigler [Blank and Stigler, 1958] were the first to investigate whether the relationship between public and private R&D investments is complementary or substitutional. Several economists in the tradition of Blank and Stigler find positive spillover effects of scientific knowledge generated by publicly funded R&D stimulating private R&D, refer *e.g.* to [Levy and Terleckyj, 1983], [Jaffe, 1989] and [Adams, 1990].

David, Hall and Toole [David, Hall and Toole, 2000] examine the economic impacts of R&D investments made by the government on private sector R&D. If public R&D expenditures have got a positive effect on private R&D activities, they want to verify the assumption that public R&D programs do not displace private R&D investments, but give rise to more company-funded R&D. The authors find that R&D activities funded by the government do stimulate as well as complement private R&D indirectly because in areas such as military technology and logistics or public health, the government often assigns R&D work to the staff of private R&D-performing companies. In general there are two main governmental policy instruments in order to support private R&D activities: tax incentives reducing the cost of R&D and direct subsidies raising the private marginal rate of return on investment in research activities. While tax instruments are usually not aimed at any specific kind of research, subsidies are distributed for research areas selected by the government. The latter allows the government to fund projects that are supposed to offer high marginal social rates of return to investments in knowledge. On a macroeconomic level the relationship between public and private R&D spending is characterised by complementarity [Robson, 1993].

Schumpeter who regarded the entrepreneur and their innovations as the major driving force for economic growth, mainly in his late work [Schumpeter, 1942], comes to the conclusion that the innovation process would become more and more automated by means of modern techniques and modern modes of organisations. According to Schumpeter's view in a world of limited knowledge innovation is a completely unpredictable venture and thus left to some genius individuals. As limits to knowledge disappear, not a single entrepreneur but a large organised team of specialised researchers will be responsible for innovative research directed towards predefined needs with results that should work in predictable ways. While basic inventions used to be more or less exogenous to the economic system, transformed to innovations by entrepreneurs, large firms would endogenise scientific and technological activities in order to succeed on the competitive market. Thus the once loose and long-term relation between science, technology, investment in innovations and the market would become much closer and continuous [Freeman, 1982].

Whether Schumpeter's arguments hold is subject to discussions. R&D today is definitely more structured and organised as it was in Schumpeter's days, for one reason due to the growing division of labour. According to Smith [Smith, 1776] however, increasing division of labour is not a driving force for innovation because the outcome thereof is made predictable but growing division of labour results in growing diversity of ideas in society—which may be an important basis for new ideas and thus innovations, as will be discussed within the next section.

Hollingsworth investigates the influence of institutional structures on innovativeness and the according conditions under which major discoveries and breakthroughs in research occur. The author finds that radically new ways of thinking and the resulting new approaches to the solution of existing problems strongly depend on the interaction of researchers with diverse backgrounds [Hollingsworth, Schmitter and Streeck, 1994], [Hollingsworth and Boyer, 1997], [Hollingsworth and Hollingsworth, 2000a] and [Hollingsworth and Hollingsworth, 2000b].

Hollingsworth [Hollingsworth, 2003] identifies the following characteristics of organisations as beneficial for research breakthroughs:

- Organisational autonomy referring to the independence of an organisation of governing authorities when it comes to making scientific appointments, engaging in new lines of research and creating new laboratories or departments.
- Organisational flexibility facilitating a rapid shift towards new and different fields of research.
- Moderate scientific diversity with respect to various disciplines and areas of expertise within the field of research. Scientific diversity *i.e.* the collaboration of researchers providing various complementary skills, induces novel approaches to the solution of existing problems, because these problems are regarded from new and different perspectives. This collaboration may facilitate the communication and eventually the codification of tacit knowledge.
- Communication and social integration among the scientific community.
- Qualified leadership capacity providing focused research and supporting, guiding and integrating scientific diversity. Leadership has to provide the means to overcome the problems of communication caused by the diverse backgrounds of the collaborating researchers.

On the other hand organisations conducting excellent science but lacking major innovations are characterised by a high differentation into departments recruiting highly specialised researchers but with narrow research interests. Another characteristic is hierarchical authority and bureaucratic coordination including centralized decision-making about research programs and standardised procedures. Also hyperdiversity *i.e.* diversity to a degree that researchers of the various fields of science cannot communicate effectively anymore hampers scientific breakthroughs.

The state and the according government obviously play a critical role concerning the conditions under which research is undertaken. The government can influence the innovation process through scientific research policies and laws with respect to property rights [Hollingsworth and Boyer 1997]. Radical product or process innovations within particular market segments can be the result of industrial policies.

The political background also influences the institutional environment in which research organisations are embedded. Accordingly the proportion of research undertaken at universities, technology centers and other non-firm organisations varies from society to society. Societies characterised by low autonomy of research organisations and a pressure to conform to institutional norms, habits and rules offer little space for variation. A more flexible institutional environment provides higher autonomy and flexibility to respond to the development of new knowledge and hence to be innovative [Hage and Hollingsworth, 2000]. The style of innovation is rather incremental in societies with highly standardised quality controls and legal sanctions as monitoring instruments and where companies have long-term stable relationships with collaborators.

Basic research tends to be a more and more global activity, however radical research breakthroughs usually only take place when researchers are having frequent face to face interaction [Petrella, 1995].

Chapter 2 — Risk and Uncertainty

Literature provides many definitions of risk and uncertainty and of course there are distinctions depending on the context in which the terms are used. The fields and according definitions relevant for this thesis are economic theories for decision taking under uncertainty, project management and finance. This chapter provides definitions and scopes for risk, uncertainty and other terms often mentioned in the context of risk and uncertainty. Various kinds of risk and uncertainty concerning research projects are presented.

2.1. Introduction

The consideration of risk and uncertainty for economic theory dates back at least to Knight's "Risk, Uncertainty and Profit" in 1921 [Knight, 1921]. Knight was the first to distinguish between measurable risk and uncertainty, which cannot be measured, by providing the definition: "Risk is measurable by means of probability theory and therefore calculable and insurable. Uncertainty, on the other hand, is neither measurable nor calculable, and therefore is not insurable" [Knight, 1921]. A similar argument is made by Keynes [Keynes, 1937], saying that uncertain matters are characterised by a lack of a scientific basis on which any calculable probability can be formed. Thus one simply does not know. Contrary to the then established economic view of assuming certainty of foresight Keynes regarded uncertainty—unlike mathematical risk—as a pervasive fact of life.

One criticism of Knight´s distinction between risk and uncertainty is that the assigning of probabilities does not fail because probabilities do not exist but because they simply are not known by the decision maker. Consequently there is no difference between Knight´s risk and uncertainty. Other economists support the view that there are no probabilities to be known at all but only subjectively-assigned beliefs. Supporters of Knight´s definition of risk and uncertainty, such as Shackle [Shackle, 1986] argue that mathematical probabilities can only be assigned in rare cases when experiments can be repeated and alternatives are clear. Knightian uncertainty thus refers to the common situation when decision makers have to take unique real world decisions.

Kaplan and Garrick [Kaplan and Garrick, 1981] define risk as involving both uncertainty and some kind of loss or damage. Furthermore they note that risk includes the likelihood of conversion of that source into actual loss, injury, or some form of damage. Risk therefore depends on the probability or frequency of an adverse outcome and the severity of that outcome. Rowe [Rowe, 1977] defines risk generally as the potential for realisation of unwanted, negative consequences of an event. Sage and White [Sage and White, 1980] define risk in a more quantitative approach as the probability per unit time of the occurrence of a unit cost burden. Furthermore they state that risk represents the statistical likelihood of a randomly exposed individual being adversely affected by some hazardous event.

Literature provides many, and also contradictory, distinctions between risk and uncertainty and the debate on risk versus uncertainty goes on and has not yet been resolved. The most common distinction between risk and uncertainty, however, is based on whether one can find a way to measure the degree of uncertainty about future states or not.

2.2. Economic Choice Facing Risk and Uncertainty

In 1926 Ramsey [Ramsey, 1931] provided one of the first approaches towards a consistent theory of choice under uncertainty using subjective probabilities but distinguishing between preferences and beliefs. Risk and uncertainty were formally integrated into economic analysis by von Neumann and Morgenstern publishing "Theory of Games and Economic Behaviour" in 1944 [Von Neumann and Morgenstern, 1944].

In the von Neumann and Morgenstern approach a rational basis for decision making facing risk is derived based on expected utility rules.

Theories of choice under uncertainty can be classified into those which assign mathematical probabilities to the outcomes of random situations and those which do not. From this point of view the expected utility theory using objective probabilities of von Neumann and Morgenstern [Von Neumann and Morgenstern, 1944] belongs to the risk category. The theory of objective probabilities is based on the assumption that randomness and probabilities are exogenously given.

In contrast to objective probabilities another approach is to regard probabilities as a lack of knowledge about the outcome of a situation. Accordingly probabilities measure this lack of knowledge and just represent the beliefs of the decision makers. Thus they are called subjective probabilities. Following Knight [Knight, 1921] if knowledge is complete, there is no probability, but certainty. Savage [Savage, 1954] reformulated the expected utility theory using subjective probabilities. This approach can be regarded as lying in between of the category risk and the category uncertainty.

The state-preference approach proposed by Arrow and Debreu [Arrow, 1953], [Debreu, 1959] on the other hand does neither attach subjective nor objective probabilities and thus can be regarded as belonging to the uncertainty category. Uncertainty in the Arrow-Debreu approach is represented by a set of mutually exclusive and exhaustive states of nature, one of which will be realised. This cannot be influenced by the decision maker. The state-preference approach explicitly accounts for a different treatment of commodities by agents depending on the current state. A decision maker´s preferences for hot tea will vary according to whether it is a hot summer or a freezing winter day. Choices under uncertainty are reduced to a conventional choice problem by changing the commodity structure appropriately.

The individual value of an uncertain event's utility is usually determined by the application of a risk-utility function, defining the certainty equivalent of the value of an uncertain event [Friedman and Savage, 1948]. According to the shape of the risk-utility function we distinguish between risk-prone, risk-neutral and risk-averse behaviour. Being risk-neutral, the mathematical expected value of an uncertain event is equal to the certainty equivalent. For risk-averse behaviour, the certainty equivalent is lower and for risk-prone behaviour higher than the mathematical expected value. Measures of a decision makers risk aversion were introduced by Pratt and Arrow [Pratt, 1964] and [Arrow, 1965].

2.3. Uncertainty and Information

Decision making under uncertainty implies having to make decisions based on incomplete information. Therefore, under conditions of uncertainty, information becomes a commodity and thus gets an economic value. The ones knowing more can benefit from their head start with respect to information [Arrow, 1971]. Arrow also popularised the terms "asymmetric information" and its aspect of "moral hazard", which refers to a change in an individual's risk behaviour due to *e.g.* an insurance contract, where coverage against loss might increase the risk-taking behaviour of the insured, refer to [Arrow, 1971]. Selling insurance contracts to previously uninsured individuals can have the effect that these individuals, due to the introduction of insurance, take fewer precautions than before, resulting in a raise of losses above historical levels. In an extreme form, moral hazard arises when the insurer can only observe the occurrence of an accident but has got neither information on the states of nature nor on individuals´ actions. The insured however have got no incentive to reveal the state of nature or their levels of precaution. The provision of insurance affects the probabilities of the insured-against events happening, see *e.g.* [Arnott and Stiglitz, 1988]. Thus basing the premiums of the insurance contracts on historical data of these individuals will be unprofitable for the insurer.

The moral hazard problem can be formulated as a principal agent relationship with the agent fulfilling a certain task for the principal. Apart from the state of nature that cannot be affected, the agent´s effort has got a significant impact on the outcome, but is the agent´s private information and cannot be monitored by the principal.

There is a wide range of applications for models of moral hazard for any kind of contractual relationships, such as agricultural sharecropping contracts in development economics, capital structure and executive compensation in corporate finance or employee compensation in labour economics [Prescott, 1999]. Moral hazard problems can also occur with respect to external financing of highly risky business activities such as innovation [Arrow, 1962]

Based on the fact that acquiring information about the uncertain future in the present is costly, Simon [Simon, 1957] developed the theory of "bounded rationality". Decision makers do not take completely rational decisions, because acquiring information about these might be too expensive or they simply lack information processing capacity. Thus their decisions are based on satisfying certain aspiration levels instead of maximising their utilities. Simon thus assumes the existence of an optimal solution although the decision makers may not be able to find that solution due to the capacity constraints mentioned before. Fundamental uncertainty on the other hand refers to the occurrence of unimagined and unimaginable new situations—either through the intended or through the unintended consequences of people´s actions—for which no optimal solution exists *ex ante*. In contrast to complexity, which might prevent the decision maker from knowing a set of predetermined states with an according set of predetermined alternatives, fundamental uncertainty is not the result of a deficiency of the decision maker. Bounded rationality is thus related to the decision makers´ behavioural characteristics, while fundamental uncertainty refers to the essential unknowability of the future [Dunn, 2000].

2.4. Related Concepts

Variability

The term variability refers to real and identifiable differences between for example individuals within a population. Variability does not disappear with better measurement. Quite the opposite is true: More aggregate consideration smoothes out variety, higher granularity amplifies differences. Variability in the context of an R&D project could refer to the heterogeneous level of knowledge of the various team members. Variability relates values of variables varying dependent on measurement, whereas uncertainty refers to imperfect knowledge. Uncertainty is mostly relevant for forecasts, because the present can in principle be measured (although the effort might be extremely high) and thus the uncertainty can be resolved.

Hazard

Hazard is defined by Stern and Fineberg [Stern and Fineberg, 1996] as an act or phenomenon that has the potential to produce harm or other undesirable consequences to humans or what they value. Kaplan and Garrick [Kaplan and Garrick, 1981] give the following example to distinguish hazard and risk: considering the ocean as a hazard, they note that the degree of risk undertaken in crossing the ocean will depend on the level of safeguards adopted (or on the means of transportation used). This implies that taking according measures can reduce the risk.

Extreme Events

According to Bier *et alii* [Bier et al., 1999] extreme events are extreme with regard to their low frequency and high severity. The authors point out that an event may be rare but not extreme and give the example of a room temperature of exactly 17.34571° C that may occur extremely rarely, but would hardly seem to be extreme by most people's definitions.

Considering R&D projects, the outcomes of the projects may have extreme consequences. It might for example be determined, during a research project, that some kind of food, that has been produced and marketed successfully for a long time, does in fact seriously damage health. Although this insight is highly severe, the consequences are probably much more extreme for the company producing that kind of food than for the research team. Thus researchers are normally not made responsible for the outcome of their research. Considering the knowledge gained, this project can be regarded as very successful, even though the consequences are extreme.

2.5. Project Risk and Uncertainty

Especially in the context of highly innovative R&D projects it is important to stress that the innovative character of the projects is a challenge that causes uncertainty, but a challenge is not necessarily a threat. It can also be an opportunity and in most cases it contains elements of both. So R&D projects are characteristically high-risk investments with a deferred payoff.

Arrow defines research as a venture into the unknown. "The outcome of any research project is necessarily uncertain, and the most important results are likely to come from projects, whose degree of uncertainty to begin with was greatest" [Arrow, 1971, p.138]. The economic incentive of invention and research is the creation of information. The process of invention and research is inherently risky as the output—referring to the information gained—can never be perfectly predicted from the inputs [Arrow, 1971].

Kline and Rosenberg regard uncertainty as the "central dimension that organises innovation" [Kline and Rosenberg, 1986, p.294]. The process of innovation implies creating something new, which is comprised of elements the researchers do not understand at the beginning and thus are uncertain about. Consequently the outcomes of innovations including technical performance, market response or the ability of organisations to utilise the proposed changes effectively, are highly uncertain. However major financial commitments are often required at the earliest phases of the project, precisely when uncertainties are greatest.

Focusing on project risks, literature on project management provides a lot of classifications concerning various kinds of risk and uncertainty[1]. One common classification is to distinguish between endogenous and exogenous uncertainties. Technological uncertainty, for example, is endogenous, and can be resolved over time during the research process, whereas market uncertainty is exogenous, and more information about what might happen can in most cases only be gained through waiting.

Technological Uncertainty

Technological uncertainty typically arises from new techniques brought to an emerging industry. Technological uncertainty is an endogenous uncertainty, as the company doing research can to a great extent resolve the uncertainty. Sources for technological uncertainty are:

- *Uncertainty About a New Technology*

Uncertainty about a newly discovered technology results from a lack of knowledge, evidence and understanding thereof. The potential of the newly discovered technology is uncertain and that which will provide the superior within future development must be determined. This kind of technological uncertainty applies to emerging fields. As soon as knowledge is accumulated and firms go down the learning curve the uncertainty about the new technology is reduced [Lint and Pennings, 2001].

- *Research and Development Uncertainty*

Research and development uncertainty applies to the results of research efforts such as their significance and applicability. This kind of uncertainty can be found in any research and development based industry and is not reduced with the evolving of the industry [Martino, 1995].

- *Technological Obsolence*

The newly developed technology or technology still under development can become obsolete because other technologies have been found that provide a better way to solve the task. It can of course also happen that the task or problem, the technology was designed to solve, does not exist any more. The risk of a technology becoming obsolete is more inherent if the research and development takes a long time and if competition is high.

[1] Unfortunately no clear distinction is made between risk and uncertainty and the terms are often used interchangeably.

- *Unexpected Side Effects*

Side effects that were not foreseeable during the research and development phase of the technology can prevent the technology from finally being applied to products or processes. Reasons can be that these side effects are dangerous or do not meet regulations.

According to Mansfield *et alii* [Mansfield et al., 1971] the probability of technological success varies according to the industry, because of the different characteristics of the technologies used. The pharmaceutical industry with a very high empirical degree is given as an example as opposed to electro-technical research with a very low empirical degree or cumulative technology. The higher the empirical degree of the research the lower the percentage of reusable knowledge regarding the R&D's outcome, and the higher the technological uncertainty.

Market Uncertainty

As mentioned above market uncertainty is often referred to as an external uncertainty, as the company engaging in R&D cannot really influence the drivers or sources for this kind of uncertainty. In most cases the only possibility is to wait what is going to happen and to react to changes. The potential value of the technological knowledge depends on the variations of the following factors, which are the main sources for market uncertainty:

- *Size of Potential Market*

One of the most important factors determining market uncertainty is the volatility of the size of the potential market.

- *Customers' Needs and Uses*

The type and extent of customer needs that can be satisfied by a particular new technology are ambiguous. Doubt about what needs the new technology will meet and how well it will meet those needs can provoke customers to delay adopting a new innovation. Furthermore customers' needs may change rapidly and in an unpredictable way.

- *Spreading of the Innovation*

Considering the market for high-tech innovations, it has been observed that the innovations spread much slower than most would predict [Moore, 1991]. In most cases visionaries in the market first adopt radically new innovations and it is difficult to predict to what degree and if at all the mainstream market will follow.

- *Competitors*

The earnings and cash flows on a project can be affected by the actions of competitors. Although this factor should be taken into account during the project analysis the actual actions taken by competitors may differ from the expectations. Thus competitive volatility refers to changes in the competitive landscape. Issues to be taken into account are: who will be the future competitors, what will their tactics be, which tools do they use to compete, and which products will the new technology have to compete with. According to Cooper and Schendel [Cooper and Schendel, 1976] in most cases, new technologies are developed and launched by new companies that do not belong to the threatened industry. These new players change the face of the market completely.

- *Interest Rates, Inflation Rates and Economic Growth*

Changes in interest rates, inflation rates and economic growth essentially affect all companies and all projects, but should nevertheless be taken into account.

Operational Uncertainty

Operational uncertainty refers to all of the uncertainties concerning the scheduling and management of a project. Operational uncertainty belongs to the endogenous uncertainties as the company can influence it. Huchzermeier and Loch [Huchzermeier and Loch, 2001] define uncertainty as the stochastic variability of parameters' distributions and identify the following potential drivers of operational uncertainty:

- *Budget Variability*

In most cases it is not possible to exactly plan the development costs of the project and for most projects budget overruns are common.

- *Schedule Variability*

Will the delivery timetable be met or will the project finish ahead of or behind schedule? This issue of course is closely related to human resource management and thus also affects the budget.

Apart from the kinds of uncertainty explained above there are also uncertainties that are inherent to the evaluation process and the model that is used to evaluate the projects. According to Parry [Parry, 1998] the following kinds of uncertainty can be distinguished:

- *Data and Parameter Uncertainty*

The data used for quantitative analysis can be gained from historical sources if such sources are available. If the access to historical data is possible, there is always the problem that the system will not exactly behave the same way in the future as it has done in the past because of, for example, a change in the underlying factors.

Normally the parameter values for the models, which are used to quantify uncertainty, are not perfectly known. Parameters can also be subject to natural variability. To overcome this problem probability distributions can be assigned to the parameters.

- *Model Uncertainty*

Every model that is used to quantify uncertainty is always a simplification of reality and therefore uncertainty is always incorporated in the selection and use of the model.

- *Completeness Uncertainty*

Completeness uncertainty arises from the fact that not all contributors to risk can be addressed in the model.

Uncertainty can also be classified according to its changing impacts over time[2]:

- *Permanent Uncertainty*

Permanent uncertainty describes the possibility of recognition of a number of various alternatives. No indication is present that the uncertainty may change over time, or that it can be affected in any way (diminished or resolved).

- *Quasi-Permanent Uncertainty*

Quasi-permanent uncertainty refers to situations where the uncertainty can be reduced in a negligible period of time relative to the decision alternatives.

- *Temporary Uncertainty*

Temporary uncertainty can be resolved over time. As time passes, uncertainty is resolved through certain developments of external inputs that can then be successfully removed from further discussion.

- *Unspecified Uncertainty*

This kind of uncertainty cannot be met with any programmed planning measures at all.

Risk and Uncertainty Factors in Product Innovation Projects

Halmann, Keizer and Song define risk in [Halmann, Keizer and Song, 2001] as the extent to which there is uncertainty about realising potentially significant and/or disappointing outcomes within a product innovation project.

Within a study the authors identified the following risk and uncertainty factors concerning product innovation projects through interviews, in-depth case studies and using survey data.

Risk and Uncertainty	**Description**
Product design risk	Risk concerning the realisation of a reliable and technically sound product that fulfils the expected functions.
Manufacturing technology risk	Risk that the product will achieve the required quality and that the desired quantities can be produced.
Commercial viability risk	Risk concerning the reliability of the estimates about the commercial success of the product.
Consumer acceptance risk	Risk that the final product will satisfy the consumers' needs and meet the expectations concerning, for example, the use and price of the product.

[2] The distinction of the varying impacts of uncertainty over time was originally made by Gerking [Gerking, 1987], who referred to what is here called permanent uncertainty as static uncertainty, and to temporary uncertainty as dynamic uncertainty. However, describing these uncertainties as permanent and temporary seems more appropriate, because these terms better describe the remaining and passing aspects of uncertainty. In contrast, the terms static and dynamic describe the time-dependent and time-independent aspects of a model.

Organisational risk	Risk concerning the active support and sponsoring of the project team by the parent organisation, including management support, feasibility of objectives and availability of resources.
Project team risk	Risk with regard to a product innovation team's effectiveness concerning the internal organisation, management style and operational practice in order to achieve the intended project results.
Public acceptance uncertainty	Uncertainty if the new product will satisfy the demands, regulations, legal and political restrictions of external bodies such as government agencies, concerning, for example, environmental and safety standards.
Supply and distribution risk	Risk concerning the reliability of supply partners for incoming parts or materials and for outgoing products.
Competitive positioning risk	Risk regarding actions of the competition damaging the intended success of the new product.
Technological uncertainty	Uncertainty if the product innovation team will master the required technology, if the necessary technology is available and feasible and if the technology to be developed is capable of fulfilling the desired functions.
Project positioning risk	Risk concerning the positioning of a new project in the company's business strategy and project portfolio.
Co-development risk	Risk that efforts, performance of external development partners and the exchange of know-how will not be adequate to achieve the expected project goals.
Market uncertainty	Uncertainty about the type and size of a new product's market considering the type and extent of customers' needs, price sensitivity and stability in the marketplace.

Table 2.1: "Risk and Uncertainty Factors in Production Innovation Projects"—Source: [Halmann, Keizer and Song, 2001]

While organisational risk, project team risk and technological uncertainty are mostly relevant for the research phase, product design risk, commercial viability risk and supply and distribution risk gain significance when it comes to development and production. The company launching the innovative product faces competitive positioning risk, consumer acceptance risk und market uncertainty at market launch. The authors do not make a clear distinction between risk and uncertainty. Furthermore timeliness of research and development and the resulting consequences from being behind or ahead of schedule are not considered.

2.6. Risk in Finance

Following a statement by Merton[3] "much of the structure of the financial system we see, serves the function of the distribution of risk".

Financial risks can broadly be divided into market risk, credit risk, liquidity risk, operational risk, and legal or regulatory risk, but describing these kinds of risk in detail is beyond the scope of R&D applications. Generally spoken, risk in the world of finance is defined as the variance in actual returns around an expected return.

The foundations of modern risk analysis are contained in Markowitz's paper [Markowitz, 1952] concerning the principles of portfolio selection. Making use of the expected utility theory of von Neumann and Morgenstern [Von Neumann and Morgenstern, 1944] Markowitz introduced the theory of optimal portfolio selection based on the trade-offs between risk and return, focusing on the idea of portfolio diversification as a method of reducing risk Markowitz showed that a rational investor, *i.e.*, an investor who behaves in a way that is consistent with expected utility maximisation, should analyse portfolios based on the mean and on the variance of their rates of return; for an introduction to financial portfolio theory refer to chapter five.

Apart from mean-risk approaches stochastic dominance is another way to model the choice among uncertain outcomes, refer *e.g.* to [Hardy, Littlewood and Polya, 1934], [Hanoch and Levy, 1969], [Rothschild and Stiglitz, 1970], [Whitmore and Findlay, 1978], [Levy, 1992]. The stochastic dominance criteria allow modelling the choice between various strategies with only partial information on the decision maker´s preferences. Using the stochastic dominance approach random variables are compared by pointwise comparison of performance functions which are constructed from the according distribution functions. Considering two random variables *a* and *b*, each of which being associated with a cumulative distribution function, *F*, *G* respectively. Using the von Neumann-Morgenstern utility function, expected utility from each of the random variables can be written as

$$U(F) = \int_a^b u(x)\, dF(x) \tag{2.1}$$

and

$$U(G) = \int_a^b u(x)\, dG(x) \tag{2.2}$$

With *U(.)* being the von Neumann-Morgenstern utility function and *u(.)* the associated elementary utility function. If $U(F) \geq U(G)$, *F* is preferred to *G* by the agent under consideration. If *F* is preferred to *G* by every reasonable agent, then *F* is said to dominate *G*.

Thus *F* dominates *G* if for every

$$u \in U^0, F \geq_1 G \tag{2.3}$$

With U^0 being the set of all elementary utility functions $u{:}X \rightarrow R$ that are monotonically increasing, and $\geq_1$ being a transitive and incomplete binary relation on the set of cumulative distribution functions on X.

The order of stochastic dominance can also be expressed on the quantile functions.

[3] Robert C. Merton in his foreword to "Risk Management" by Crouhy, Galai and Mark [Crouhy, Galai and Mark, 2000].

The concept of first order stochastic dominance corresponds to the trivial partial information assertion that agents prefer more utility to less utility. *F* dominates *G* according to first order stochastic dominance if

$$F \geq_1 G \Rightarrow F(x) \leq G(x) \quad for\,all\, x \in [a,b] \tag{2.4}$$

If *F* is preferred to *G* according to the criteria of first order stochastic dominance, then expected utility of *F* is greater than expected utility of *G* for every decision maker with a non-decreasing utility function. First order stochastic dominance allows to (partially) order distributions with respect to their returns. The concept of first order stochastic dominance however does not work when the distributions under consideration cross. In this case assuming risk-averse utility functions second order stochastic dominance can be applied to determine dominance. According to the criteria of second order stochastic dominance distributions are ranked with respect to relative riskiness measured as the spread of the cumulative density function`s probability mass.

F dominates *G* according to second order stochastic dominance $\geq_2$ if

$$F \geq_2 G, if\; T(x) = \int_a^x [G(t) - F(t)]dt \geq 0 \quad for\,all\, x \in [a,b] \tag{2.5}$$

which implies that the area *T* between the two functions *F* and *G* is non-negative for all intervals [*a, x*].

First order stochastic dominance implies second order stochastic dominance, but not vice-versa. The advantage of the paradigm of stochastic dominance is that it helps to determine the choice for a majority of decision makers between two strategies without knowing each of the individual preferences. If strategy *F* dominates *G* by first order stochastic dominance all rational agents will prefer *F* over *G*. If strategy *F* dominates *G* by second order stochastic dominance all agents with risk-averse preferences will prefer *F* over *G*.

Rothschild and Stiglitz [Rothschild and Stiglitz, 1970] provide four different approaches to the question: "When is one variable riskier than another?" –assuming that both variables have got the same mean.

Adding some uncorrelated disturbance term to one of the random variables makes this variable riskier than the original.

If every risk averse person, *i.e.* having a concave utility function, prefers one variable to the other, then the preferred variable reasonably should be less risky than the other one.

Assuming that both variables have got density functions and one variable has got more weights in the tails than the other, the variable with the heavier tails is riskier.

A distribution is said to exhibit higher variability than a second distribution if both have the same mean and the former has a higher variance. Focusing on variability distinguishes changes in distribution means from changes in risk.

Rothschild and Stiglitz [Rothschild and Stiglitz, 1970] claim that a definition of higher risk should be transitive.

While mean-risk approaches quantify the problem of choice under risk using only two criteria namely the mean representing the expected return and the risk in terms of a scalar measure of the variability of outcomes, the stochastic dominance approach is a multiple criteria model with a continuum of criteria, leading to results which are consistent with the axiom of risk-averse preferences. Mean-risk approaches on the other hand are not capable of capturing the entire range of risk-averse preferences. The mean-variance model by Markowitz [Markowitz, 1952] and related Markowitz-type mean-risk models are not consistent with the order of stochastic dominance [Mueller and Stoyan, 2002]. The resulting set of a Markowitz-type mean-risk model may include portfolios which are inferior according to second order stochastic dominance and characterised by low risk accompanied with low return [Porter and Gaumnitz, 1972], [Porter, 1974]. The stochastic dominance approach does not lead to such unwarranted results, but is much more complicated leading to large efficient sets [Yitzhaki, 1982]. While the stochastic dominance approach compares random variables by pointwise comparison of performance functions constructed from the according distribution functions, mean-risk models compare two scalar characteristics, namely mean and *e.g.* variance. Mean-risk approaches thus depict a very descriptive trade-off analysis. The concept of stochastic dominance has got the advantage that little information on the preferences is necessary and no assumptions concerning specific distributions of the results, *e.g.* normally distributed outcomes, have to be made. Thus stochastic dominance is a set of distribution-free decision rules. The drawback of stochastic dominance is that it does not provide information on the optimal diversification of assets within a portfolio [Levy, 1992].

Value-at-Risk

According to Jorion [Jorion, 2001] financial theory defines risk as the dispersion of unexpected outcomes due to movements in financial variables. Thus both positive and negative deviations should be viewed as sources of risk.

Value-at-Risk (VaR) has emerged as one of the most popular risk management tools within the last years, see *e.g.* [Jorion, 1997], [Linsmeier and Pearson, 2000]. VaR is a risk measure based on statistics of the loss distribution over a predetermined time horizon. As the main focus of risk management is to avoid losses it seems appealing to define a risk measure based on the distribution of losses. The advantage of a loss distribution is that it reflects diversification effects and loss distributions of various portfolios are comparable. The drawbacks of the method are that the estimates of the loss distributions rely on past data and that correct estimates are difficult to obtain [McNeil, Frey and Embrechts, 2005].

VaR is defined as a measure of the worst expected loss over a given time horizon at a given confidence level. VaR describes the quantile of the expected distribution of gains or losses over the defined target horizon. For a selected confidence level λ, VaR corresponds to the 1-λ lower-tail level. [Jorion, 2001].

According to Artzner *et alii* [Artzner et al., 1999] a risk measure ρ should fulfill the following properties:

- Monotonicity: For any two random variables $X \geq Y : \rho(X) \geq \rho(Y)$

  If a project π_x or portfolio with loss x has systematically higher loss than another project or portfolio π_y with loss y, then π_y should be less risky than project π_x.

- Positive homogeneity: For $a \geq 0$:

  $\rho(aX) = a\rho(X)$

  Increasing the size of a portfolio by *a* should scale its risk by the same factor[4].

- Translation invariance: For any $a \in \Re$:

  $\rho(X + a) = \rho(X) + a$

  an increase in loss by *a* should consequently increase the risk by the same amount *a*.

[4] However, this rules out liquidity effects [Jorion, 2001].

- Subadditivity: For any two random variables $\rho(X+Y) \le \rho(X) + \rho(Y)$

  Subadditivity implies that merging portfolios cannot increase risk.

However, Artzner *et alii* show that for some examples of short option positions quantile-based VaR does not satisfy subadditivity [Artzner et al., 1999]. For returns following a normal distribution VaR based on standard deviation σ satisfies the subadditivity property $\sigma(X+Y) \le \sigma(X) + \sigma(Y)$. As shown by Markowitz [Markowitz, 1959], the volatility of a portfolio is less than the sum of volatilities of its constituent projects.

While for the valuation of derivatives the underlying distribution is regarded as risk-neutral, risk management uses the actual distribution. For the former the focus is on the center of the distribution, risk management however, concentrates on the tails of the distribution [Jorion, 2001]. The framework presented in chapter six incorporates both due to the application of the real options approach as well as by determining a project's risk based on the VaR and optimising a portfolio with the help of the project candidates' expected utilities.

Chapter 3 — Project Evaluation under Risk

The following chapter is a brief comparison of common project evaluation techniques. Among other important features of project evaluation methods such as taking multiple objectives and interrelations between projects into account, special attention is paid to the methods' ability to handle the risk of a project. This chapter starts with a presentation of models for the estimation of a project's risk, which can serve as a basis for the project evaluation techniques described later. Finally an introduction to sensitivity analysis is given, which should be conducted for every model.

3.1. *Causal Analysis*

All standard methods for risk analysis require some sort of causal analysis in order to identify the sources for risks and to estimate the probability for the undesired events. Three main techniques to estimate event frequencies are based on:

- Using relevant historical data
- Deriving event frequencies using analytical or simulation techniques
- Using expert judgements

These methods can of course be combined. However, all of them are afflicted with uncertainties because of subjective judgement of the dynamics of the variables affecting the risk-prone activities which use past data as an uncertain prediction for future events. Therefore the result of such an analysis is an expected range of frequencies, which result in an estimate of uncertainty and not a scalar number. However mean and according variance of these frequencies can be determined.

3.1.1. Simulation Models

Risk analysis models are typically based on a simulation analysis of input data in distribution form and provide output distributions of factors such as rate of return or market share [Moore and Baker, 1969a].

Simulation models try to represent real-world systems by generating what-if scenarios. The simulation produces—originally independent—random variables which are distributed according to a distribution that does not necessarily have to be known explicitly. The simulation model is run many times with modified input parameters, yielding probability distributions of the output variables. By carrying out simulation for a large number of projects the range of possible outcomes and the likelihood of specific outcomes can be estimated. Simulation provides an estimate of the most likely outcome as well as information about the spread of possible outcomes [Martino, 1995]. With the help of simulation models the effects of different environmental conditions on R&D project selection can be studied [Fox and Baker, 1985].

The Monte Carlo method for simulation was first introduced by Ulam in 1947 [Eckhardt, 1987], see [Metropolis and Ulam, 1949]. Statistical sampling techniques were well known by then but difficult to implement due to the length of calculation. With the advent of computers however their importance and application in various fields increased drastically. Monte Carlo simulation is a traditional simulation approach which uses probability distributions of all stochastic variables of an R&D project in order to calculate the overall probability distribution of objective values and resources needed [Souder and Mandakovic, 1986]. This process is repeated a number of times. On each iteration, for each variable, a value from the relevant probability distribution is selected randomly. For specific distribution function of the input parameters Monte Carlo simulation generates values according to their distributions even if these parameters are non-uniformly distributed. After many iterations the distribution of the randomly selected values reflects the probability distribution of the input variables. The probability distribution of the model´s output gives information on the likelihood of the modelled values of the output to occur. The results of the Monte Carlo simulation thus provide risk profiles for the selected forecasts and can include detailed reports containing statistical information such as variance, percentiles, skewness etc.

Gaver and Srinivasan [Gaver and Srinivasan, 1972] point out that simulation models can give a much closer view on reality if the R&D process is not just divided into the two phases research and development, but into many sequential stages. For each stage decision rules can be defined how to respond to competitive actions, *e.g.* by pre-emption or abandonment of the idea. The simulation does not have to focus on financial returns only but can cover other objectives like market share or position with respect to competitors. Incorporating these aspects shows that simulation is a flexible approach even though it is evaluative and not necessarily optimising.

Applications

Simulation techniques and especially Monte Carlo simulation is widely used for financial risk analysis, see, for example, [Markowitz, 1959].

Fox and Baker [Fox and Baker, 1985] present a simulation model for R&D attempting to answer the question whether different market conditions have got an influence on project selection with respect to number and type of projects. Thereby the authors differentiate between projects that should increase market share, projects that should decrease production cost or projects that are supposed to increase capacity. One of these types is assigned to each project at random. The second question to be answered by the simulation model is whether patterns of project selection emerge over time independent of the market conditions, given a certain type of project.

Stummer, [Stummer, 1998], summarises applications of simulation techniques for R&D project selection by Versapalainen and Lauro [Versapalainen and Lauro, 1988] and Milling [Milling, 1986]. Further applications of Monte Carlo simulation for R&D can be found in [Hazelrig and Huband, 1985] and [Bard and Feinberg, 1989].

3.1.2. Group Decision Techniques

In the following, group decision techniques, which can also be used to identify potential risks, will be explained in greater detail because experts' judgements about the various aspects of a project are used in order to estimate the input parameters for the R&D portfolio evaluation framework presented in chapter six.

Using group decision techniques knowledge and judgements of experts in the relevant fields are systematically collected and combined to serve as support for decision-making. The problem with these techniques is that they can be very time-consuming, and the selection of the experts is a critical task. The creation of a heterogenous group of experts is recommended, including scientists as well as domain experts from industry or public administration [Aichholzer, 2002]. Group decision techniques enhance motivation and the team building process as a byproduct. A widely used group decision technique is the Delphi method.

Delphi Method

The Delphi method is formally defined as a systematic method for collecting informed judgements on a particular topic [Loveridge, 1996]. Only uncertain and incomplete knowledge exists about these topics by nature. Thus this method is useful for developments characterised by great uncertainty.

The process of conducting a Delphi survey normally starts with setting up a questionnaire concerning the various aspects of an R&D project, which is then handed out to a group of experts. These experts use the questionnaire in order to evaluate the various projects. The evaluation process can be done by assigning scores to the listed aspects for every project, finding strengths and weaknesses of the projects and pointing out special risks or other important issues. The evaluation is done anonymously. Data are collected, and statistics about the overall results are then given to the experts. With the help of this summary, the results are discussed by the experts. Thus the method allows for feedback, including the possibility that the experts can change their viewpoints during the discussion [Stummer, 1998].

In summary, the four main characteristics of a Delphi survey are anonymity, iteration, feedback and statistical aggregation of the results [Rowe and Wright, 1999]. The result of the Delphi survey after the discussion is maybe a consensus of the group, but in any case a collection of experts' estimates regarding the various projects.

An advantage of the Delphi method and related techniques is that pressure from the group on the opinion of an individual is avoided by anonymity. Furthermore every expert's judgement is valued equally.

Applications

Delphi surveys are a widely used technique to conduct foresight studies about the future relevant fields of innovation, which also include assessments about trends and appropriate measures. Irvine and Martin [Irvine and Martin, 1984] define foresight studies as a systematic attempt to look into the long-term future of science, technology, economy and society with the aim to identify the areas of strategic research and the emergence of generic technologies likely to yield the greatest economic and social benefits. The aim of Delphi surveys in foresight programmes is to aggregate experts' opinions on future events, to reduce uncertainty by using the experts' expertise and thus rationalise the future [Loveridge, 1996]. Very common are technology foresight studies, but there are also society oriented or culture Delphi surveys.

An example for a Delphi survey is the "Technology Delphi Austria", which was conducted by the Austrian Academy of Sciences [2].

The following models mentioned in [Stummer, 1998] use the data gained through a Delphi survey or related method as an input source for other evaluation models: Khorramshahgol and Gousty [Khorramshahgol and Gousty, 1986] and Khorramshahgol, Azani and Gousty [Khorramshahgol, Azani and Gousty 1988] use the data gained within the Delphi survey for a mathematical programming approach—the goal-programming approach. Thomas [Thomas, 1985] and Gear, Lockett and Pearson [Gear, Lockett and Pearson, 1982] also use the Delphi method for the collection of input data for a value benefit analysis and some variant of the Analytical Hierarchy Process AHP respectively.

3.1.3. Scenario Based Risk Assessment

One approach to quantify risk is to define risk scenarios. Each scenario is a sequence of events. One event leads to another until the sequence terminates with a consequence state. After having identified a risk scenario, the likelihood and consequence of that scenario must be derived. Turner and Hunsucker [Turner and Hunsucker, 1999] describe the approach in detail.

Input variables

m = specific risk scenario

$R(m)$ = magnitude of risk for m

$L(m)$ = likelihood of occurrence of m

$C(m)$ = consequence score for scenario m

$I(m)$ = imminence score for scenario m

In the absence of defensible probabilistic information the authors suggest to use a likelihood score of one through five to be assigned to each risk scenario.

Algorithm

The magnitude of risk can then be expressed as the product of likelihood and consequence.

$$\mathrm{R}(m) = \mathrm{L}(m) \times \mathrm{C}(m) \tag{3.1}$$

Further an imminence score, that implies the absence of time for action and therefore has a great impact on the risk magnitude, can be incorporated which yields to:

$$\mathrm{R}(m) = \mathrm{L}(m) \times \mathrm{C}(m) \times \mathrm{I}(m) \tag{3.2}$$

With a qualitative approach like the F/A-18 Risk Likelihood Method [Hayn, 1996] a score for the likelihood of the occurrence of m can be assigned. This approach includes five scores for the likelihood of the occurrence of a scenario depending on the probability with which the project team will be able to prevent the event from occurring. Similarly an imminence score can be assigned with a function reflecting management sensitivity to the imminence of risk scenarios.

In order to determine the consequence of a risk-prone scenario it is necessary to specify exactly which aspects of a project are at risk, which again makes a definition of the project's success criteria necessary. To identify the significance of risk consequence an integrated risk consequence scorecard can be used. Establishing the risk consequence scorecard involves the following steps:

- Identification of a hierarchy of project goals
- Identification of risk measures for all goals and sub-goals
- Develop risk consequence scales
- Calibration and integration of the scorecard

When a risk is identified the risk-scoring template can be used to assign scores in the different categories. These scores are then combined to create an integrated risk consequence score. The total consequence score is determined as follows:

$$C(m) = \Sigma_j C_j(m) \tag{3.3}$$

where

$C_j(m)$ = category j consequence score for risk m

Turner and Hunsucker [Turner and Hunsucker, 1999] suggest using this formula to calculate the total consequence score, but do not give a reason for the addition of the category consequence scores. The authors advice not to use weighting factors for the category consequence scores either, in order to avoid "unnecessary complications". The F/A-18 Risk Likelihood Method used an approach where the consequence score for risk scenario m is the maximum of all category risk consequence scores. This leads to the assumption that the definition of a consequence score is arbitrarily chosen.

Like any other method based on estimations, the result of scenario based risk assessment, even though computed with a couple of formulas, strongly depends on the accury of the estimates. The estimation errors are multiplied but not adjusted, as when using a larger number of estimates and the according average. The advantage of scenario based risk assessment is that it is scenario specific and thus promises to provide useful results if the scenario is known and modelled well. On the other hand scenarios can be very specific and even though the decision maker might believe to be familiar with the situation, unforeseen events may occur. The method is not based on a model with distributions and dependencies, it just multiplies the probability with the degree of damage or loss.

Applications

The scenario based risk assessment approach described in [Turner and Hunsucker, 1999] was developed in the course of an attempt to formalise the risk management process in research and development at the United States Department of Defense and the National Aeronautics and Space Administration (NASA).

3.1.4. Probabilistic Risk Assessment

According to Kaplan and Garrick [Kaplan and Garrick, 1981] the aim of probabilistic risk assessment is to answer the following three questions:

- What can go wrong? – by hazard identification
- What is the likelihood that it will go wrong? – by frequency analysis
- What are the consequences? – by consequence analysis

In order to conduct probabilistic risk assessment (PRA) internal hazards of the project and associated events have to be identified. Then, just like using scenario based risk assessment, probabilities have to be assigned to these risky events. PRA is a bottom-up approach, quantifying the probability of failure of the whole project as a function of partial failures. The strength of the method is the incorporation of interrelations between various aspects of a project, as well as interrelations between projects, into the risk assessment [Henley and Kumamoto, 1992]. This can be done by modelling the risk analysis process with a method called Failure Mode and Effects Analysis (FMEA):

Failure Mode and Effects Analysis

Failure mode and effects analysis (FMEA) is a suitable method to identify potential risk sources, which is especially useful when developing systems. FMEA analyses component-level failures and their effects on higher-level systems [Wirth et al., 1996]. Then the consequences of each event are investigated using an event or fault tree:

- *Event Tree*

An event tree is an inductive method, creating a hierarchy of all possible consequences of an event. The tree is created by starting with the initiating event and identifying all of its relevant consequences. Then each consequence is regarded as an event and the process is repeated. Afterwards a probability has to be assigned to each branch. The probabilities have to be aggregated to calculate the likelihood of each outcome. Then the severity of each outcome is quantified and combined with the probability to determine the overall risk.

- *Fault Tree*

A fault tree is similar to an event tree, but it is a deductive approach. Fault trees also start with an event but instead of following the consequences, the causes are traced.

Kaplan and Garrick [Kaplan and Garrick, 1981] define risk as a set *R* of ordered triplets:

$$R = \left\{ \left(E_i, p(E_i), \vec{c}(E_i) \right)_{i=1,..,n} \right\} \tag{3.4}$$

where E_i is a specific scenario, $p(E_i)$ is an estimation of the conditional probability for E_i to occur and $\vec{c}(E_i)$ consists of a vector of the consequences of E_i occurring. An event tree can be regarded as a visualisation of the ordered triplet representation. The final result of a PRA can be presented in the form of a risk curve, which is the plot of the frequency of exceeding a consequence value as a function of the consequence values.

Probabilistic risk assessment using event and fault trees provides a top down as well as a bottom up view on the problem under consideration, which can be checked for consistency. The risk factors and the according consequences have to be assessed, which requires identifying the sources for risk and consequently helps to avoid them. Thus probabilistic risk assessment is also a useful tool for risk analysis and not only for quantification.

Applications

Probabilistic risk assessment is part of a risk analysis framework for R&D projects at NASA developed by Dillon and Paté-Cornell, [Dillon and Paté-Cornell, 2001].

3.1.5. Risk Quantification in Software Engineering

Boehm [Boehm, 1989] describes a method to measure risk in software engineering by calculating a value for the exposure to risk. The method for risk quantification presented in the following is the basis for a model to support decision making for the management of software projects, called the “spiral model” [Boehm, 1988].

In order to quantify the expected value of the risks identified during the risk identification process, the term risk exposure is used as a measure of risk and can be calculated as follows:

$$\text{Risk Exposure} = \text{Probability(Outcome)} * \text{Loss(Outcome)}$$

Risk reduction leverage refers to a measure of effectiveness of risk reduction actions:

$$\text{Risk Reduction Leverage} = (\text{Risk Exposure}_{\text{before}} - \text{Risk Exposure}_{\text{after}}) / \text{Risk Reduction Cost}$$

The risk exposure is the expected value of the risky event. *Risk Exposure* $_{before}$ refers to the exposure to risk before the risk reduction actions were carried out and *Risk Exposure*$_{after}$ refers to the exposure to risk after having applied the risk reduction actions.

The advantage of using an expected value as a measure of risk is that it can be used with different measurement units and scales and it allows aggregation and disaggregation of results. Risk exposure makes it possible to list the risks in priority order, with the risks of most concern given the highest priority.

Risk identification, assessment and management are important topics in software engineering and the literature on the topic is extensive. Some of the most well-known books on software engineering covering the topic of risk management are: [Pressman, 1997], [Sommerville, 2000], [Gilb, 1998], [Boehm, 1989], [Boehm, 1991], [Charette, 1989], [Hall, 1998] and [Kontio, 2001]

The frameworks for risk management presented in the literature focus on the risks inherent to projects in software engineering. The main problems are completing the project in time and on budget, misunderstanding the requirements, losing key personnel, or allowing insufficient time for testing. Boehm [Boehm, 1991] emphasises that an important issue when developing large systems is that the exposure to risk rises with the complexity of the system—for a definition of the complexity of software projects see [Otto, 1995]. Some of these issues are also important for R&D projects, such as the risk of losing key personnel, but in general the risks in software engineering stem from uncertainties and unexpected events concerning the planning and management of the project. As R&D projects cannot be planned exactly due to their high degree of innovation, these are not the primary risks faced when undertaking an R&D project. Furthermore an R&D project is not likely to be subject to changing requirements by customers. Of course there can be sponsors or investors who try to influence the direction of the research according to general trends or changing governmental regulations. Thus the method for risk quantification described above is presented here, because it is generally applicable and not concentrating on the specific risks inherent to software engineering.

3.2. Project Evaluation Techniques

The risk analysis methods introduced in the previous section can be used to provide the necessary input data for project evaluation techniques taking the risks and uncertainties of the projects into account. The following section gives a brief overview of the most widely used project evaluation methods.

3.2.1. Comparative Models

Comparative models compare one project proposal to another or a set of alternative proposals. Decision support systems based on mathematical models can be used to explicitly compute the overall merit of each of the projects in order to identify the best one [Souder and Mandakovic, 1986]. Using the comparative method to evaluate projects is a straightforward easy to use and comprehend approach. The disadvantages of the method are that it relies on subjective judgements also concerning the risk of a project [Poh, Ang and Bai, 2001]. Applying the method is rather time consuming because of the large number of comparisons [Lockett and Stratford, 1987]. Furthermore changes in the set of projects can affect the overall preferences and ranking of the projects. Thus the whole process must be repeated if a single project is added or removed from the set. Multiple objectives can be considered by attaching weights to the various criteria for evaluation of the projects. Comparative models do not take interrelations between different projects or phases of one project into account.

Two widely used comparative selection methods are the Q-sort approach, described in [Stummer, 1998], and the Analytical Hierarchy Process (AHP) developed by Saaty [Saaty, 1980].

Applications

Souder [Souder, 1978] uses the Q-sort approach for the selection of R&D projects. The AHP is a widely used method for project evaluation and selection. Further R&D applications of the AHP approach can be found in [Lootsma, Mensch and Voss, 1990], [Melachrinoudis and Rice, 1991], [Versapalainen and Lauro, 1988], [Gear, Lockett and Pearson 1982], [Khorramshahgol, Azani and Gousty, 1988], [Liberatore, 1988], [Lockett et al., 1986], [Kuei et al., 1994] and are briefly described in [Stummer, 1998].

3.2.2. Scoring Approaches

In order to use scoring approaches for the evaluation of R&D projects a relatively small number of decision criteria for the project must be defined. Then each project is given scores reflecting how well it meets the defined objectives. Each of these criteria can be weighted to reflect its importance relative to the other criteria [Poh, Ang and Bai, 2001]. Each project's scores are finally combined by multiplication or addition and the projects are ranked according to their overall scores. However the projects can also be compared on the basis of one criterion at a time [Martino, 1995].

Scoring approaches are quite popular because they allow for input data in the form of point or interval statistical estimates as well as estimates provided by experts. The set of projects can be altered without affecting the scores of the projects that have already been evaluated. On the other hand a large amount of information is necessary for these methods and they assume that factors are independent which in reality is rarely the case [Heidenberger and Stummer, 1999].

Scoring models can be extended to use interval estimates to reflect the uncertainty associated with a given measure of project performance [Moore and Baker, 1969b]. In order to take uncertainty into account, aspects such as the likelihood of success can also be an evaluation criterion for the scoring model [Martino, 1995]. This process can be referred to as the traditional scoring approach.

As there is no formal operational structure for scoring models they might appear to be less accurate than more formalised models for project evaluation, especially models which focus on financial and economic factors. The basic feature of scoring models namely that they offer the possibility to include multiple and also non-monetary qualitative aspects into the evaluation, implies that the resulting overall score is dimensionless, which for some users might be less significant than financial numbers. However scoring models avoid the necessity to express non-economic aspects more or less accurately in financial numbers just in order to make them processable by the economic model.

Checklists

A more simplified scoring method is the checklist approach. Checklists evaluate on a yes/no basis whether a project fulfils a certain criterion or not. In order to get an overall result for the project, 1 can be assigned to the project of it meets the criterion and 0 if not. Then these scores are added resulting in one number for an overall evaluation of the project [Souder and Mandakovic, 1986]. A major shortcoming of the checklist approach is that all criteria are assumed to be equally important and uncertainty is not taken into account.

Multi-Attribute Utility Analysis

Multi-attribute utility analysis (MAUA) is only introduced briefly here. An extensive explanation of the approach can be found in chapter six. The method is based on the assumption that the decision maker maximises a utility function, which aggregates the evaluation criteria. The utility function can be additive or multiplicative, and takes the decision maker's attitude towards risk into account. MAUA such as single attribute utility analysis should fulfill the characteristics of a "von Neumann-Morgenstern utility function", *i.e.* in case of alternative outcomes of a decision taken and according probabilities, the total utility is the weighted sum of the alternative utilities weighted by their probabilities to occur [Von Neumann and Morgenstern, 1944].

As with all the other scoring approaches, the method is especially useful whenever the factors are not measurable in monetary units. The problem with the approach is to specify the utility function according to the decision maker's preferences.

Keefer and Kirkwood [Keefer and Kirkwood, 1978] use the MAUA approach for R&D resource allocation. Neely [Neely, 1998] incorporates MAUA in his hybrid decision tree and real options framework, described in 3.2.5. in order to get input data for the project evaluation model. Further applications of MAUA can be found in [Bard and Feinberg, 1989], [Monks, 1976], [Mehrez, Mossery and Sinuany-Stern, 1982] and [Mehrez 1988].

Neither traditional scoring approaches nor checklists or MAUA take interrelations between various projects or phases of one project into account. The evaluation of projects with respect to multiple objectives however is an important characteristic of scoring techniques. An advantage of the method is that the computation of the overall score is straightforward and easily comprehendible.

Applications

Moore and Baker [Moore and Baker, 1969b] describe a way of designing scoring models for early stages of research. Stummer [Stummer, 1998] lists the following scoring approaches for R&D project selection as the most important and well-known examples among others: [Mottley and Newton, 1959], [Pound, 1964], [Bobis, Cooke and Paden, 1971], [Albala, 1975], [Krawiec, 1984], [Spharim and Szakonyi, 1984] and [Ulvila and Chinnis, 1992]

3.2.3. Game and DecisionTheory

The aim of game theory is to model the possible strategies of decision makers facing uncertain future events and maximising their expected utilities. Von Neumann and Morgenstern introduced the formal conception of game theory [Von Neumann and Morgenstern, 1944]. In game theoretic models the decision makers do not base their decisions on exogenous variables but react as best response to the actions of other agents. The game reaches a Nash equilibrium—

identified in 1950 by Nash as a fundamental solution to non-cooperative games—when the best responses of all players are in accordance. The Nash equilibrium corresponds to the best response of every agent to the prospective plays of all the other agents. A Nash equilibrium is a best mutual response criterion, where the predictions of the agents form an equilibrium and no agent would benefit from changing their strategy unilaterally. It thus reflects self-confirming beliefs of the agents and rational agents will play equilibrium strategies if they anticipate the strategies of the other agents correctly, refer *e.g.* to [Montet and Serra, 2003]. Thus a Nash equilibrium specifies what rational players are supposed to do if playing optimally [Rubinstein, 1987]. However the underlying assumption is that the agents involved are hyperrational individuals having correct expectations and being capable of optimizing strategies of arbitrary complexity [Lomborg, 1996]. Following Simon a more realistic assumption is that agents have bounded rationality, meaning that their strategies are chosen from incomplete considerations [Simon, 1957]. As real agents have only got finite resources to take decisions within a finite time horizon, they are content with satisfactory instead of optimal levels of utility. Including these aspects may reduce the number of possibly multiple resulting Nash equilibria. The assumption of hyperrational agents is relaxed by evolutionary game theory, which can help to solve the problem of a multitude of equilibria. As it turned out evolutionary processes tend to converge to Nash equilibria in a wide range of applications [Van Damme, 1994]. The Nash equilibrium could thus be reinterpreted as the outcome of a repeated evolutionary game to which limited rational agents converge after having gone through an evolutionary process,— this interpretation of a Nash equilibrium was first introduced by Nash himself, refer to [Weibull, 1995].

The equilibria of a zero-sum game are the solutions to a linear program, which can be solved algorithmically *e.g.* by the Simplex algorithm [Dantzig, 1963]. As mentioned above, an equilibrium of a two player game is a pair of mutual best responses. Regarding a zero-sum game the maxmin strategy of the first player corresponds to maximising the minimum return, whereas the minmax strategy of the second player refers to minimising the maximum amount to be paid. The connection of these two perspectives corresponds to the duality principle as introduced by von Neumann and Dantzig [Dantzig, 1991]. Consequently there is a linear program for the solution of the maxmin problem as well as for the minmax problem yielding analogous results, leading to the duality of these two linear programs. Conversely, linear programs can be formulated as zero-sum games [Gale, Kuhn and Tucker, 1950]

Game Theoretic Models for R&D

Game theoretic approaches to R&D resource allocation explicitly account for competition and consequently the timing of successful innovation [Reinganum, 1982]. Game theory allows for modelling the information available to the decision maker concerning the status of the competitors. The models also provide insight into the consequences of patenting and licensing [Reinganum, 1984].

Game theory is such a broad area of research that discussing all aspects that can be considered by the models and the according insights provided, is beyond the scope of this thesis. Thus in the following just the game theoretic approaches to R&D by Reinganum [Reinganum, 1982], and Fudenberg *et alii* [Fudenberg et al., 1983] are presented.

Reinganum [Reinganum, 1982] presents a dynamic game theoretic model for R&D resource allocation considering technical advance, the possibility of a protracted development period and the effects of rivalry with respect to patents and imitation. The number of rivals as well as the possibility of patent protection influence rivalry. As pre-emption by a competitor can occur at any time, companies facing uncertainty about the timing of a successful innovation must be able to adjust their expenditures depending on the temporal resolution of market uncertainty. In the model there are n identical competitive, *i.e.* non-cooperative players, having the same technological potential. The innovation process consists of only one development stage. A company winning the race for an innovation receives a payoff for being the innovator whereas a company succeeding in the innovation but not being the first on the market receives the imitator´s payoff. The conditional probability of a company succeeding increases with time. Thus, if a company has not succeeded yet it becomes increasingly likely that it will succeed in the next period. Assuming that each company maximises its own payoff, and takes the strategies of the rivals as given, the game results in a Nash equilibrium.

Reinganum finds that in a deterministic game without technological uncertainty, in case there is an equal payoff for the innovator and the imitator, each company will prefer imitation and the game will not result in a Nash equilibrium. Incorporating technological uncertainty as in Reinganum´s framework makes it possible that none of the rivals will succeed in innovating and thus a company cannot rely on a successful rival in order to imitate. Given perfect patent protection the companies´ rate of generating knowledge is much higher as they can be sure to get the entire payoff. Furthermore each company´s Nash equilibrium rate of R&D investment increases with the number of rivals. However perfect patent protection implies that as soon as the first company is successful in innovating there will be no imitators. Assuming imperfect patent protection competition remains—even after the first successful innovation—for rewards as well as for the perfection of the patent. In this case an increasing number of rivals may have a positive or a negative impact on the Nash equilibrium R&D investment and thus on the speed of innovating depending on the rivals´ payoff structures.

Fudenberg *et alii* [Fudenberg et al., 1983] present a model to analyse the factors influencing rivals in R&D patent races and hence to study the dynamic interaction between the rivals. The model allows for learning and knowledge accumulation during the R&D process. According to their current position in the race relative to the competitors, the rivals can revise their decisions and decide whether to continue or to drop out. The model gives insights on the circumstances under which it is possible for a company to pre-empt—especially in the case of an unfavourable starting position—and to move ahead of, or leapfrog, the current leader.

Fudenberg *et alii* [Fudenberg et al., 1983] assume a deterministic R&D process, meaning that more investment in R&D results in a fixed amount of research progress. There are three levels of research effort among which the competitors can choose. Choosing a higher level of effort makes it possible for a follower to move ahead of a leader in the research process, which consists of multiple stages. The competitors face a one-period delay when observing the research efforts of the other rivals, resulting in an information lag. Such information lags allow for catching up before the others have got a possibility to respond and thus increase the probability of leapfrogging. With the information lag getting shorter it becomes more and more difficult for the follower to leapfrog the leader because the follower has to make an effort sufficient to catch up with the leader while the possibility to be detected and responded to by the leader gets higher. Thus the follower will eventually drop out of the race.

Fudenberg *et alii* [Fudenberg et al., 1983] find that the probability of followers to move ahead of a leader with a small headstart determines the leader´s chances for pre-emption. If the followers´ probability of leapfrogging the leader is high, competition becomes vigorous. The leader will pre-empt when there is a high prospect of retaining competitive advantage throughout the race. Thus in case the initial starting position is approximately equal among the competitors, the race will start with an R&D boost. When the followers fall sufficiently behind they drop out of the race, which eventually leads to a monopoly position for the leader. The monopoly profit is dissipated by the initial competition for the patent.

Further game theoretic models for R&D project selection are *e.g.* presented by [Scherer, 1967], [Loury, 1979], [Dasgupta and Stiglitz, 1980], [Lee and Wilde, 1980], [Reinganum, 1981], [Park, 1987], [Grossman and Shapiro, 1987], [Gruver, 1991], [Ali, Kalwani and Kovenock, 1993].

Reinganum [Reinganum, 1984] provides a discussion on selected game theoretic models for R&D, comparing the investment modelled as a fixed cost by the stochastic invention model of Dasgupta and Stiglitz [Dasgupta and Stiglitz, 1980] and Loury [Loury, 1979], to the investment modelled as a flow cost in a modified version of the model by Lee and Wilde [Lee and Wilde, 1980]. The comparison of the different models shows that whether competition is conducive to technical advance very much depends on whether it is a fixed or flow cost being most important in determining the date of successful innovation. The fixed cost model implies that an increase in the number of competitors increases the time until success for an individual company. Applying the flow cost model it turns out that the time until successful innovation decreases with an increasing number of rivals. In case there is no perfect patent protection the flow cost model suggests that the individual rate of investment decreases with the number of competitors. This is due to the fact that imitation becomes a more and more attractive alternative with an increasing number of companies conducting research. Furthermore incentives for R&D investment given current monopoly power, anticipation of future innovation and simultaneous investment of the competitors are investigated, as well as the consequences from altering the timing of the game.

Grossman and Shapiro [Grossman and Shapiro, 1987] analyse the dynamics of R&D competition of two companies in a patent race. Assuming that there are two sequential research phases, the authors find that competition is most intense when the two competitors have both finished the first phase and are even. The research efforts by both competitors are increased when the one that has previously been behind catches up with the leader. In case the competitors find themselves in different phases of the research, the incentive to invest by the leader is higher than for the follower. Furthermore the incentives for cooperation of the competitors are studied, refer to.

To summarize game theoretic approaches to R&D project evaluation provide a more complex way of modeling than *e.g.* comparative or scoring approaches, which provides the possibility to take aspects like competition, various kinds of uncertainty, timing of market introduction and information asymmetries into account.

Decision Theory

Decision theory is a special case of game theory as it just describes the possible strategies of a decision maker playing against nature. It is assumed that the changes the decision maker is facing do not depend on their actions. Preferences among risky alternatives in uncertain situations are modelled by a numerical utility function that is maximised to find the optimum decisions and according strategies. Kamien and Schwartz present decision theoretic approaches to R&D resource allocation that also account for competition, refer to [Kamien and Schwartz, 1972] and [Kamien and Schwartz, 1976].

Decision Tree Analysis

Decision trees are the most well-known models of decision theory and one of the most popular methods for research and development project selection [Perlitz, Peske and Schrank, 1999]. Decision tree analysis is used when decision makers have to take a sequence of decisions. A classical decision tree consists of three kinds of nodes, stochastic event nodes, decision nodes and end nodes. Each decision has chance outcomes and thus the previous decision always has an influence on the next decision to take. The problem is so structured by evaluating all intervening and final outcomes. The principle of maximum expected utility is applied to determine the best project alternative. The representation and analysis of a series of decisions taken over time is the main strength of the model because that is what R&D project evaluation normally requires to do [Martino, 1995]. Decision trees can be efficiently evaluated using linear programming.

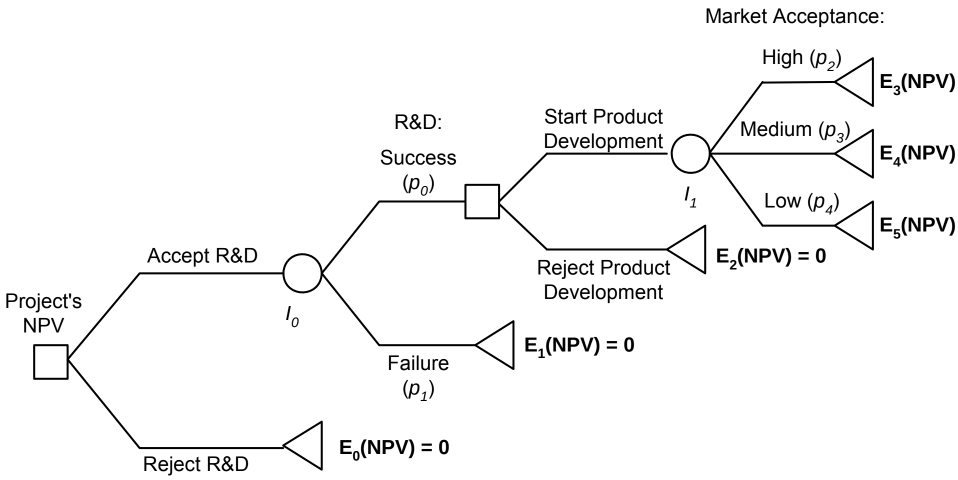


Figure 3.1: "Example of a Decision Tree"

In this example decision tree, squares represent decision nodes, circles are event nodes and triangles are end nodes. An investment *I* is assigned to each decision. *p* represents the probability of the outcomes of the stochastic event nodes. Thus a decision is taken and then the outcome of the decision is revealed. In this example the criteria to be optimised is the expected net present value *E(NPV)*, assigned to each of the end nodes. The discounted net present value (NPV) of the project is calculated by discounting the expected cash flows starting from the end of the tree and working backward to the beginning.

A problem with decision trees, as with all decision-theoretic approaches is, that the decision maker has to assign probabilities to uncertain variables and preferences to uncertain outcomes [Poh, Ang and Bai, 2001]. Another shortcoming of the method is that the construction of the decision tree can become quite complex and thus time consuming as the number of different paths on the tree increases exponentially. In chapter four section 4.5. decision tree analysis is discussed in detail.

Stummer [Stummer, 1998] summarises the following applications of decision trees for R&D project selection and resource allocation: [Gear and Lockett, 1973] and [Granot and Zuckermann, 1991].

Thomas [Thomas, 1985] describes the use of decision trees for the selection of projects in the electronics and pharmaceutical industry.

3.2.4. Economic Models

Economic analysis of R&D projects is based on capital budgeting techniques. Traditional economic models include net present value (NPV), internal rate of return on investment (IRR) and cash flow payback. All of the methods take the cash flows (CF) of the project into account. NPV is a method to compare future returns with current investments. IRR is used to compare alternative investments considering the return on investment that they represent. Cash flow payback measures the time from the start of the project until the net cash flow becomes positive [Martino, 1995].

The use of economic models requires satisfying relatively strict conditions for which the models are valid. Usually, however, it is quite difficult to measure the contributions of R&D projects and to gather accurate input data in monetary terms. R&D decisions have to take multiple objectives into account whereas economic methods consider only economic return [Poh, Ang and Bai, 2001]. Relying on financial measures only can lead to an unbalanced portfolio of innovation products and processes [Liberatore, 1987]. Furthermore traditional economic models assume the underlying discount rate to be constant, which does not hold in reality. Another shortcoming of these models is that they are not able to capture managerial flexibility. Instead it is assumed that a project is either started now or not carried out at all. Implementation always occurs even when the early results of the project are not promising. Also the focus is on a single stream of income and expenses [Neely and De Neufville, 2001]. These assumptions are not valid in reality though and therefore these models are inadequate for innovative and thus risky projects. Managers can initiate projects and then decide whether to carry them to completion or stop them. The scientific results of R&D projects can, for instance, be used for the development of new products or processes at a later point in time. Furthermore, economic conditions can change, and thus change the streams of incomes and expenses of the project. The real options approach tries to overcome this problem by assigning value to operational flexibility, refer *e.g.* to [Dixit and Pindyck, 1994], [Trigeorgis, 1996], [Hommel, Scholich and Vollrath, 2001].

There are also discounted cash-flow methods which take the probability of technical feasibility and applied research costs into account and thus try to be suitable for research and development project selection. These techniques, as well as the real options approach are briefly described in the following:

Probabilistic NPV, IRR and CF Payback

NPV, IRR and cash flow payback do not allow for managerial flexibility, because it is assumed that there is a single cash flow profile from the beginning to the end of the project. In order to model various alternative profiles, which is a more realistic assumption, as economic conditions may change during the project, introducing expected cash flow profiles can extend the traditional models. A probability of occurrence, based on the estimated probability of the outcome of the R&D project or the development of economic conditions, is assigned to each possible cash flow profile. Multiplying each possible cash flow profile by its probability and summing the products generates an expected cash flow profile. Then, an expected NPV, IRR or cash flow payback can be computed for the expected cash flow profile [Martino, 1995]. Amran and Kulatilaka [Amran and Kulatilaka, 1999] point out that by modelling scenarios within traditional discounted cash flow analysis uncertainty can be introduced. However this approach does not allow for choosing between different scenarios and each scenario remains fixed on a single stream of income and expenses.

Real Options

Another more recent economic approach is to treat the opportunity to invest in an R&D project like an option. Options involve the right but not the obligation to take a course of action. A real option refers to investments with option-like characteristics that are not traded as securities in financial markets [Trigeorgis, 1996]. Real options take uncertainty into account and offer the flexibility to respond to changing situations and increasing information when time goes on. The theory behind the approach is to use the sophisticated option pricing models used in capital market theory to the valuation of risk-prone R&D projects. The three most important standard option-pricing models are the Black-Scholes formula, the Binomial Model and the Geske Model. For a detailed description of the real options approach refer to chapter four.

Applications

Thomas [Thomas, 1985] compares the use of decision trees, NPV, IRR and CF payback for the selection of projects in the electronics and pharmaceutical industries. A model for the expected net present value of R&D projects is presented by Hess [Hess, 1985]. Aaker and Tyerbjee [Aaker and Tyerbjee, 1978] develop a model for the selection of a portfolio of R&D projects that maximises the expected increment to NPV and takes interrelations between projects into account.

The first pioneers using the real options approach for pricing natural resources were Tourinho [Tourinho, 1979] and Brennan and Schwartz [Brennan and Schwartz 1985]. Siegel, Smith and Paddock [Siegel, Smith and Paddock, 1987] and Paddock, Siegel and Smith [Paddock, Siegel and Smith, 1988] find that a series of options is involved in a licence to do something, for example to develop specific areas or products whenever the market is favourable. Further applications of real options valuation of R&D projects are described in [Perdue et al., 1999], [Newton and Pearson, 1994], [Lint and Pennings, 2001], [Jensen and Warren, 2001], [Tsekrekos, 2001], [Faulkner, 1996], [Perlitz, Peske and Schrank, 1999] and [Lin, 2001].

Boer [Boer, 2002] reports that the three main groups of companies today making use of real options valuation for R&D projects are:

Pharmaceutical and biotech companies such as: Merck. See [Nichols, 1994], Eli Lilly, Baxter International, Amgen, Genentech, Genzyme, and Smith & Nephew.

Petroleum companies such as: Mobil, Chevron, Petrobras,Texaco, Conoco, and Anadarko Petroleum.

Energy Firms: Dynegy, Amerada Hess, Duke Energy, and Aquila Energy.

3.2.5. Integrated Decision Analysis and Real Options Models

The models integrating decision tree analysis and real options theory are based on the distinction between endogenous project risks and exogenous market risks. Options analysis is recommended for the treatment of market risks, because choices about exercising options to enter a market change the perspective risk and the associated level of the discount rate. Options analysis covers the problem of constantly varying discount rates through a process known as "risk-neutral" valuation as decribed in chapter four. Then standard decision or expected value analysis with a consistent discount rate can be used for the analysis of both kinds of risk.

Applications

Neely [Neely, 1998] developed an integrated decision analysis and real options framework for automotive producer's investments in advanced materials R&D. Another method is presented by Smith and McCardle [Smith and McCardle, 1998], refer to chapter four. Initially the model was developed to analyse oil properties, but the authors briefly describe how the model could be used for the evaluation of R&D projects.

Perdue [Perdue et al, 1999] present another model combining option pricing and decision analysis methods, applied to a portfolio of research projects at the Westinghouse Science and Technology Center. The project's value at the commercial stage is calculated with the options model, as well as the value of the option to delay or abandon the project because of unfavourable market conditions. Uncertainties concerning the technical success of the project and key research and development decision points are represented with a decision tree.

All of the integrated approaches presented above rely on the different treatment of exogenous and endogenous uncertainty. Neely [Neely, 1998] suggests the following application of evaluation methods according to the kinds of risks that affect the project:

Low Exogenous – Low Endogenous Uncertainty

When there are no uncertainties, the value of an option approaches zero and NPV, decision analysis and real options will converge.

High Exogenous – Low Endogenous Uncertainty

The real options approach is well suited for projects with a high level of exogenous uncertainty as options become more important when uncertainty increases. Only real options models are capable of valuing project options that are dependent on the price path of traded assets. Decision trees represent the structure of the option but do not solve the discounting problem properly.

Low Exogenous – High Endogenous Uncertainty

Endogenous project uncertainties are not correlated with external market events. Therefore the proper discount rate for evaluating the cash-flows is the risk-free rate and discounting cash-flows in a decision tree using the risk-free rate is sufficient.

High Exogenous – High Endogenous Uncertainty

In this case a combination of decision analysis and real options is suited best. Projects are evaluated by translating any exogenous uncertainty into risk-neutral distributions, which are then combined with the endogenous uncertainties in a decision tree. The resulting project cash-flows are discounted at the risk-free rate.

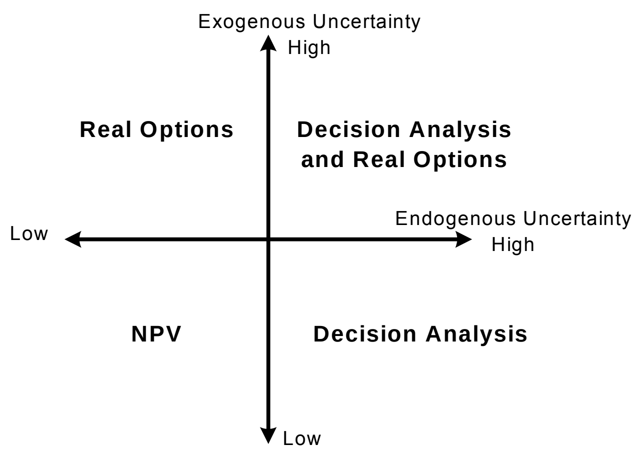


Figure 3.2: "Comparison of Real Options, Decision Trees and NPV Concerning the Level of Uncertainty" —Source: [Neely, 1998]

For a detailed comparison of traditional discounted cash flow techniques, decision trees and real options their strengths and weaknesses, and how the models could be extended in order to cover the option value introduced by the possibility to react to changing situations, refer to chapter four.

3.3. Sensitivity Analysis

Sensitivity analysis is used to determine to what extent a model´s output is affected by changes or errors in input parameter values [Rappaport, 1967], which is referred to as parameter sensitivity. With respect to the conceptual model itself sensitivity analysis can also be used to analyse the effects of uncertainty concerning the underlying structure, assumptions and specifications in order to test the confidence in and predictions made by the model [Helton and Burmaster, 1996].

A predecessor of sensitivity analysis is the theory of design of experiments [Fisher, 1935] used for physical experimentation, which involves designing a relationship between inputs and outputs within an experiment. The first approach to designing an experiment was to vary one of the input factors at a time to study the effect on the output with the other input factors remaining constant [Daniel, 1958].

The early approaches to sensitivity analysis only incorporated uncertainty concerning the input factors and model parameters [Tomovic and Vukobratovic, 1972] while nowadays also uncertainty concerning the structures, assumptions and specifications of the model can be taken into account [Helton and Burmaster, 1996]. Thus sensitivity analysis can be conducted to determine which input factors influence the output´s variability most, interactions of the input factors, the quality of the model and to investigate how the model resembles with the process under consideration. Sensitivity analysis can thus be used to examine the joint impact of uncertainties such as operational, environmental, financial and technical uncertainties.

Risk estimation based on uncertainty analysis is often complemented by sensitivity analysis. The main difference between uncertainty analysis and sensitivity analysis is that the latter examines the effects of varying key input data on the risk estimates either individually or collectively over some range of possible variation. Uncertainty analysis is conducted in order to determine which uncertainties are the sources for risk in the project, and how these uncertainties propagate through the project evaluation and combine to produce a final risk estimation. A sampling–based approach to uncertainty and sensitivity analysis requires a mapping of uncertain analysis input factors to uncertain analysis outputs, where the outputs $y(x) = [y_1(x), y_2(x), \ldots, y_n(x)]$ are functions of the inputs $x = [x_1, x_2, \ldots, x_n]$. Uncertainty analysis investigates the resulting uncertainty in $y(x)$ given the uncertainty in x, whereas sensitivity analysis provides insights on the influence of x on the uncertainty in $y(x)$.

Sensitivity analysis can be divided into two approaches, local sensitivity analysis and global sensitivity analysis. Using local sensitivity analysis one input factor is varied at a time while the others remain fixed to a central (nominal) value. In doing so the local response of the output is investigated. Local sensitivity analysis is mainly based on differential calculus and can only be applied to linear models.

Applying global sensitivity analysis the input factors are varied along their joint distribution. As the inputs are varied simultaneously the resulting variation of the output is averaged over the variation of all the input factors. The advantage of global sensitivity analysis is that the entire output´s uncertainty can be apportioned according to any subgroup of input factors. Having a large number of input factors the results of sensitivity analysis with grouped factors are easier to interpret than considering each factor separately. It becomes transparent to the decision maker to what extent the output´s uncertainty is caused by uncertain input parameters or poorly defined weights attached to the criteria and thus to what extent the model´s result is biased by the estimations [Saltelli, Tarantola and Chan, 1999a], [Saltelli, Tarantola and Chan, 1999b]. Another way of grouping the sources of uncertainty would be to consider uncertainty resulting from intrinsic stochastic properties of the problem, uncertainty with respect to the model and its parameters or subjective uncertainty [Helton and Burmaster, 1996]

By conducting sensitivity analysis, one can capture the new states a system might come to after a major shock instead of only examining incremental changes, because conditions can be defined under which the value of specific project benefits might dramatically change [Neely, 1998]. By finding out which parameters are most sensitive to change one has a good indicator on where to focus the attention under which circumstances when trying to capture the risks of a project. Sensitivity analysis provides a way to determine the robustness of the risk results with respect to key assumptions in the analysis. Thus it is a useful tool in identifying which are the key drivers in a project and indicates how large the forecast error on a key driver can be tolerated before the project becomes unacceptable. Sensitivity analysis should be applied to all of the models mentioned above, as well as to the models for the selection of an optimal portfolio as described in chapter five, in order to check if the behaviour of the models is still consistent when changing the input parameters. Furthermore it can be determined how robust the optimum portfolio is. If the resulting optimum changes significantly after having changed the values of a few input parameters slightly, then the result is highly sensitive to these parameters. If, on the other hand, the resulting portfolio does not react significantly to minor changes in the values of the input parameters, the portfolio is robust and will not be affected by the inevitable errors, which are contained in the estimates of the parameters' values [Martino, 1995].

3.4. Comparison of the Methods

In the following the project evaluation techniques will be compared according to the ways they account for risk, interrelations, multiple objectives and which mathematical model is used for the calculation of the results. Furthermore the granularity of the models is discussed.

Risk and Uncertainty

Comparative models incorporate risk only by defining the riskiness of a project as a criterion for comparison. This risk estimation is based on subjective judgements.

Scoring models can be extended by attaching interval estimates to the various measures of project performances.

Game theoretic models for R&D represent market or technological uncertainties by means of distribution functions of the successes of competitive projects.

Decision trees represent risk and uncertainty by means of stochastice event nodes.

Traditional economic models can account for risk by creating scenarios and calculating expected NPV, IRR or cash flow payback.

The real options model adjusts for risk by using the riskless interest rate. If risk and uncertainty depend on the deviation of the underlying probability distribution, the real options model takes into account risk and uncertainty by incorporating this probability distribution into the valuation.

The hybrid real options and decision tree model covers endogenous project risks through the decision tree and exogenous market risks through the real options valuation.

Interrelations

This refers to interrelations between various aspects of one project, between various phases of one project and to interrelations between different projects, according to the level of granularity of the evaluation.

Neither comparative models nor scoring approaches nor traditional economic approaches take interrelations into account.

Game theory incorporates dependencies between competitive projects.

Decision trees model project dependencies by the branches of the tree.

The real options model regards one project as being atomic and thus requires a separated modelling of project dependencies.

If the success of project *A* is a precondition for project *B*, then, using the real options approach, one evaluates project *A* and then project *A* and *B*. Using decision trees project *A* simply is a node in the tree, which is followed by *B*.

The hybrid real options and decision tree approach can handle interrelations in the same way as decision trees.

Multiple Objectives

This criterion refers to the ability of an R&D evaluation technique to deal with multiple objectives. As R&D projects can have a number of benefits and success criteria, it is important to incorporate multiple objectives into the evaluation process.

Comparative models and scoring approaches take multiple objectives into account through the various evaluation criteria. Weights can be attached to the various criteria in order to represent the relative importance thereof.

Game theoretic approaches to R&D project evaluation do not take into account multiple objectives.

Decision trees can represent any kind of objective by virtue of the decision nodes.

Traditional economic evaluation and real options focus on a one-dimensional evaluation of projects, and evaluate only the financial aspects of the project.

The hybrid model presented by Neely [Neely, 1998] uses multi-attribute utility analysis in order to translate a number of benefits contributing to the success of a project into a single monetary value. Thus the overall result is also a monetary value.

Granularity

The techniques are compared according to the level of detail with which the projects can be modelled. If the granularity is low, it is not possible to model the projects in great detail concerning, for example, the various aspects or stages of the projects. If the granularity is high the evaluation technique requires a very detailed representation of the projects. If the granularity is optional a very detailed representation of the project is possible but not necessarily required.

When using comparative or scoring models the granularity can be high but that is not predefined by the model, thus it is optional.

Game theory does not inherently include the splitting of projects into phases, but allows for the modelling of various phases.

Decision trees support representing the project with a high level of granularity but this is not necessary and therefore optional.

Traditional economic models are techniques of low granularity, as they focus on a monetary valuation only. Furthermore the standard models assume a single cash flow profile from the beginning to the end of the project, which limits the flexibility. Extended techniques trying to avoid that shortcoming are described in 3.2.4.

Real options provide modelling with medium granularity as they allow for a monetary valuation only, but incorporate the flexibility to respond to changing situations.

The hybrid real options and decision tree approach, on the other hand, requires a highly detailed modelling of the project, because concerning the exogenous market risks the project is evaluated with the real options model and decision trees are used for the endogenous project risks. Therefore the different views on the project have to be separated carefully, and thus a detailed modelling of the project is necessary.

Calculation

Calculation refers to the mathematical model that is used for the computation of the results of the various evaluation techniques.

Using comparative models for project selection Souder and Mandakovic propose decision support systems to compute the overall merit of the projects [Souder and Mandakovic, 1986].

The overall score for a project can be calculated by a straightforward multiplication or summation of the scores multiplied by the attached weights.

Game theoretic approaches determine a Nash equilibrium to calculate the optimum strategies for the competitors, which can be mapped to a linear program.

Decision trees can be evaluated using backward induction.

Traditional discounted cash flow techniques provide formulas for the calculation of NPV, IRR or cash flow payback.

The put or call values of real options can be calculated using the binomial model, the Black and Scholes formula or the Geske model (as introduced in chapter four). Only the Black and Scholes formula and the Geske model, used for the calculation of compound options, provide a closed formula solution.

The hybrid real options and decision tree framework, after having performed the required transformations, evaluates a classical decision tree.

Abbreviations

The following abbreviations are used in Table 3.1:

Abbreviation	Meaning
DCF	Discounted Cash Flow
RO	Real Option
PV	Present Value
NPV	Net Present Value
IRR	Internal Rate of Return
CF	Cash Flow

	Risk/Uncertainty	Inter-dependencies	Multiple Objectives	Granularity	Calculation	Input	Output
Comparative Models	subjective judgements	no	some models	optional	decision support system	criteria for comparison	ranking of projects
Scoring Models	interval estimates	no	yes	optional	multiplication or addition of scores	criteria, weights, scores	overall score
Game Theory	distribution function	dependencies between competitors	no	optional	Linear programming based on Nash equilibrium	nr. of competitors, discount rate, PV of innovation, investments, time	Nash equilibriu m strategies
Decision Tree Analysis	stochastic event nodes	yes	yes	optional	Simplex algorithm	probabilities, dependencies, CFs, discount rate	strategies and benefits
Traditional Economic Models	interest rate, probabilistic DCF models	no	financial evaluation only	low	capital budgeting techniques	investments revenues, time, discount rate	NPV, IRR, CF payback
Real Options	volatility, riskless interest rate	compound options	financial evaluation only	medium	closed formula when using Black&Scholes model	time, volatility,disount rate, PV of investments, PV of CFs	call or put values per project
Hybrid RO and Decision Tree Analysis	ROs for market risks, dec. trees for project risks	yes	financial evaluation only	high	evaluated like decision trees	real options and dec. tree inputs	strategies and benefits

Table 3.1: "Comparison of Project Evaluation Techniques"

Chapter 4 — Real Options Theory

The present chapter discusses the real options approach for the valuation of R&D projects, which has been briefly introduced in chapter three. The approach is discussed in further detail and a comparison is made with decision tree analysis. Real options valuation is also used for the valuation of projects in the framework presented in chapter six.

Considering the literature—refer for example to [Trigeorgis, 1996], that compares real options and decision tree analysis—it is usually assumed that decision trees are evaluated using standard net present value (NPV) techniques, which refers the problem to comparing the real options approach with calculating a project's NPV. The present chapter follows the argumentation found in literature, but also goes one step further and compares the underlying concepts of the two approaches from a structural point of view.

It is often argued in literature that the NPV of a project favours short-term projects with low risk, and thus long-term projects with higher risk such as R&D projects are systematically undervalued. Therefore, the real options approach is suggested for the valuation of such projects because real options provide a new perspective on risk. A project is regarded as a process that managers can continually reshape in the light of technological or market changes. Therefore the concept of treating projects like options introduces the valuable perspective that risk can be a source of advantage, and risk-taking can be financially rewarding. In such cases the options approach can demonstrate a substantial positive value for future gain when traditional discounted cash flow techniques suggest that the project will generate a loss.

Consequently the real options approach seems appealing for the valuation of R&D projects. The technologies or processes to be invested in may, at some point in the future, result in a wide range of possible outcomes and potential new markets. However, there is also a high probability of technical or market failure.

In order to explain the differences in evaluating a project using traditional discounted cash flow techniques, and option pricing, this chapter provides a detailed introduction to the concepts of option pricing theory, and the according underlying assumptions. Possible extensions to the traditional NPV approach are presented. These extensions try to avoid the shortcomings of the approach that were briefly introduced above, and in the previous chapter.

Starting with the analogies between options in the world of finance and real options, models for options valuation are derived, such as the binomial model and the Black-Scholes formula. Then, the requirements necessary for option pricing will be explained, together with how these can be fulfilled by projects regarded as real options.

In addition, the chapter introduces an approach for the combination of decision trees with an extended net present value valuation. This incorporates some ideas of the options pricing approach into decision tree analysis. Then a comparison of the results given by decision tree analysis and option pricing is presented, including the conditions under which the two approaches provide similar or the same results.

The present chapter closes with a summary and discussion of the assumptions underlying the real options approach and decision tree analysis.

4.1. Financial Options and Real Options

An option provides the right to buy or sell an asset, such as a stock, for a predetermined price at some point in time in the future. However, the holder of the option is not forced to exercise this right, and will thus only do so if it seems to be opportunistic. Therefore the decision to exercise an option is very similar to decisions that have to be taken when managing a project, such as using the results of promising research for product development. The insight, that the real value of investing in research is equivalent to the purchase of a real option, led to attempts to use options theory for the valuation of research [Newton and Pearson, 1994], [Roll, 1994].

The term "real option" is used to distinguish options arising in contexts other than purely fincancial ones, *i.e.* contexts from financial options relating to securities or commodities. The application of options valuation to "real" projects was proposed by Myers [Myers, 1977] and Ross [Ross, 1978] in order to close the gap between finance and decision-making and popularised by Myers [Myers, 1984] and Kester [Kester, 1984]. Amram and Kulatilaka [Amram and Kulatilaka, 1999] provide an extensive description of how to apply classic option-pricing to real investments. The approach is also recommended in [Brennan and Schwartz, 1985], [Trigeorgis and Mason, 1987] and [Copeland, Koller and Murrin, 1990].

Since then increasing interest has been directed towards the application of option pricing theory to the valuation of R&D, —refer to empirical findings by Ellis [Ellis, 1997] and Busby and Pitts [Busby and Pitts, 1997]. Myers [Myers, 1984] defines an R&D investment as an option that gives a company the right—at some future point in time—to exercise that R&D investment, or to not exercise it. The inherent uncertainty in research has been resolved by the end of the research phase, and if the outcome is a success, it will be exercised by making an additional investment for the commercialisation of the outcome. If the outcome is not a success, the loss can be limited to the initial R&D investment by simply letting the option expire. Kester [Kester, 1984] compares R&D projects to growth options (4.4.1.) whose underlying values depend on uncertainty, deferability of the investment and the interest rate, refer also to [Kester 1993], [Newton and Pearson, 1994], [Hamilton and Mitchell, 1990], [Pennings and Lint, 1997] and [Lint and Pennings, 1998].

Merton [Merton, 1973] and Black and Scholes [Black and Scholes, 1973] developed the basic techniques for the correct valuation of options by discovering ways to account for the constant variation in the level of risk. Statistical measurements of historical risk associated with the underlying assets of the project, their performance in the market and their volatility compared to the overall market form the basis of the options' valuation. If statistical records over time are available such as for financial assets and commodities, the Black-Scholes formula (4.3.2.) and related techniques for option pricing can be applied immediately. Brealey and Myers [Brealey and Myers, 1988] as well as Newton and Pearson [Newton and Pearson, 1994] recommend to apply the Black-Scholes model to the valuation of R&D investments. Luehrman [Luehrman, 1998a] shows how to map an R&D project onto a European call option using the Black-Scholes model and explains under which circumstances traditional NPV and option pricing yield the same results or diverge.

Angelis [Angelis, 2000] proposes a simplified approach to the Black-Scholes model for measuring the option value of R&D, based on the underlying distributions of costs and revenue instead of net cash flows and does not assume a log-normal distribution. Perlitz, Peske and Schrank [Perlitz, Peske and Schrank, 1999] suggest to treat R&D investments as compound options (4.4.1.), as the value of the R&D investment consists of the value of the initial R&D project plus the value of resulting future investment opportunities. Herath and Park [Herath and Park, 1999] use the binomial option model for analysing the value of R&D projects.

Morris, Teisberg and Kolbe [Morris, Teisberg and Kolbe, 1991] use an option valuation approach to show that "riskier" R&D projects are more valuable than "safe" ones, given that they have got the same expected payoffs and the same costs, but different risks and ranges of possible outcomes. The authors compare R&D to a call option because future opportunities are created without having to commit to the full investment. If the research fails the option will not be exercised and only the initial R&D investment is lost. As the "safe" and the "risky" project have got the same costs not more money is lost when choosing the "risky" project that, on the other hand, might be exceptionally successful when being commercialised.

A similar reasoning is provided by Mitchell and Hamilton [Mitchell and Hamilton, 1988] who argue that managing R&D as a strategic option improves the valuation of early and basic R&D in comparison to traditional return on investment analysis. By providing a structural comparison of stock options and R&D projects they point out that, regarding the effects of volatility and time, the value of an option moves in the opposite direction to the value of an investment. R&D programs addressing high-impact opportunities and having a low probability of success do not imply higher risk. Roberts and Weitzman [Roberts and Weitzman, 1981], Kester [Kester, 1984] and Luehrman [Luehrman, 1998b] also use real options analysis to explore the strategic opportunities inherent in R&D projects. They find that under uncertainty one can benefit from initial strategic investments in order to obtain more information about future growth opportunities. Grenadier and Weiss [Grenadier and Weiss, 1997] analyse the innovation investment strategy as a sequence of embedded options which implies that taking an investment decision influences the future options available.

Sharp [Sharp, 1991] argues in favour of options analysis for investments subject to high risk such as many R&D investments. Kensinger [Kensinger, 1987] as well as Trigeorgis and Mason [Trigeorgis and Mason, 1987] use the options valuation approach to capture the value of managerial flexibility.

Childs, Ott and Triantis [Childs, Ott and Triantis, 1998] use real options to analyse how interdependencies affect the optimal ordering of projects in a portfolio. Childs and Triantis [Childs and Triantis, 1999] examine dynamic R&D funding strategies by taking into account interactions among projects concerning learning and cash flows, periodic reevaluations of the R&D program, varying intensities of investment as well as competition.

Copeland and Weiner [Copeland and Weiner, 1990] supported the application of option pricing theory to practical R&D decision making. They report that R&D managers may benefit from flexibility by splitting R&D programs into phases and then decide at each review point whether to continue the program or abandon it depending on changing conditions. Hamilton and Mitchell [Hamilton and Mitchell, 1990] argue in favour of the practical application of real options theory to R&D because long-term strategic options for the company are created by conducting R&D. Consequently R&D programs should be evaluated based on real options theory. The authors analysed the introduction of options thinking into the evaluation of R&D at General Electric Co. Since 1990 the international management consultancy firm McKinsey has used options valuation methods for R&D investments in work for its clients [Copeland, Koller and Murrin, 1990]. Faulkner [Faulkner, 1996], based on his experience within Eastman Kodak, reports that valuable insights into the valuation of R&D can be gained when regarding the process from an "options thinking" point of view. Nichols [Nichols, 1994] in an interview with CFO Judy Lewent explaines how real options analysis has been successfully deployed at Merck. Lint and Pennings [Lint and Pennings, 1998] developed an option pricing model based on the assumption of a discontinuous arrival of new information and thus capturing breakthroughs in research or business shifts in market or technology conditions. Their model was applied to the valuation of R&D projects at Philips Corporate Research.

4.2. Net Present Value under Uncertainty

As already mentioned in the introduction to this chapter, it is often argued in literature—see for example [Huchzermeier and Loch, 2001], [Faulkner, 1996], [Graves and Ringuest, 2003]—that the NPV technique tends towards favouring short-term investments with low risk, and thus is perfectly adequate for valuing projects with safe cash flows, but undervalues highly risky and long-term projects.

The reasons for this undervaluation are explained in the following section, but for completeness, the equation for calculating the NPV is presented first [Trigeorgis, 1996]:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - I \tag{4.1}$$

where r is the (risk-free) opportunity cost of capital, C_t is the net cash inflow in year t, I is the single initial investment outlay, and T is the number of years of the project's life.

The NPV of a project is quite sensitive to the discount rate chosen, because the impact of the up-front cost is constant: the present value of a payment today is simply the full amount of that payment. However, the influence of the benefit stream declines with an increasing discount rate and thus makes the project look less attractive for larger discount rates. According to Pindyck [Pindyck, 1991] often quite inappropriately high discount rates are chosen for the valuation of projects, which leads to an unfair bias towards projects with benefits that occur far in the future compared to costs. This is unfortunately often the case with R&D projects and therefore discounted cash flow techniques tend to understate the value attached to research projects [Myers, 1984].

Finance theory provides models in order to identify a discount rate that adjusts project cash flows for the time value of money and accounts for the risks the cash flows might face.

4.2.1. Certainty-Equivalent Approach

Traditional NPV can be extended to account for uncertainty by replacing the uncertain cash flows of each period by their certainty-equivalent. The certainty equivalent is defined as the certain cash flow in period t that has got the same present value as the uncertain cash flow in that period [Trigeorgis, 1996]. The certainty-equivalent version of the NPV can be written as:

$$NPV = \sum_{t=1}^{T} \frac{\alpha_t E(c_t)}{(1+r_1)...(1+r_t)} - I \tag{4.2}$$

where $E(c_t)$ is the expected cash flow in period t, r_t is the risk-free discount rate in period t that can vary from period to period and a_t is the certainty-equivalent coefficient, which compensates for the financial risks inherent to the investment and allows for using the risk-free rate for discounting. a_t varies between zero and one, and the closer it is to one, the lower the risk compensation for the uncertain cash-flow. Formally a_t is given by:

$$a_t = 1 - \frac{RP_t}{E(c_t)} \tag{4.3}$$

where RP_t is the risk premium, defined as the uncertain cash flow's expected value minus its certainty-equivalent [Trigeorgis, 1996]. Thus each certainty-equivalent cash flow in a period t, can be regarded as the expected cash flow in period t minus a risk premium, that can vary from period to period according to the level of risk associated with that period's cash flow.

4.2.2. Risk-Adjusted Discount Rate Approach

Under uncertainty, the traditional NPV approach—discounting the future cash flows at the risk-free opportunity cost of capital, or the required rate of return that is demanded of comparable investments—can be used when the comparable investments belong to the same risk category. In practice, projects are classified according to risk characteristics, and then a discount rate is assigned to each risk category, instead of determining a unique risk-adjusted discount rate for each project [Trigeorgis, 1996].

The risk-adjusted discount rate approach obviously fails to account for important differences in risk between investments belonging to the same risk class. Furthermore, if the same constant discount rate is used for the entire duration of the project, it is implicitly assumed that the riskiness of the project's cash flows stays the same for every period. A straightforward solution to that problem would be to determine different risk-adjusted discount rates in order to reflect the riskiness of each period of the project, which yields to the extended NPV form:

$$NPV = \sum_{t=1}^{T} \frac{E(c_t)}{(1+k_1)...(1+k_t)} - I \tag{4.4}$$

where k_t is the risk-adjusted discount rate in period t.

However this approach is rarely used in practice because risky events are not commonly clear and discrete. As Graves and Ringuest point out: managers have enough difficulty in specifying a single value for a discount rate, so that estimation of a time profile of discount rates may be out of question [Graves and Ringuest, 2003].

4.2.3. Capital Asset Pricing Model

The Capital Asset Pricing Model (CAPM) is probably the most well known model for estimating the appropriate discount rate for an investment. The CAPM assumes that there are two kinds of risk:

- Risk that is unique to the project and diversifiable, also known as unsystematic risk
- Systematic or market risk that is not diversifiable

The CAPM proposes that the level of return an equilibrium market requires from an investment is a function of its market risk component, as the unique risk can be diversified away [Sharpe, 1964].

The CAPM equation is given by

$$E(r_i) = r + \beta_i \left[E(r_m) - r\right] \tag{4.5}$$

The CAPM relates the expected (required) return on an asset i, $E(r_i)$, to the risk-free interest rate r, to a metric of the relative level of market risk in the investment β_i and to the expected return from the market portfolio $E(r_m)$. β_i refers to the covariance of the asset's return with the return on the market portfolio divided by the variance of the market return. β_i can be determined from ordinary least squares regression analysis.

$$\beta_i \equiv \frac{\operatorname{cov}(r_i, r_m)}{\operatorname{var}(r_m)} \tag{4.6}$$

The CAPM equation gives the return that any asset in equilibrium must earn to compensate for its systematic risk. With the CAPM a hurdle rate for the project's acceptance can be specified or the project's risk-adjusted discount rate can be determined.

In practice it is still difficult to estimate an investment's discount rate, as projects are not traded assets and thus it is not possible to conduct a direct regression analysis in order to determine the market risk [Neely, 1998]. If a project's beta is determined by measuring the beta of a security in the same risk class, then the project and the security should match considering the following factors:

- The growth rate of the expected cash flows,
- The pattern of the expected cash flows over time,
- The characteristics of any individual underlying components of these cash flows,
- The procedure by which investors revise their expectations of cash flows and the relationship between forecast errors for the cash flows and those for the market return [Myers and Turnbull, 1977].

When it cannot be assumed that the beta of a project is a constant over all periods of the project—which means that risk does not increase at a steady rate over time—then the risk-adjusted discount rate approach, with changing discount rates for every period of the project, is more appropriate for determining a discount rate [Trigeorgis, 1996].

4.2.4. Arbitrage Pricing Model

The name of the Arbitrage Pricing Model (APM), introduced by Ross [Ross, 1976], is based on the fact that it analyses assets when there is no arbitrage in asset markets. Similar to the CAPM, the APM determines the expected return on an asset, but the covariance is measured with respect to a number of risk factors. The APM assumes that asset returns are linearly related to these factors. The APM does not *a priori* specify the set of factors that determine the equilibrium return on the asset. Common factors identified by Campbell, Lo and MacKinlay [Campbell, Lo and MacKinlay, 1997] through empirical analysis, include interest rate spreads, prices of traded assets, prices of goods and metrics of economics strength. The general form of the APM is given by:

$$E(r_i) = a_i + \beta_i (F - E(F)) + e_i \tag{4.7}$$

where, similar to the CAPM $E(r_j)$ is the expected (required) return on an asset i, a_i is a constant specific to asset i, β_i, much like the beta in the CAPM model, is a measure of sensitivity of returns on asset i to factor F. F is a factor explaining returns and $E(F)$ is the expected value of F. e_i represents an error term with an expected value of zero.

In summary, using traditional discounted cash flow techniques, including NPV, a twin-security is defined for each project, having the same risk characteristics as the project and traded on financial markets. Under the assumption of complete markets, the required expected rate of return of that twin-security is then used as the appropriate discount rate.

4.3. Option Pricing

Standard techniques of option pricing are based on the ability to use a traded underlying security with riskless borrowing in a dynamic portfolio. This portfolio is supposed to replicate the payoff of the option in any situation, which is the basis for the concept of risk-neutral valuation, refer to 4.3.1.

The most prominent models for option pricing are the Binomial model and the Black-Scholes formula, which is used to value call and put options. The Binomial model is more flexible and allows for a valuation of a wider range of option categories. The shortcoming of the method is that it is a discrete time model, rather than a continuous, as the Black-Scholes formula, and thus does not allow for closed-form solutions.

All standard option pricing models are based on the following assumptions [Trigeorgis, 1996]:

Standard Assumptions for Option Valuation:

- Markets are frictionless: allowing for continuous trading. This means there are no transaction costs or taxes. Furthermore, there must not be any restrictions on short sales and the full use of proceeds is allowed. All shares are infinitely divisible and unrestricted borrowing and lending at the same rate is provided.
- The risk-free interest rate is constant over the life of the option.
- No dividends are paid by the underlying asset, over the life of the option. This assumption is removed when using the Black-Scholes formula for option pricing (4.3.2.).
- Stock prices follow a stochastice diffusion Wiener process described in the following.

4.3.1. The Binomial Model

The general, multiplicative binomial option-pricing model by Cox, Ross and Rubinstein [Cox, Ross and Rubinstein, 1979] is based on constructing a replicating portfolio and determining the according cost, in order to determine the value of the option equivalent. Assuming that it is possible to create a portfolio that consists of buying a number of shares of the underlying asset, and borrowing an appropriate amount against them at the riskless rate, that would exactly replicate the future returns of the option, and fulfilling the no-arbitrage condition, the option and the equivalent portfolio must be sold for the same current price. This leads to what is known as the risk-neutral approach to valuation.

Risk-Neutral Valuation

Given the possibility to create such a replicating portfolio, the model can be extended by the assumption to be in a risk-neutral world, because the owner of the portfolio will get a certain return anyway regardless whether the stock moves up or down. If risk was irrelevant all assets would earn the risk-free return. Thus, expected cash flows weighted by the risk neutral probabilities—the probability that would be used in a risk-neutral environment where the investors are indifferent to risk—could be discounted at the risk-free rate. The risk-neutral probability can also be derived using the argument that in a risk-neutral world the expected return on the stock must equal the riskless rate.

The Binomial model is an iterative process dividing the time to expiration of the option into discrete steps. Working backward from the last period to the present, the range of possible underlying prices is considered at each discrete point, and so the optimal strategy for the holder of the option can be determined. The result is a valuation of the option accompanied by a set of strategies to follow as the price of the underlying asset changes. Thus the binomial model appears very similar to decision tree analysis.

It is assumed that the underlying stock price follows a stationary multiplicative binomial process over successive periods. The current value of the underlying *S* may increase by a multiplicative factor *u* with probability *q* to *u*S or decrease with complementary probability (1-*q*) to *d*S. With $d = 1/u$. Thus *u* and *d* represent the logarithmic or continuously compounded rate of return if the stock moves up or down [Trigeorgis, 1996].

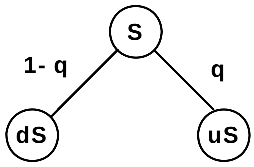


Figure 4.1: "Stationary Multiplicative Binomial Process"

Assuming that the outcome of a down move followed by an up move is the same as an up move followed by a down move we get to the Brownian motion metaphor for the value of the underlying.

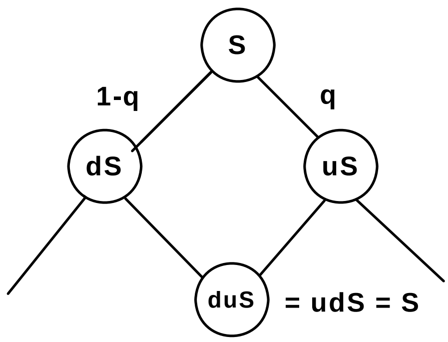


Figure 4.2: "Brownian Motion Metaphor"

Stochastic Processes

All of the option-pricing models described here assume that stock prices—and in terms of real options, gross project values—follow stochastic processes. This means that their value changes over time in an uncertain way. There are discrete-time and continuous-time processes. The Markov process is a stochastic process assuming that only the present state of the process or current stock price is relevant for the state in the next period (assuming that the information from history is incorporated in the current price). Thus, stock prices only change responding to new information and price changes or returns are independent over time. The Wiener process or Brownian motion, that has been used to describe collisions of particles in physics, is only one type of a Markov process. The two assumptions underlying the Brownian motions are:

If a random variable z follows a Wiener process then the changes in z, Δz over small time intervals Δt, are independent of t.

Δz are normally distributed with mean $E(\Delta z) = 0$ and variance $\mathrm{Var}(\Delta z) = \Delta t$. Specifically $\Delta z = \varepsilon_t \sqrt{\Delta t}$ where ε_t is a normally distributed random variable with mean zero and standard deviation 1.

The second assumption does definitely not apply to stock prices because if price changes were normally distributed, some prices would be negative. So it is more appropriate to regard stock prices as log-normally distributed, and that the natural logarithm of price follows a Wiener process [Trigeorgis, 1996]. Therefore a geometric Brownian motion or standard diffusion Wiener process is the most common model of stock price behaviour. The discrete-time version of a standard diffusion Wiener process is given by:

$$\frac{\Delta S}{S} = a\Delta t + \sigma\varepsilon\sqrt{\Delta t} \tag{4.8}$$

where ΔS is the change in the stock price in a small time interval, Δt, ε is a standardised normally distributed random variable, a is the expected multiplicative stock return per time unit and σ is the stock price volatility.

The continuous time version of the standard diffusion Wiener process is given by:

$$\frac{\mathrm{d}S}{S} = a\mathrm{d}t + \sigma\mathrm{d}z \tag{4.9}$$

where a is the constant instantaneous expected return of the stock, σ is the constant instantaneous standard deviation of stock returns and dz is the differential of a standard Wiener process with mean 0 and variance dt. The expected change in the stock price is $E(\mathrm{d}S) = aS\mathrm{d}t$ and the variance $\mathrm{Var}(\mathrm{d}S) = \sigma^2 S^2\,\mathrm{d}t$. Therefore the expected change in the stock price is proportional to its amount.

Binomial Option-Pricing Formula

Extending the concept of the Brownian Motions as illustrated above to multiple periods leads to the Binomial option pricing formula for the call value if the option expires after n periods.

$$C = S\,\phi[m;n,p'] - \frac{K}{(1+r)^n}\phi[m;n,p] \tag{4.10}$$

where Φ is the complementary Binomial distribution function (giving the probability of at least m ups out of n steps and r is the riskless rate. K is the exercise price and p' is given by:

$$p' \equiv \left(\frac{u}{1+r}\right)p \tag{4.11}$$

where p is the risk-neutral probability.

For $n \to \infty$ the multiplicative Binomial model approximates the log-normal distribution or smooth diffusion Wiener process. Choosing u, d and p so that the mean and variance of the continuously compounded rate of return of the discrete binomial process are consistent in the limit with their continuous counterparts, the stock price will become log-normally distributed. Furthermore, as stated by the central limit theorem for $n \to \infty$ the Binomial distribution function $\Phi[.]$ converges to the standard cumulative Normal distribution function N. Thus the call value converges to the continuous time Black-Scholes formula.

4.3.2. The Black-Scholes Model

The value of a call option in the Black-Scholes model is a function of the following variables:

Variable	Meaning
S	Current value of the underlying asset
K	Strike price of the option
t	Life to expiration of the option
r	Riskless interest rate corresponding to the life of the option.
y	Dividends/current value of the asset
σ^2	Variance of the underlying asset

Table 4.1: "Input Parameters to the Black-Scholes Formula"

Using these input parameters the value of a call option *v* is given by:

$$v = Se^{-yt}\mathbf{N}(d_1) - Ke^{-rt}\mathbf{N}(d_2) \tag{4.12}$$

where
$$d_1 = \frac{\left(\ln\left(\frac{S}{K}\right) + \left(r - y + \frac{\sigma^2}{2}\right)t\right)}{\sigma\sqrt{t}}$$

$$d_2 = d_1 - \sigma\sqrt{t}$$

N(.) is the cumulative Normal density function

The Black-Scholes formula corresponds to a continuous time model taking dividends into account[5]. If dividends are not considered in the valuation process *y* can be set to zero [Copeland and Weston, 1988].

From the Black-Scholes equation it can easily be concluded that the value of a call option, other factors being constant, increases with the value of the underlying asset *S*, the time to expiration *t*, the variance of asset returns σ^2, and the riskless interest rate *r*. The value of a call option is higher the lower the exercise price *K*. The option value increases the higher the volatility σ and the time to expiration *t*, because if chances are greater that the stock price varies, one can benefit from higher upside movements but at the some time potential losses are limited because there is no obligation to exercise. As the exercise price does not have to be paid until the real exercising of the option, the present value of the exercise price, *K*, would be lower the higher the interest rate *r*.

Underlying Assumptions

The option may be exercised only at maturity: it is a so-called European option[6]

[5] With respect to the valuation of real options dividends can be necessary to model payments that are lost to competitors through waiting to invest [Perlitz, Peske and Schrank, 1999].

- There is only one source of uncertainty
- The option is contingent on a single underlying risky asset: compound options are ruled out
- The current market price and the stochastic process followed by the underlying are known (observable)
- The variance of return on the underlying is constant through time
- The exercise price is known and constant
- Future uncertainty can be described by a log-normal distribution

4.4. *Real Options*

The value of real options can be determined using the option pricing models introduced above. However, the most difficult issue of the evaluation of real options is to find the according input parameter, as R&D projects, projects in general or any other kind of real option such as a patent or a licence do by nature not have the same characteristics as financial assets. This section starts with a brief introduction to the various kinds of real options. Afterwards it is shown how the input parameters provided by real options can be mapped to the input parameters required by option pricing models. If such a direct mapping is not possible, because the projects do not provide the necessary data, possible ways are explained how the necessary input variables can be derived or estimated, or which kinds of available data can serve as an acceptable replacement for the requested data. The section closes with a discussion of the value of uncertainty or managerial flexibility that is always considered as the main advantage of option valuation. In the case of R&D projects however, some kinds of uncertainties do not necessarily have to enhance the value of flexibility.

4.4.1. Kinds of Real Options

Depending on the situation at hand an R&D project can be regarded as a call, put or compound option [Ritchkern and Rabinowitz, 1988], [Kemna, 1993]. The following table presents an overview of the most common types of real options that can be involved in the research and development phases of a project.

[6] There is also an extended version of the Black-Scholes formula in order to value American options.

Kinds of Real Options	**Description**
Defer option	Management holds an option to start a project, or more general to take a decision, and can wait *x* years without exercise. Thus the possibility to wait until more information is available is offered.
Abandonment option	If market conditions decline severely, management can abandon current operations permanently and realise the resale value of capital equipment.
Expansion/ contraction option	The scale of an investment can be adjusted depending on whether market conditions turn out favourably or not. In extreme cases the project can also be halted and restarted after a while.
Switching option	Allows changing the mode of operation of an asset (for example, switching suppliers) or changing the output mix of the processes (product flexibility). Alternatively, the same outputs can be produced using different types of inputs (process flexibility).
Improvement option	During the R&D project the performance of the project can be improved or the targeting can be corrected to market needs.
Growth option	An investment in R&D opens up future growth opportunities like new products or processes.
Time-to-build option	The investment can be made in stages and at each stage newer information is available which makes it easier to decide whether to proceed further or not. Each stage can be viewed as an option on the value of subsequent stages and thus be valued as a compound option.

Table 4.2: "Kinds of Real Options" —Source: [Trigeorgis, 1996]

There are often various options involved in an R&D project. Their combined value may differ from the sum of their separate values because of the interaction among the different options. Additivity of options is given when options are written on distinct assets, but it is no longer trivial when the options are written on the same underlying asset, which is the case when the single underlying asset is the project's gross value. When multiple options belong to the same asset, the value of the underlying asset for earlier options is increased through the presence of subsequent options. Thus exercising a prior real option has effects on the value of the underlying and thereby the value of subsequent options on that underlying. Therefore the interaction of real options depends on the probability of their joint exercise during the life of the project. Trigeorgis [Trigeorgis, 1996] gives a detailed analysis of the effects of the combination of various options belonging to one project.

Compound Options

A compound option is an option to acquire another option. An investment in R&D can be regarded as a compound option, as it is not just undertaken in order to obtain the underlying asset's cash flows but also for the new opportunities that may be opened up. One can distinguish between intraproject compoundness and interproject compoundness [Trigeorgis, 1996]:

Intraproject compoundness refers to multiple stages of one project. There no longer is one single investment at the beginning of the project—the investment can be made in stages. An earlier investment cost instalment represents the exercise price required to acquire a subsequent option to continue the project.

Interproject compoundness means not regarding projects as isolated, but as one part in a sequence of projects. If for example a research project turns out to be a success it opens up the opportunity to start a new project for product development, and to acquire the revenues of the product to be developed and commercialised. Thus each investment provides an opportunity to begin a new project rather than continuing another phase of the same, as in the case of intraproject compoundness. The strategic importance of compoundness between projects lies in the fact that it can justify undertaking a project whose net present value is negative, but it opens up subsequent future investment and thus benefit opportunities.

Therefore the model of compound options can be applied for the valuation of growth opportunities that only become available after having undertaken earlier investments. The problem with compound options is that analysing them is more complicated because they must not be seen as independent investments but rather as links in a chain of interrelated projects. Geske [Geske, 1979] developed a model for the valuation of compound options. The formula is similar to the Black-Scholes formula, but the variable entering the boundary condition now is itself an option on an asset whose value is given by the Black-Scholes solution.

Jensen and Warren [Jensen and Warren, 2001] used the Geske model in order to value research in the service sector, specifically British Telecommunications plc. The project to be evaluated is split into three phases: the research phase, the development phase and the implementation phase. The phases of the project are represented by a compound call option where the research phase buys the option to launch the development phase, which in turn buys the option to launch the implementation phase. The investment in the development phase thus represents the exercise price of the first stage option. The combined investment in the implementation phase represents the exercise price of the second option and the present value of the cash flows represents the value captured upon exercise of this second option.

4.4.2. Input Variables

This section introduces the input variables that are necessary for option pricing and shows possible ways how these variables can be derived for the valuation of R&D projects. Normally there are the following five input variables used in option pricing models with the corresponding values when the model is used for the valuation of R&D projects:

Input Variables	**Corresponding Values for R&D Projects**
Underlying	(Gross) present value of expected cash inflows
Dividend payments	Payments lost through waiting to invest
Exercise price	Present value of investment cost
Interest rate	Riskless interest rate
Time to expiration	Project duration

Table 4.3: "Input Variables for the Real Options Model" —Source: [Perlitz, Peske and Schrank, 1999]

There are certain assumptions concerning these variables, which apply to financial options, but not necessarily to real options. The following paragraphs give an overview of how these variables can be modelled and how corresponding values can be found for the valuation of real options.

Underlying

Asset price movements can be modelled with continuous or discrete time. The Binomial Model (4.3.1.) uses the discrete time approach, while the Black and Scholes method (4.3.2.) applies the continuous time approach and uses Brownian Motions as a diffusion process to model price movements without sudden jumps up or down. The asset prices are log normally distributed. If diffusion processes are not regarded as realistic enough, and one wants to model sudden jumps up or down, jump processes with fixed or stochastic price jumps can be used. The asset prices are then Poisson distributed. The problem with jump processes is that the principle of creating a duplicating portfolio, which is the basis of the common option pricing models, cannot be applied in a straightforward manner in the presence of jump processes. Thus for these processes it is difficult to find analytical formulas.

As mentioned above option valuation models are based on the duplication principle and, in order to carry out an arbitrage free evaluation the underlying has to be traded. The underlying of an R&D project is normally not traded, which makes it impossible to determine the market value. There are several approaches how to find an appropriate underlying [Perlitz, Peske and Schrank, 1999]:

- *Spanning*

Applying spanning to an R&D project means that one has to create a twin security in order to duplicate a non-traded asset. This is done by duplicating the cash flows of the non-traded asset to a portfolio of traded assets, called twin-security [Bjerksund and Ekern, 1995]. The value of this portfolio equals the value of the R&D project and can thus be used as the underlying.

- *Hotelling Valuation Principle*

Using hotelling valuation in order to determine the value for the underlying involves estimating the market potential of the future products created by the R&D project. This potential is then evaluated and used as the underlying [Sick, 1995]. The Hotelling valuation principle is mainly used when treating natural resources like real options. It implies that the value of the exhaustible natural resource can be regarded as a function of its current price less the expected extraction costs less the expected development costs and multiplied by the resource size. To be precise this is not quite correct for a credible option analysis but may provide a reasonable estimate for practical applications.

- *Future Cash Flows*

In practice the future cash flows of a project are in most cases taken as the underlying.

Risk and Uncertainty[7]

Uncertainty in options models refers to the range of outcomes over which the underlying is likely to vary. The basic metrics of uncertainty is a standard deviation. Reinhardt [Reinhardt, 1997] criticised the real options models valuating R&D as they did not consider that the technological risk of R&D projects is different from the market risk inherent in financial options. Recent research distinguishes between endogenous technical uncertainty and exogenous market uncertainty that together determine the volatility of a project [Huchzermeier and Loch, 2001]. Weeds [Weeds, 1999] for example incorporates technical uncertainty into an options valuation model by allowing cash flows to be realised only after a random event representing discovery or a technological breakthrough.

To measure the risk of an underlying one has to know the volatility of the price movements to determine the volatility of the rate of return. Calculating the volatility of an R&D project is normally quite difficult because most of these projects do not have a historic volatility, as an R&D project is by its nature something new.

- *Historic Volatility*

One solution to derive some sort of historical volatility is to apply past data from the volatility of completed R&D projects to forecast the volatility of a new R&D project. Furthermore, in order to classify the risks belonging to various categories of R&D, time series of R&D intensive companies can be applied.

- *Spanning*

If the methods described above are not suitable for deriving the volatility, the volatility of the duplicated portfolio that has been created through spanning can be used.

- *Risk Premium*

If the methods described above cannot be applied a risk premium has to be chosen—with for example the Capital Asset Pricing Model CAPM (4.2.3.) or the Arbitrage Pricing Model APT (4.2.4.)—reflecting the market price of risk [Hull, 1997]. The risk premium *RP* per period can be derived with the CAPM as follows:

$$\mathrm{RP} \equiv \mathrm{E}(\mathrm{r}_i) - \mathrm{r} = [\mathrm{E}(\mathrm{r}_m) - \mathrm{r}]\beta_i$$

Substituting for β_i and rearranging results in

$$RP \equiv \frac{E(r_m) - r}{\operatorname{var}(r_m)} \operatorname{cov}(r_i, r_m) \tag{4.13}$$

where $[E(r_m) - r]/var(r_m)$ is the market price of risk for the period, representing the premium *i.e.* excess return, per unit if risk in the market [Trigeorgis, 1996].

In financial option pricing theory the risk of the underlying is only exogenous, whereas concerning R&D projects the risk can be partly endogenous because of the risk-averse or risk-friendly decisions of the management. CAPM and APT are only concerned with the degree to

[7] The terms risk and uncertainty in this section follow the use of these terms in the real options literature.

which the expected cash flows of an investment are correlated with the prices of exogenous factors such as securities and traded goods.

The effects of the various kinds of uncertainty on the option value of a project are discussed in section 4.4.3.

Dividend Payments

Dividend expenses are represented by the payments that get lost over the duration of the option. These can either be costs needed to preserve the option, *e.g.* for preventing competitiors from using the opportunity, or cashflows lost to competitors investing in the opportunity. The amount and the frequency of the dividend payments can either be deterministic or stochastic. Furthermore one distinguishes between continuous and discrete dividend payments. If the time, frequency and amount of the cash flows generated by an R&D project are not precisely known, one normally uses a dividend yield that duplicates the dividend payments [Hull, 1997].

Exercise Price

Normally the present value of investment costs and all other fixed costs of R&D represent the exercise price of a real option. If the investment costs of an R&D project are not known in advance, they have to be replicated by a stochastic variable [McDonald and Siegel, 1986].

Riskless Interest Rate

The riskless interest rate is normally known for the period of financial options, but considering the long terms of real options it is rather likely to be unknown, and thus stochastic. In practice, the riskless interest rate is normally derived from government bonds having the same maturity as the option. This approach is based on the concept of creating a replicating portfolio, described in 4.3.1.

Time to Maturity

Other than financial options, R&D projects are usually long-term activities and thus have a long time to maturity. In practice, the expiration date corresponds to the approximated duration of the project. Looking at R&D investment projects, one has to take into account not only the expiration of the embedded options, but also the expiration of the underlying investment project. Because of the long-term maturity of real options it is not unlikely that the project is stopped before the expiration of the real option. This corresponds to the exercising of the option to abandon [Perlitz, Peske and Schrank, 1999]. Other than options on stocks, R&D projects can be stopped at any time. The real options model does not take into account this aspect, because it is assumed that the underlying exists.

In summary, when R&D projects are treated as call options the projects' expected benefits represent the underlying, implementation costs act as the strike price and the implementation date is the expiration date of the option. The total costs of conducting R&D are the acquisition price of the option and the combination of endogenous and exogenous uncertainties create the volatility.

4.4.3. Value of Uncertainty

With the real options approach, a higher level of uncertainty normally increases the value of the option. The higher the uncertainty, the more possible outcomes there are, and the ability to avoid unfavourable circumstances, or to take advantage of favourable opportunities, is more valuable when there are greater prospects of using this flexibility. As the contingent decision-making (theoretically) limits the loss of a bad outcome to the first investment, the only effect of greater uncertainty should be an increasing upside potential. As a consequence, the more uncertain the project's payoff is the more efforts should be made to delay commitments and maintain the flexibility to change the course of action. Thus the potential gains that can be achieved are basically a result from flexibility in the timing of the investment.

In practice, however, more uncertainty may also reduce the value of a project, if for example an alternative project with a lower degree of uncertainty is available. Time is again a critical factor in order to determine if operational uncertainty increases or decreases the option value of managerial flexibility. This value strongly depends on the point in time when uncertainty is resolved. Resolving uncertainties before final decisions are made and, more importantly, investments or revenues are incurred, increases the option value, because flexibility to alter decisions can still be used in order to protect the project from potential losses. On the other hand, if uncertainty is resolved after final decisions were taken or investments were made, the ability to respond to changing situations is reduced and thus the option value of flexibility is reduced as well [Huchzermeier and Loch, 2001].

To find out if higher uncertainty increases or decreases the value of an option, the sources for the project's uncertainty must be investigated separately. Huchzermeier and Loch [Huchzermeier and Loch, 2001] identify five example types of uncertainty surrounding R&D and investigate their influence on the value resulting from managerial flexibility.

Market Payoff Uncertainty

Competitor moves, demographic changes and substitute products are drivers for market uncertainty. Assuming that the project plan is unbiased, *i.e.* that the probability for an upside move is the same as for a downside move, and for an increasing convex, convex-concave or concave payoff function, uncertainty in the market payoff enhances the project's option value because decisions can be delayed in order to be able to react to new market information.

Budget Uncertainty

As the development costs of a project are not completely foreseeable, there is always a certain probability for completing the project with an overrun budget. It is assumed that there is some sort of continuation cost necessary for continuing the project in every period, instead of a single investment at the beginning of the project. The impacts on the value of flexibility are investigated if the continuation cost becomes stochastic:

Two cases must be considered: First, if the project costs in every period are independent of each other, flexibility does not have an impact on the option value of the project. Although the variance of the project payoff increases, the value of flexibility remains unchanged because past variations of the project costs carry no information about the future. Second, if the project costs are correlated over time, for example, a budget overrun in period t makes a budget overrun in period $t+1$ more likely, the costs at a certain point in time carry information about the future and flexibility can be used to improve the expected payoff.

Performance Uncertainty

Performance uncertainty refers to the risk that the targeted performance of a product to be developed cannot be achieved as initially assumed. Performance uncertainty increases with the technical novelty of a product.

Assuming an unbiased project plan, the effects of performance variability on the value of managerial flexibility and thus the option value of the project, depend on the type of the payoff function. If the payoff function is convex-concave higher uncertainty averages out the achievable performance over a wider range. Starting at any current performance state during the project, the reachable performance range is increased by higher performance uncertainty. As a result the expected payoff function flattens out, which is illustrated in Figure 4.3. Furthermore uncertainty about the performance of a product is in most cases resolved in the future after possible decisions have been made. As a consequence the downside protection, which the decision maker can achieve by improving or abandoning the project, is reduced. So in case of a convex-concave payoff function performance uncertainty causes mean reversion, which decreases the payoff variance that enhances the value of flexibility.

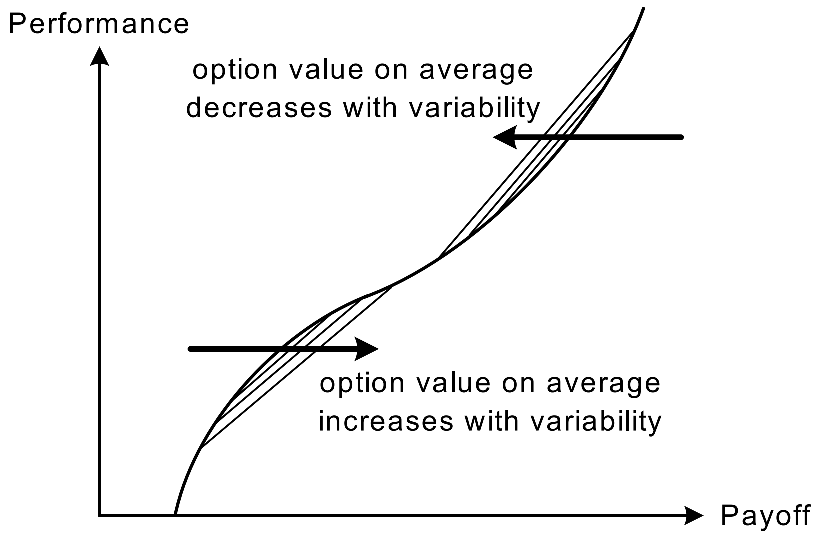


Figure 4.3: "Effect of Higher Performance Uncertainty" —Source: [Huchzermeier and Loch, 2001]

In case the payoff function is linear, mean reversion does not occur, and thus performance variability does not affect the option value.

Market Requirements Uncertainty

Uncertainty concerning the requirements of the market comprises changing customer requirements and uncertainty about the performance level required by the market. Especially for conceptually new products it is difficult to estimate the performance targets.

Variability of market requirements can only influence the option value if it is combined with a corresponding increase in the payoff variability. Otherwise, according to [Huchzermeier and Loch, 2001], "parts of the probability mass escape beyond the performance range in reach of the development project". This can be compared to an investment in a flexible production facility with a capacity limit. Increasing variability in demand resulting in an upside potential has no positive effect if the capacity limit has already been reached.

Again, as the uncertainty concerning market requirements is usually resolved after all decisions have been made, the added value gained through the option is lost.

Schedule Uncertainty

Schedule uncertainty refers to a project being finished behind or ahead of schedule.

Assuming that the expected market payoff depends on the time-to-market, a delay in the launch of the product reduces the payoff value, which is consistent with empirical results [Datar et al., 1997]. Suppose a project suffers from a critical delay during the research phase, management might decide to abandon the project (exercising an abandonment option) before the launch costs are incurred. Schedule uncertainty may reduce the probability of flexibility ever being exercised, which also reduces its expected value.

4.5. Option Pricing and Decision Tree Analysis

As already mentioned in the introduction to this chapter, it is often argued that the NPV approach does not account for managerial flexibility, and thus favours short-term projects with low risk at the expense of long-term projects that can be revised over time in response to gaining knowledge or changing requirements.

The reason for this is that standard NPV ignores the value of the ability to make future decisions. As will be shown later, a combination of the NPV evaluation method with decision tree analysis is capable of incorporating the value of flexibility into the NPV evaluation.

Using decision trees in order to find the alternative, that maximises the expected NPV, comprises the difficulty of finding an appropriate discount rate. As explained in 4.2. this might not be easy, but is not the only problem when using the NPV approach.

Trigeorgis [Trigeorgis, 1996] argues that there are the following limitations when evaluating a project using the decision tree approach:

Decision trees can quickly become unmanageable, as they grow exponentially with the number of decisions, outcome variables or states for the variables. Furthermore, discrete chance events are assumed and in reality the resolution of uncertainty is a continuous process[8].

As already explained in 4.2. an appropriate discount rate has to be found, because using a constant discount rate implies that the risk is constant in every period, and that uncertainty is resolved continuously at a constant rate over time. Under the assumption of discrete chance events, at least different discount rates should be used for the various stages of the project. The possibility to abandon the project, for example, reduces the project's risk and thus the discount rate should be lower. The use of a higher risk-adjusted discount rate for the project without the option to abandon would undervalue the project as the risk is reduced as soon as the possibility for abandonment is given. Trigeorgis argues further that expected utility maximisation could be used in order to avoid the presented problem, but according to Trigeorgis determing the appropriate utility is not easier.

[8] Following the view that uncertainty can also be resolved discontinuously, *e.g.* by sudden breakthroughs in research, jump processes can be used to model this behaviour of R&D projects, refer to [Pennings and Lint, 1997].

The following example will demonstrate how the options' value of flexibility can be included into the evaluation of a decision tree with an extended NPV approach:

Consider the example that management takes the decision to abandon a project that has already been started if its abandonment or net salvage value exceeds the NPV of all expected subsequent cash flows. Thus in reality, any operating decisions taken at the beginning of the project and based on the information available at the time of the first decision, and future decisions may be revised later as uncertainty is resolved through new information. Trigeorgis shows that, when evaluating a decision tree with the NPV approach, this flexibility and the according value of the project can be incorporated into the valuation.

The resulting expanded expected NPV is given by:

$$\text{Expanded expected NPV} = \text{Static expected NPV} + \text{Total abandonment value}$$

where the *total abandonment value* is the present value of the flexibility to abandon, which is the difference between the expected present value *including* the possibility to abandon, and the expected present value *without* the possibility to abandon. If the possibility to abandon exists in some or all years of the project's life, then the optimal year for abandonment is the year in which the expanded NPV is maximised.

Decision tree analysis, which is well suited for analysing a sequence of decisions, can be extended to incorporate the flexibility to abandon a project at certain discrete pre-specified points in time, based on the expected cash flows with their associated probabilistic estimates that have been quantified at the time of the initial decision.

The following decision tree is an extension to the tree in Figure 3.1, including a new decision node for the option to abandon the project for salvage, if the market acceptance turns out to be low.

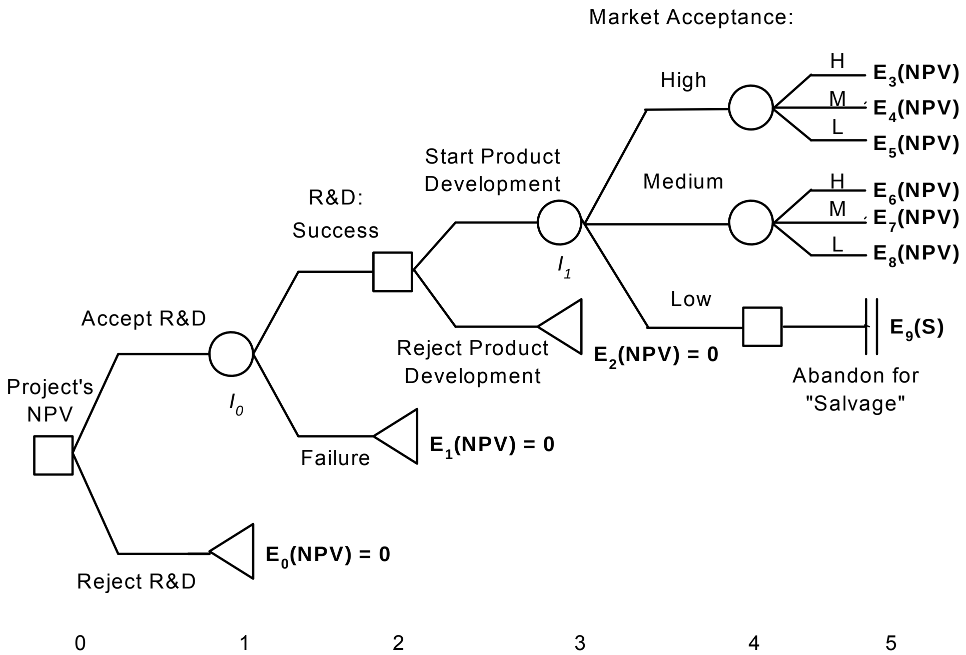


Figure 4.4: "Decision Tree Including the Option to Abandon"

The abandonment value in the example tree is given by the difference of the expected present value of period 4 using the possibility to abandon the project for salvage and thus getting the salvage value instead of the expected NPV of the branch with the probability that market acceptance turns out to be low and the original expected present value of subsequent cash flows of period 4 including the expected NPV of the low branch. This difference times the probability that R&D will be successful and discounting back is referred to as the abandonment value.

In a generalised way, including various kinds of options, standard NPV can be extended to the so-called expanded strategic NPV given by:

$$\text{Expanded Strategic NPV} = \text{Standard NPV} + \text{Option Premium}$$

where the option premium includes the value of operating and strategic options from active management and interaction effects of competition, synergy and inter-project dependence. Thus, theoretically, all kinds of options could be included into an NPV evaluation with the help of decision trees. By doing so, one can solve the problem of undervaluing a project using standard NPV.

Nevertheless, it is argued, in [Trigeorgis, 1996], that the project is still not correctly valued, because the same discount rate is used as if the option did not exist. As the option adds protection from downside effects to the project evaluation, for example through the option to abandon, usage of the riskless rate and risk-neutral probabilities is suggested for the expanded NPV valuation, based on the idea that a replicating portfolio can be created with the same value as the option. Contingent Claims Analysis (CCA), which can be regarded as the application of the replication methodology used in option pricing to the valuation of other assets [Merton, 1973] is operationally identical to decision tree analysis, but the probabilities are transformed in order to allow the use of a risk-free discount rate. The risk-neutral probability p of S increasing to S_u is given by:

$$p = \frac{(1+r)-d}{u-d} \tag{4.14}$$

and can be derived as follows:

If the stock moves up the return is $S_u/S\text{-}1$ with S being the initial stock price and similar if the stock moves down the return is $S_d/S\text{-}1$. As in a risk-neutral world the expected return on the stock must equal the riskless interest rate r the following condition holds:

$$p\ (S_u/S\text{-}1) + (1\text{-}p)\ (S_d/S\text{-}1) = r$$

Denoting S_u/S by u and S_d/S by d yields to

$$p\ (u\text{-}1) + (1\text{-}p)\ (d\text{-}1) = r$$

Solving for p results in equation 4.14. The results are now independent of the "real" probability, earlier denoted by q in 4.3.1. and depend instead only on this "fictious" new probability, p, the risk-neutral or risk-adjusted probability [Bingham and Kiesel, 1998].

Using the original discount rate or the original probabilities would lead to an incorrect valuation of the project, which can be shown by referring to the replication, arbitrage-free argument, as introduced in 4.3.1. In order to eliminate the possibility of riskless arbitrage, profit opportunities of the value of the opportunity to invest in a project must be the ones given by the CCA method. CCA, which takes into account open market opportunities of buying, selling, borrowing and lending, can be used for an economically corrected version of conventional decision tree analysis [Trigeorgis, 1996].

In summary, the expanded expected NPV solves the discount rate problem by relying on the notion of a comparable security to properly price risk, while still being able to capture the dynamic interrelations between cash flows and future optimal decision through the decision tree model.

The option premium and thus the value of managerial flexibility is characterised as follows, refer to [Trigeorgis, 1996] and [Faulkner, 1996]:

It is higher if the environment is more uncertain, because the decision maker can benefit from the asymmetry that is introduced by the option. By holding an option, one has got the right to benefit from any potential increases in the value of the asset. On the other hand there is no symmetric obligation to exercise the option if the value of the asset moves down.

The option premium is also higher if the availability of future information that will resolve some of the uncertainties surrounding the project can be anticipated.

It can be higher if the real interest rates are high, because *ceteris paribus* and in the case of no dividends paid by the project (*i.e.* no intermediate cash flows) the present value of the future investment for exercising the option is reduced as the interest rate increases and thus the value of the option increases.

The option premium can be higher for long-term investments or for investments that can be delayed longer. Again, in the case of no dividends, as the time to expiration increases, the total uncertainty of the asset's value will increase, which increases the value of the option and furthermore the present value of the investment or exercise cost will decrease. If the project pays dividends then a longer time to expiration can decrease the value of the option, as dividend payments are payments lost through waiting to invest and with a longer time to expiration, the present value of the dividends lost for the owner of a call option gets higher.

The value of the option premium increases if the exercise price of the project or the future commercialisation investment is high, compared to the initial R&D investment.

Of course, these characteristics do not only apply to the option premium that is used for the expanded expected net present value, but to the value of real options in general.

Standard NPV evaluation of a project does not take into account interactions, synergies and parallels between projects. Using NPV in combination with decision trees and extending the valuation approach by incorporating flexibility can incorporate interactions among projects. As decision tree analysis is perfectly well suited to represent a series of decisions, and thus various stages of one project, it can also be used in order to evaluate a series of interrelated projects, such as compound options.

4.5.1. Comparison of the Results – Certainty

First it will be shown that under certainty standard NPV, decision tree analysis and option pricing yield exactly the same results.

Consider a project that involves taking a decision concerning the implementation in period $t+1$. There is no uncertainty about the future price of an asset that drives the project revenues. Referring to [Neely, 1998] the NPV of the project is given by:

$$NPV = \frac{E(S) - K}{R} - I \tag{4.15}$$

where $E(S)$ is the expected value of revenues, which is known with certainty. K are the costs necessary for implementing the results of the project, and I are the initial R&D costs. R refers to 1 plus the risk-adjusted discount rate.

A decision tree with two branches avoiding implementation of the low outcome, S_d, is given by:

$$DTA = \frac{p(S_u - K)}{R} - I \tag{4.16}$$

where p is the probability for the high outcome S_u. The loss avoided would be given by $\frac{(1-p)(S_d - K)}{R}$, but in case of certainty the probability p for S_u is 1 and thus $E(S)$ is S_u. Therefore decision tree analysis yields the same result as NPV.

Using a Binomial model the value of the project can be described by:

$$C = \frac{[pC_u + p'C_d]}{r} \tag{4.17}$$

where: $C_u = Max[0, S_u - K]$ = value of the call option if the stock moves up

$C_d = Max[0, S_d - K]$ = value of the call option if the stock moves down

p is the risk-neutral probability of S increasing to S_u, p' is $(1-p)$, and r is 1 plus the risk-free interest rate

In the certainty case, $S_u = S_d = rS$. Furthermore $p + p' = 1$ and thus the value of the project is given by:

$$C = \frac{[(p + p') \cdot C_u]}{r} = \frac{C_u}{r} = \frac{rS - K}{r}$$

As $rS=E(S)$ and $R=r$ for revenues under certainty, the results of the three models are consistent, assuming certainty and taking initial R&D costs into account.

$$C = \frac{E(S) - K}{R} - I \tag{4.18}$$

4.5.2. Comparison of the Results - Uncertainty

Smith and Nau show in [Smith and Nau, 1995] that decision tree analysis and real options yield exactly the same results for the valuation of a simple discrete time, two-period capital budgeting problem.

This example consists of an investment opportunity that in period $t+1$ will generate an uncertain payoff represented by a "good" and a "bad" state, which are believed to be equally likely. Furthermore there is an option to defer the investment for 1 period until the state is known. This option can be obtained by buying a one-year license for a price to be negotiated. If this option is chosen, the investment can be made in period $t+1$ for the investment cost of period t growing at the riskless interest rate, or the option expires. It is also assumed that there are two securities: a risk-free security that allows for borrowing and lending at the risk-free rate, and a twin-security that generates values depending on the uncertain states of the future.

These are the summarised results of the model:

When markets are complete (*i.e.* one can construct a portfolio whose payoffs exactly replicate the payoffs of the project and all project risks can thus be perfectly hedged by trading securities) and the real options model provides a unique project value and an optimal strategy, the same results will be provided by decision tree analysis, if market opportunities are included in the model and if time and risk preferences are calculated by a utility function, instead of using a single risk-adjusted discount rate.

When markets are incomplete and the real option method provides upper and lower bounds for the project value and a set of potentially optimal strategies, decision tree analysis will yield a solution between these bounds and an optimal strategy that is a member of the potentially optimal set of strategies.

Ad 1) Complete Markets

The two existing securities assumed in the model make the markets complete. Given the two possible states of the future and two linearly independent securities, a linear combination of the payoffs of these securities can represent the payoffs of every risky cash flow.

Smith and Nau [Smith and Nau, 1995] distinguish between three valuation methods. What they call naïve decision tree analysis, option pricing analysis and full decision tree analysis. The assumptions underlying each of the methods and the according results are summarised in the following:

- *Naïve Decision Tree Analysis*

The naïve decision tree analysis corresponds to evaluating a decision tree using a standard NPV approach, defining the value of a project as the future expected cash flows discounted at the rate that reflects the riskiness of the cash flow [Copeland, Koller and Murrin, 1990], with the discount rate defined as the equilibrium expected rate of return on securities equivalent in risk to the project being valued [Myers, 1984]. The discount rate acquired by determining the market-required rate of return for the twin security is used to calculate the expected NPV. The value for the alternative to defer the investment is calculated, and then a decision is taken which discount rate to use. Using the same discount rate as determined for the twin security is obviously not the right approach, as the value of the option to defer the investment is not at all correlated to the twin-security. However, Copeland, Koller and Murrin suggest to "use it anyway" [Copeland, Koller and Murrin, 1990].

Including the value of the option into the valuation of the decision tree suggests that if the cost of the license is less than the expected NPV given by naïve decision tree analysis, the optimal strategy is to use the option and to defer the decision whether to invest or not to period $t+1$.

- *Option Pricing Analysis*

Following the concepts of option pricing described in 4.3.1. instead of defining one security that is equally risky as the project, a replicating portfolio of securities has to be created, representing the value of the project. For the example, such a replicating portfolio can easily be constructed by buying a number of shares of the twin security and thus determining the option pricing value of the alternative to invest now—which in the example given is exactly the same as the naïve NPV of the project without the option to defer. Again constructing a replicating portfolio for determining the payoffs of the project and the portfolio for the good and bad states of the future yields the option value of the defer alternative, which in this case is less than the value suggested by naïve decision tree analysis. Using the replicating portfolio in order to find the right answer, one could argue in favour of the option pricing model that if it is possible to obtain a portfolio of securities having the same payoffs as the defer alternative one would not pay more for the license. The reason for the different result given by naïve decision tree analysis is obviously the use of a discount rate that was based on a security not related to the option to defer.

Using risk-neutral probabilities in the decision tree, and then computing NPVs for all cash flows, discounting with the risk-free rate gives exactly the same results for the "invest now" alternative and the "option to defer" alternative, as suggested by the option model based on the explicitly created replicating portfolio.

- *Full Decision Tree Analysis*

Traditional decision analysis uses a decision maker's subjective probabilities and utility function in order to represent time and risk preferences. The value of a project has got no relation to the value of a replicating portfolio, but is often subjectively defined as the project's breakeven buying or selling price. The breakeven buying price is known as the lump-sum payment in period 0, equalling the maximum expected utility of the project, and the maximum expected utility without the project. In order to include market opportunities to trade into decision analysis, the decision maker can buy or sell shares of the risk-free and the twin-security. Using a strictly concave utility function, although the authors argue that their results hold for arbitrary utility functions, and defining the values of the invest now and the defer alternative as the breakeven buying price, the price at which the decision maker is indifferent between investing in the project and declining, decision tree analysis gives exactly the same results as the option pricing model for the values of the invest now and defer alternatives.

Smith and Nau [Smith and Nau, 1995] confirm that the consistent results given by decision tree analysis and the option model are valid in general and not limited to the restrictions given by the model used as an example[9]. Under the assumption of a complete market, it is possible to construct a replicating portfolio for the payoffs of the project. The project is obviously unattractive if it costs more than the portfolio; if it costs less than the portfolio, it is attractive. The decision maker could invest in the project and sell the replicating portfolio and make a certain profit. Therefore, similar to the no arbitrage argument, the breakeven buying or selling price must be equal to the value of the replicating portfolio, which is equal to the value given by option pricing.

Even though the results of the decision tree approach and option pricing are consistent, when incorporating market opportunities into decision analysis process, the required inputs and the outputs are quite different. State-contingent cash-flows and securities for all times and all possible project management strategies must be defined for both models. Decision analysis additionally requires specifying probabilities and a utility function for the preferred cash flows over time, but it also provides an additional output: the optimal investment strategy.

Ad 2) Incomplete Markets

In the case of incomplete markets one has to distinguish between exogenous uncertainties resulting from the market, and endogenous uncertainties stemming from the project. The latter cannot be hedged, whereas market uncertainties can be perfectly hedged by trading securities. Thus the market is partially complete, *i.e.* complete with respect to market uncertainties. This means that security prices only depend on the market states, and implies that risk-neutral probabilities can be assigned to the market states.

[9] Faulkner [Faulkner, 1996] discusses that binomial lattices can be regarded as decision trees, which implies the consistency of the results of the methodologies. Amram and Kulatilaka [Amram and Kulatilaka, 1999] and Copeland, Koller and Murrin [Copeland, Koller and Murrin, 1990] calculate options to abandon and modify by using decision trees. This implies that some authors view traditional decision tree analysis as options pricing and just use a new name and terminology.

The evaluation method suggested by Smith and Nau [Smith and Nau, 1995] is to decompose project cash flows into market and private components, and to use market information to value the market risks, while using subjective estimates and preferences to value the project risks. Private risks are substituted by certainty equivalents 4.2.1. through certainty-equivalent replicating strategies matching the project's effective certainty equivalent for each state of the market. Thus the setting under partially complete markets is transformed into an equivalent setting where markets are complete. Furthermore, additive independence is assumed for the decision maker's preferences concerning risky cash flows. If the decision maker is indifferent between receiving a certain amount in period *t*, and a period-*t* gamble, he is also indifferent between receiving a certain amount plus Δ and the period-*t* gamble plus Δ, for any constant Δ.

The decision tree is then evaluated by calculating the net present values for all endpoints, discounting at the risk-free rate. Risk-neutral probabilities are used for market uncertainties and the decision maker's subjective probabilities are used for project specific uncertainties.

The result for the current market value of the certainty equivalent replicating portfolio, thus also the value of the project, matches exactly the breakeven buying price found when applying full decision tree analysis under the assumption of complete markets. The results also hold when including the option to defer the investment into the valuation. Smith and Nau [Smith and Nau, 1995] prove that their results hold in general.

The integrated valuation procedure described above was applied to the valuation and management of oil properties [Smith and McCardle, 1998], demonstrating that the approach can also be used in continuous time models.

A similar approach for an R&D project evaluation procedure, integrating decision tree analysis and option pricing, is proposed by Neely [Neely, 1998]—refer also to 3.2.5—and by Perdue et al. [Perdue et al., 1999].

4.5.3. Summary and Discussion

This section gives a summary of the main assumptions made by option pricing valuation models and in which ways these assumptions can be fulfilled when applying option pricing to real options. It is also discussed how the concepts underlying traditional option pricing methods could be changed or extended in order to make the models applicable and more realistic for the characteristics of R&D projects. Furthermore, a comparison of the assumptions and concepts of option valuation and decision tree analysis is given.

Traded Versus Non-Traded Assets

As Smith and McCardle [Smith and McCardle, 1998] point out, decision analysis models rarely take into account market opportunities to hedge project risks by trading securities, but they could do so by using integrated procedures, as described in the previous sections. Applying option pricing models to project evaluation assumes that one finds a portfolio that exactly replicates the project cash flows, and in many cases it seems unrealistic to take for granted that project specific uncertainties can be hedged by trading securities.

Thus the question remaining is whether option-pricing techniques based on the no-arbitrage equilibrium condition and using portfolios of traded securities to replicate the option's payoff can be applied to projects that are not traded. The argument of Mason and Merton [Mason and Merton, 1985] is that, given the assumptions made by traditional discounted cash flow approaches hold—namely defining a traded twin-security for every project that has got the same risk characteristics as the project—it is possible to replicate the returns to a real option by purchasing a certain number of shares of the twin-security and partly financing this investment by borrowing at the riskless interest rate. Fulfilling the no-arbitrage condition for non-traded assets the equilibrium value of an option must be equal to the no-arbitrage value of the option on its traded twin-security [Trigeorgis, 1996].

However, this assumes that the underlying asset is traded in equilibrium, which is often not the case for real options. Non-traded real assets may earn a return below the equilibrium rate of return for comparable traded securities. Nevertheless, risk-neutral valuation can be applied by replacing the actual growth rate, a, of a standard Wiener process by a risk-neutral growth rate, $\acute{a}$, after having subtracted an appropriate risk-premium, RP. Thus $\acute{a} = a - RP$ and the risk premium of an asset i is given by $RP_i = ([E(r_m) - r]/var(r_m))\sigma_i$, with $[E(r_m) - r]/var(r_m)$ being the market price of risk for asset i as defined in equation 4.13, times its volatility, σ_i. For a non-traded asset the market price of risk would be equal to the market price of risk of an equivalent traded financial security whose price depends on that asset and time alone [Kulatilaka, 1993].

Relation of Decisions to Time

When using option pricing models the order of decisions or events does not matter. Thinking of the Brownian Motions that are used in order to model the behaviour of stock price movements, it does not make any difference if the prices move up and then down or the other way round, in both cases the result is the same node. Using the same argument for the continuous Black-Scholes formula, Faulkner [Faulkner, 1996] states that describing future uncertainty by a log-normal distribution can be a reasonable assumption for describing the volatility of stock prices, but it may not always be appropriate for describing the uncertainty inherent to the outcomes of R&D activities.

Thus when interpreting standard option pricing models for R&D projects, decisions or events are assumed to be reversible: ups and downs are the inverse of each other. The historic volatility is extrapolated into the future. Thus the volatility is scalar and does not take recent up and down trends into account.

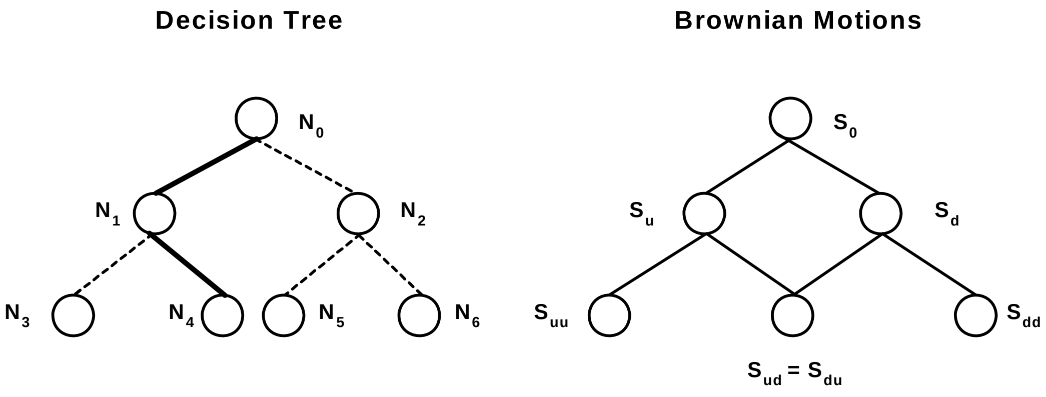


Figure 4.5: "Propagation of Decisions or Events"

Figure 4.5 shows that when ending up at N_4, in the decision tree one knows exactly the path that leads the decision maker to that point (represented by the thick line), whereas for the Brownian Motions—represented by an acyclic directed graph—going down and up leads to the same point as going up and down in the graph. Note that N_4 and N_5 in the decision tree can incidentally get the same values during the evaluation, but will usually yield different results. For the Brownian Motions on the other hand, S_{ud} always exactly equals S_{du}. Whether a certain state can be reached or not in a decision tree depends on the history and thus on the path.

Path dependency, introduced by Arthur [Arthur, 1988] and David [David, 1985], is a characteristic of non-ergodic stochastic processes, whose asymptotic distribution evolves as a consequence the process's own history. Ergodic processes on the other hand evolve independently of their past states. Economic processes are, according to Arthur and David, typically non-ergodic. Hence, path-dependency is a fundamental concept in evolutionary economics [Nelson and Winter, 1982]. Originally the concept of path dependency was used to show that through minor, maybe accidental or random events, a system can converge—through self-reinforcing mechanisms—towards multiple and even sub-optimal equilibria, refer to [David, 1985] and [Arthur, 1988]. Their theory contrasted the traditional view that market forces spontaneously reach a single efficient equilibrium. Arthur and David demonstrated that sub-optimal, inefficient technologies can become locked in as standards. Increasing returns through self-reinforcement are often the result of random events, which may lead to a lower-quality product dominating the market or less-efficient companies gaining a monopoly position. Network effects, referring to the effects of previous adopters` choices among competing technologies on the choices of further consumers, can cause the prevailing of these inefficient technologies for a long time. Standardisation, technology interrelatedness and economies of scale and scope are reasons for the lock in of a technology into a market [David and Foray, 1994]. The choices of decision makers are also restricted by past choices, due to bounded rationality. As a new situation is always perceived in association with similar other past situations [Hayek, 1952], the individual knowledge used by decision makers is strongly related to their past experience. Path dependency in the context of decision making thus implies that every decision taken depends on the previously covered path.

Brownian motions can be regarded as ergodic, as the same state can be reached in various ways independently of the path. Using decision trees on the other hand a state resulting from a decision taken can be irreversible, meaning that it is impossible to reach another branch of the tree from the current state. Decision trees can thus be path dependent, whereas real options are based on the assumption of path-independency. In this respect path dependency is the more general assumption, as the real options approach can be modelled using decision trees but not the other way round.

Proprietary Versus Shared Options

Considering a standard call option the owner of the option has got the exclusive right when to exercise, or if to exercise at all. There is no kind of competition concerning the underlying investment and the option is proprietary. When looking at real options, some of them are proprietary, for example a patent for the development of some product. On the other hand, there are also shared real options, which are held by a number of competitors. Being collective opportunities of a whole industry sector, these kinds of real options can be exercised by any of the competitors, because the products to be developed are not protected against substitutes or there are no barriers to entry for a new market.

Competition

Broadly there are two kinds of strategic interactions between competitors: first mover advantages, *e.g.* patent races or entry into a natural monopoly industry, and second mover advantages, which occur whenever the second mover can benefit from spillovers of the first mover's investment.

It has turned out that one of the main characteristics of innovative, technologically complex products is that there are numerous difficulties in their early stages that often take a long time to adjust. This clearly is a drawback for the first mover on the market, whereas the fastest imitator, who learns from the mistakes of the pioneer, may end up being the market-leader [Kline and Rosenberg, 1986].

Facing first mover advantages each company anticipates an advantage by investing first, which gives rise to pre-emption. Thus there is no possibility to delay and the value of the option to wait is eliminated. Taking game theory into account however, each company must in addition to the other companies´ actions also take into account the others´ reactions to its own action. In case of a patent race investment by the leader increases the speed of investment of the followers which makes their chances for getting the patent approximately equal. Anticipating the followers´ behaviour might cause the leader to delay investment. Thus, even if there are first mover advantages the option to delay can remain valuable.

One reason for second mover advantages is the uncertainty concerning the demand of a new technology, service or product. The leader will reveal the true state of demand, whereas the follower, while waiting, can learn from the leader and enter the market only if it is profitable. Second mover advantages can also be caused by spillovers of information. In the presence of information spillovers the follower is usually the one who benefits. In case of continuous research it may however be possible that the leader benefits again from the knowledge generated by the follower.

One of the crucial questions therefore is if decisions can be delayed when undertaking an R&D project, *i.e.* exercising the option to wait until uncertainty will be resolved. Taking competition into account can thus attach significant costs or losses to delays, refer to [McDonald and Siegel, 1986], [Trigeorgis, 1991], [Trigeorgis, 1996], [Urban et. al., 1986] and [Kulatilaka and Perotti, 1998].

However, traditional real options models as well as decision analysis assume one decision maker to play against nature and do not take the strategic interactions in the presence of competitors into account. The broad concept of game theory models the strategic interactions among agents and thus decision analysis is just a special case of game theory.

Taking competitive actions into account, the main issue is the timing of the investment. Standard option models assume the timing of exercising the option to be simultaneous and agents are supposed to have perfect information about the parameters of the option [Grenadier, 1999]. Game theoretic approaches to the timing of irreversible investments under imperfect information constitute the background for the combination of game theory and real options. Such a game theoretic basis is *e.g.* presented by [Reinganum, 1981], [Fudenberg et al., 1983], [Gilbert and Harris, 1984], [Fudenberg and Tirole, 1985] and [Fudenberg and Tirole, 1986]. The market for most kinds of research is characterised by a relatively small number of competing institutions. Combining game theoretic models with real options analysis has recently turned out to be a promising approach to endogenize competitive reactions in such oligipolistic settings, refer *e.g.* to [Grenadier, 2000a]. A collection of relevant papers can be found in [Grenadier, 2000b].

Weeds [Weeds, 2002] develops a leader-follower game in continuous time, assuming full information, where the competitors invest at strategically chosen trigger points. The assumption of complete information is relaxed by Lambrecht and Perraudin [Lambrecht and Perraudin, 2003], who present an equilibrium model in which groups of companies invest strategically. Hoppe studies second mover advantages in a timing game of technology adoption facing an uncertain environment [Hoppe, 2000].

To provide an example of some of the many insights that can be gained by applying game theoretic aspects to real options analysis, the model of information revelation through option exercise by Grenadier [Grenadier, 1999] is in the following presented in greater detail. Grenadier develops a model for option exercise games with asymmetric private information, where the agents may infer the private signals of the other agents by observing their exercise strategies.

The *n* agents in Grenadier´s model hold options on a continuous time stochastic price process. Each agent has got private information about a parameter affecting the payoff of the option and can exercise at any time. The agents are not completely certain about the payoff upon exercise. Each agent has got an independent signal of the true realised payoff from exercising. The precision of the agents´ signals to estimate the uncertainty surrounding the option´s payoff differs among agents. The agents have to find the optimal time for exercising the option by observing their own signals as well as the signals of the other agents, which are revealed through their exercise strategies. This allows for the agents to update their information and learn. Information is thus revealed only through actions, as communicated information might be intentionally misleading. Having only incomplete information enhances the value of waiting for more information to be revealed.

While in case of perfect information all agents exercise simultaneously the exercise in equilibrium under imperfect information is sequential. The most informed agent reveals their information first and allows the less informed to free ride on the information revealed by their exercise strategy. If the signal of the most informed agent is positive the expected value of exercising exceeds the value of waiting and learning from the other agents. In case the most informed agent´s signal is negative no early exercise will occur and the agent will prefer to wait and copy the next exercising agent´s behaviour. Thus the most informed agent´s signal is fully revealed by early or late exercise. Now the agents will wait for the second most informed agent to reveal information.

In case of an informational cascade, when the agents imitate the strategies of the other agents and ignore their own information, the exercising of agents does not convey any information any more. An informational cascade is triggered by two consecutive agents revealing positive singnals. The other agents observe the behaviour of the better informed agents and will thus exercise independently of their own private information.

The model can be extended by assuming that the actions of other agents not only influence the information revealed but also the payoff from the option. Such payoff externalities can *e.g.* occur in markets where the benefits from adopting a new technology increase with the number of adopters. Thus the payoff from exercising is increased by an additional payoff when two or more options are exercised. If the most informed agent reveals a positive signal and in case of a large additional payoff, the second most informed agent will exercise immediately ignoring the private signal. Thus an informational cascade can occur even after the revelation of only one positive signal. In case of negative exercise externalities the opposite effect occurs. Agents may never choose to exercise simultaneously but respond to the exercising of a previous agent by waiting. Informational cascades are eliminated as the agents´exercise strategies reveal their full information.

European Versus American Options

Modelling an R&D project as a European call option implies that as long as the project has not been finished, no benefits can be enjoyed from the results of the project. Taking competition into account, the model of Europen options is realistic when waiting to introduce the outcome of R&D to the market would lead to a loss of first-mover advantages [Lint and Pennings, 1998]. Using American options instead of European would suggest that one could benefit from the results of the project before it is finished, the moment the project looks very promising or as soon as the project value reaches a certain threshold [McDonald and Siegel, 1986]. An American option on market introduction is suitable when waiting and learning from potential mistakes of the first-mover at the market is reasonable [Lieberman and Montgomery, 1988]. Similarly Smit and Ankum [Smit and Ankum, 1993] find that it is adviseable to invest early under competition and to postpone the investment in a monopoly setting, assuming that no coordination between the competitors is possible.

Time Intervals Between Decisions

Decision trees, as well as the Binomial model, assume that decisions are taken at discrete points in time. The transition from the binomial distribution to the log-normal distribution introduces the possibility of continuous decision taking and causes a discretisation error. For R&D projects it seems more realistic to assume that decisions are taken at discrete points in time, especially thinking of monthly or quarterly project reviews, where the results of a project are presented and based on these results a decision is taken, on what way the project should be continued.

Figure 4.6 shows that a decision tree models the decisions to be taken and events to occur in the future, whereas real options extrapolate the trends of the past into the future. Both models can be repeatedly evaluated as new information becomes available.

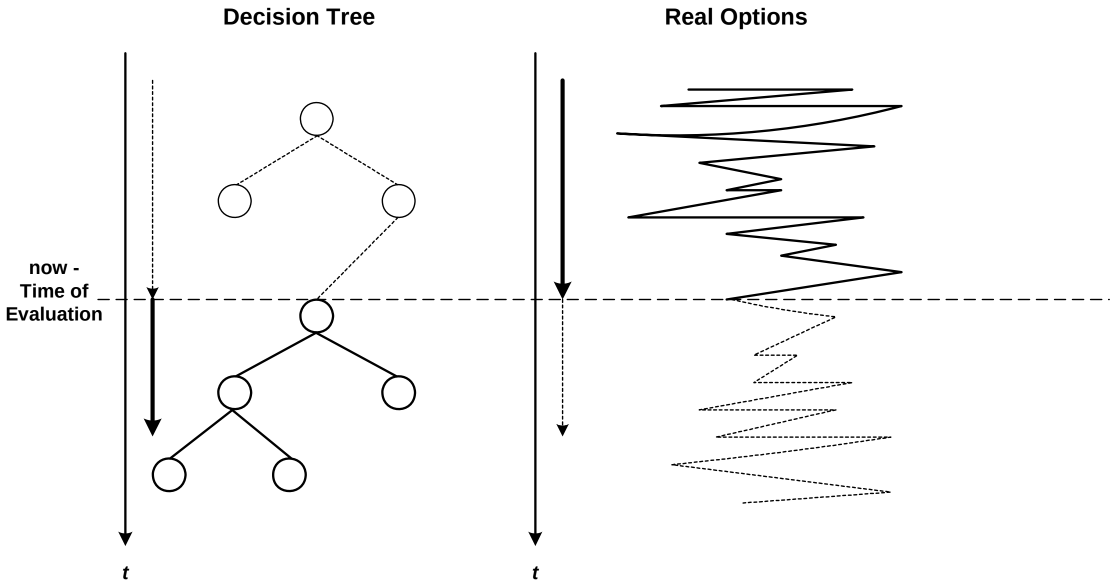


Figure 4.6: "Life Cycle of Decision Tree and Real Option Models"

Project Interrelations

In order to model dependencies between projects, or interrelations between various stages of one project, the option pricing model has to be extended by compound options and the according valuation procedure, refer to 4.4.1.

Decision tree analysis allows for an arbitrarily detailed mapping of project structures, and thus dependencies, to the decision tree. Decision trees are therefore more flexible and can be adapted to the individual project structure. However, with the level of detail the complexity of the model and also of the valuation increases. Furthermore the according input parameters have to be found, and this gets more complicated as the model's level of detail increases.

4.5.4. Conclusions

The common aim of real options theory and decision analysis is the modelling of (investment) decisions under uncertainty.

The advantages of modelling R&D investment possibilities with real options are usually highlighted by comparing the real options approach with decision tree analysis. However, it is assumed that the decision trees are evaluated using discounted cash flow techniques and in most cases the net present value of the project is calculated. Thus the comparison between real options and decision tree analysis is referred to comparing the assumptions made by, as well as the modelling options given by real options with the assumptions and results of discounted cash flow models, with all the according benefits and shortcomings, similarities and differences that were discussed in this chapter (4.5.).

A comparison of real options and decision tree analysis, independently of the calculation method that is used to evaluate the decision tree, shows the following differences concerning the structure of the two models:

Decision trees support models with arbitrarily detailed granularity, while the real options approach regards the project as an atomic entity. As a consequence, the detailed modelling using decision trees with n levels of decisions implies an exponential number of 2^n alternative paths. This results in a complexity of order $O(2^n)$. Due to the fact that the underlying projects for the evaluation with real options are regarded as being atomic, the complexity of the real options model is constant—or of order $O(1)$.

Dependencies between projects can easily be modelled with decision trees. Even the special case of one project being a precondition for another project can be handled. Modelling dependencies between projects with the real options approach is restricted to special kinds of options, such as compound options.

A fundamental difference between decision trees and real options is the way the models take the decision process into account. Decision trees mirror the history of the decision process in every path from the root of the decision tree to a specific node. In contrast, real options represent a snapshot at a specific point in time. The history of the decision process is only taken into account by the volatility of the stock prices. Even the order of the stock prices with regard to the time scale is irrelevant.

	Decision Trees	**Real Options**
Complexity	exponential order of magnitude: $O(2^n)$	constant order of magnitude: $O(1)$
Granularity	arbitrary	projects are regarded as atomic
Dependencies	included	restricted to specific kinds of options
History	represented by path	restricted to volatility

Table 4.4: "Comparison of Concepts"

The underlying concept of real options theory that flexibility creates value is appealing. Options are inherent in a project whenever the investment decision is characterised by an irreversible initial investment, high uncertainty about the future benefits and information arrival during the project. The following kinds of options support the modeling of managerial flexibility:

- The option to wait, to stage an investment or to shelve an R&D project allow for learning. Based on the uncertainty resolved and the insights gained, the option for corrective action can be exercised.
- The options to abandon or shut down are supposed to prevent from negative developments.
- The options to expand, innovate or accelerate an R&D project are used to benefit from new business opportunities.

Even though the analogy between various kinds of options and the opportunities of how and when to use the results of an R&D project seems intuitive, finding the necessary input parameters to finally calculate the option value is often not straightforward, as discussed in this chapter (4.4.2.). Consequently there are two streams in real options literature. One that highlights the insights gained by options thinking and stresses the importance of identifying options inherent in investment opportunities—refer *e.g.* to [Faulkner, 1996]—and the other that provides a variety of models in order to quantify the option value of real projects. Approaches to simplify the calculation by integrating the additional value gained by the option into classical methods are *e.g.* provided by Trigeorgis [Trigeorgis, 1996] or Luehrman [Luehrman, 1998a].

Some of the assumptions made by options theory are unrealistic for real projects. Real options theory, originated from corporate finance, values an asset according to the value the asset would have if it was traded at the market. Consequently it is assumed that the underlying is traded, which allows for creating a hedge portfolio and thus using risk-neutral valuation. However, most project evaluation techniques are based on similar or other assumptions which do not strictly conform to reality either, such as the assumption of complete markets. Decision analysis calculates the benefits resulting from a project according to the preferences, beliefs and resulting possibilities of a decision maker. Decision analysis has long been critised for not incorporating the market´s perspective into the risk-adjustment of the resulting values, refer *e.g.* to [Brealey and Myers, 1988].

Based on the assumption that the option´s underlying asset is traded, a hedge portfolio can be created and risk-neutral valuation can be applied. Continous trading without transaction costs is assumed. Inefficient, no-arbitrage free markets with high transaction costs could thus limit the applicability of the real options approach. However the lack of benchmark assets for comparison does also limit the applicability of other more traditional valuation models.

In order to avoid the partly unrealistic and simplifying assumptions mady by real options a number of models have been developed that explicitly aim at basing real options theory on grounds that better match the characteristics of real projects, refer among others to [Lint and Pennings, 1997], [Lin, 2001] or [Kou and Wang, 2004].

Traditional real options theory as well as decision analysis fail to account for strategic decision making with respect to competitors. In real options theory the options are assumed to be proprietary to the owner. Facing competition however, an option can be regarded as being shared among a number of competitors any of whom can exercise the option. From this point of view it becomes important to analyse the market with respect to first-mover and second-mover advantages and to find the according optimum strategy. This can be achieved by combing real options with game theoretic approaches that extend decision analysis which limits the modelling to an agent playing against nature. The much more general approach used by game theory models the strategic interactions between agents. An agent playing against nature only, as assumed by decision analysis, is thus a special case of game theory.

Applying real options models requires an analysis of possible future developments and the according uncertainty with respect to the expected outcomes. These developments have to be monitored during the project in order to decide whether one should exercise the options inherent to the project or let them expire. The necessity for continuous monitoring of the project´s progress as well as the according environment is sometimes regarded as a shortcoming of the real options approach. However it seems advisable to revise plans as uncertainty gets resolved. Thus any method that supports the continuous incorporation of new knowledge into the decision making process, provides a more realistic way of modeling, than assuming that a project is carried out as once planned.

In practice projects that do not perform well are most likely cancelled, projects that seem promising are enhanced and in case the future is too uncertain to take any actions now, one will decide to wait until some uncertainty is resolved. The merit of the real options approach is that it assigns values to these opportunities and provides a theoretical basis as well as according modeling techniques for exactly such situations.

Chapter 5 — R&D Portfolio Management

Portfolio management for R&D projects has enjoyed increased attention within the last couple of years. Companies want to evaluate their technologies from a portfolio's perspective, which means evaluation of a set, or subset, of R&D projects together and in relation to one another [Mikkola, 2001].

This chapter gives a brief introduction to the aims of creating portfolios of R&D projects, then focusing on the requirements that should be fulfilled by models for the selection of projects for a portfolio. The characteristics of R&D- and financial portfolios are compared. Special concern is devoted to the interrelations that can exist between projects in a portfolio. A technique for calculating the risk of a portfolio of interrelated projects is presented. Methods for the selection of projects for a portfolio are briefly introduced and compared according to the criteria that have been identified as important for R&D portfolio selection.

5.1. Motivations and Aims

Cooper, Edgett and Kleinschmidt [Cooper, Edgett and Kleinschmidt, 2001a] conducted a study within companies in North America to find out why portfolio management is important. Citing senior managers taking part in the study, the main aim is to maximise the value of the portfolio—the return on the R&D investments—under certain constraints, and thus to maximise R&D productivity. This can only be achieved when scarce resources are allocated properly and efficiently, which yields to limiting the number of concurrent projects appropriate to the limited resources available. The right balance has to be achieved concerning the mix of long-term and short-term projects, high-risk and low-risk projects in the portfolio.

The standard portfolio approach, introduced in 5.2. aims at minimising the expected variance of returns on asset portfolios under a constant expected mean rate of return by investing in a mix of assets in an exogeneously given environment. Assuming mean-variance utility functions this leads to a maximisation of benefit.

Regarding the multi-dimensionality of R&D projects, as described in chapter one 1.2.1 creating a project portfolio can also aim at achieving the right balance of focus on the various project dimensions. It might for example be reasonable to select projects for the portfolio, which are likely to be a financial success, in order to support projects that focus on environmental or social aspects. Similarly Stummer and Heidenberger [Stummer and Heidenberger, 2003] identified the ability of a portfolio selection method to take into account multiple—and even conflicting—objectives as a feature desired by practicians in R&D intensive industries. Furthermore the system should take various kinds of interrelations between projects into account.

The most common complaint cited by managers is that without proper portfolio management, short-term and low-risk projects are favoured as opposed to long term and riskier projects, although these are more likely to turn out to be the important future breakthroughs. Projects under development, and non-finished projects characterised by much experimentation and testing, have got a high level of risk and sometimes these projects are never completed or indefinitely delayed because of technical problems or changes in the market. Nevertheless, companies gain a lot of experience by undertaking such projects and the company's knowledge base is extended, which facilitates the development of further products or processes [Mikkola, 2001]. Graves and Ringuest [Graves and Ringuest, 2003] warn that managers who analyse projects in isolation will tend towards excessive timidity because they ignore the risk reducing effects of aggregation. Analysing a project in isolation means that the opportunities associated with future decisions are not valued, which may lead to a bias against risky projects.

Another reason for portfolio management is to provide better objectivity in project selection, which is achieved by having a generally accepted method for the selection of new projects for the portfolio and weeding out of projects that are not useful any more. A further advantage of the portfolio approach to R&D management mentioned by Mikkola is that dynamics of the projects are revealed and interrelations between projects are made explicit, which of course requires a portfolio management technique that is capable of taking project interrelations into account and modelling them appropriately [Mikkola, 2001].

5.2. R&D Portfolios and Financial Portfolios

In [Graves, Ringuest and Case, 2000], R&D portfolio management is defined as a dynamic process aiming at evaluating, selecting and prioritising new and existing R&D projects. An important issue is the allocation and re-allocation of resources to the projects selected for the portfolio. Decisions have to be taken concerning which projects should be continued, prioritised, de-prioritised and stopped. Typical characteristics of the portfolio decision process are uncertainty, changing information, multiple objectives and interrelations among projects. Based on the evaluation of the individual projects, all projects are compared against each other and periodic reviews of the total portfolio of all projects take place.

Managing R&D investments for a portfolio of R&D projects can be compared to the portfolio management of financial investments in the stock market managed by a fund manager. The optimisation of financial as well as R&D portfolios is subject to resource constraints. While for financial portfolios there is only one constraint, namely the available investment volume, for R&D portfolios there can be additional constraints such as technological equipment or qualified human resources.

The basic goal of a shareholder, or investor in the market, holding a portfolio of different securities, is to maximise the return on investment while reducing the portfolio's risk through diversification. Given that prices of different stocks do not move together exactly, or returns are not perfectly correlated, opposite moves among different stocks in a portfolio tend to offset one another. Thus, the variability of the portfolio can be substantially less than the average variability of the individual stock returns.

The fluctuation in the returns can be measured by calculating the variance. The higher the variance, the riskier the investment. The covariance measures the correlation of return fluctuations of one stock with the fluctuations of another. High covariance means that an increase in one stock's return is likely to correspond to an increase in the other. A low covariance indicates that the return rates are relatively independent. If an increase in one stock's return is likely to correspond to a decrease in the other, the covariance is negative.

The issue when creating a financial portfolio is to select assets to meet a desired return at minimum variance. A way to solve this problem was presented by Markowitz [Markowitz, 1952], who introduced "Modern Portfolio Theory" based on the idea of portfolio diversification in order to reduce risk. Markowitz demonstrated how to reduce the standard deviation of returns on asset portfolios by selecting assets which do no move together exactly. According to the Markowitz portfolio theory, the two main objectives in portfolio optimisation are the maximisation of long-term expected net present value (NPV) and the minimisation of the variance of NPV of the overall portfolio [Luenberger, 1998]. Thus the objective is to determine the percentage to invest in each asset while minimising the risk of the entire portfolio.

Assuming that capital markets are perfect, and rates of return are normally distributed, Markowitz showed that a rational investor, *i.e.* an investor who behaves in a way that is consistent with expected utility maximisation, should analyse portfolios based on the mean and on the variance of their rates of return. As the two parameters—mean and variance—suffice to express the utility choices of a decision maker, the selection of portfolios of investments can also be based on these parameters. Note that this two-parameter representation is valid for well-diversified portfolios, but does not apply to individual securities, because in the case of individual securities the volatility cannot be virtually eliminated by diversification [De Jongh and De Wet, 2000]. Due to the contribution to the mean and variance of the portfolio, a security should only be evaluated in the context of the portfolio to which it belongs. Thus the risk of an investment can be measured in terms of the covariability of its rate of return with that of the portfolio.

Sharpe, Markowitz´s student, suggested to apply "Modern Portfolio Theory" to other fields apart from the management of financial assets [Sharpe, 1963], that exhibit the following characteristics: the outcome from the decisions to be taken is uncertain, this uncertainty has to be acknowledged and the interrelations of the outcomes have to be taken into account explicitly.

Regarding R&D portfolios the argument for diversification is that basic research is usually surrounded by high risk and uncertainty and thus it is adviseable to invest in a number of research projects which increases the chances that one of them will be successful, especially if the projects are not equally risky. Furthermore one has to distinguish between technological uncertainty and market uncertainty, refer to 2.5.

Technological uncertainty can be systematically resolved as research is undertaken. To reduce the risk of a portfolio of research projects the portfolio should consist of projects at various stages, short-term and long-term projects, high risk projects in their early stages and projects for which the technological uncertainty has already been resolved. However at the latest when the newly developed product or technology, a new drug for example, enters the market competitors try to develop a similar drug. Even in case of patent protection, as soon as the drug goes off-patent, generic drugs make inroads into the market and reduce the original drug´s value. Thus for a pharmaceutical company investing in R&D the consequences of competitors entering the market are in most cases negative. The consequences of competitors actions for an investor holding a portfolio of financial assets which does contain shares of this pharmaceutical company may also be negative, however the risk can be diversified by also investing in shares of the competitive company.

The possibilities for diversification among various kinds of research projects for companies investing in their own R&D projects, such as pharmaceutical campanies, are somewhat limited as in most cases the expertise of the company will consist in a certain field of research. The resulting portfolio of research projects is thus exposed to the market risk of a whole industrial sector.

Regarding financial portfolios the negative correlations of outcomes are used to reduce the spread in the distribution of returns. With respect to R&D projects various kinds of interrelations (refer to 5.3.) and their effects on the value of the portfolio have to be taken into account. In case of various possible approaches towards a new standard, technology or product, diversification can involve to invest in redundant projects (5.3.1.) in order to identify the most promising solution and reduce technological risk. Projects that create synergies (5.3.1.) when being undertaken together should be included in the portfolio as there is an additional benefit without increasing the portfolio´s risk. Preconditional projects, meaning that one project´s success is a necessary precondition for the success of other projects (5.3.2.), are positively correlated and thus do not correspond to the concept of diversification.

While the maturity of an asset is not that important for the selection of a portfolio consisting of financial assets, the duration of R&D projects is of high relevance when selecting projects for an R&D portfolio. This is due to the fact that R&D projects can either be finished or cancelled but in practise it is rather difficult to abandon an R&D project without causing a loss. In other words the trading costs of R&D projects are usually much higher than those of financial assets.

Financial assets can be traded in arbitrary quantities. R&D projects, on the other hand, are non-divisible in the sense that a single project can either be included in the portfolio or not, but there is no way of incorporating a fraction of a project into a portfolio. From this point of view, financial assets constitute a continuous repository, whereas R&D projects require discrete decisions.

A research company investing in a portfolio of R&D projects can actively influence the value of the portfolio *e.g.* by undertaking projects that create synergies (5.3.1.), by investing in new technology or by employing highly-qualified researchers. The only ways for financial investors to optimise their portfolios are to combine various financial assets and to find the right timing for purchasing and selling [Lubatkin and Chatterjee, 1994].

Typically, financial aspects are the only objective when regarding a portfolio of financial assets, whereas R&D projects usually have multiple objectives. In order to compare various R&D projects with multiple objectives—*i.e.* mapping a multi-dimensional utility to a scalar value, refer also to (6.5.)—a metrics is needed that has the following characteristics:

- The metrics is continuous
- The metrics is monotonic, for all dimensions of the multi-dimensional utility
- The metrics has a total order

Using for example, multi-attribute utility analysis (MAUA) as introduced in 6.5.2. allows the definition of a metrics that establishes an order relation, but does not define a distance function.

Diversity of a Portfolio

The concept of diversity is rooted in biology and regarded as essential for innovation. It can be applied to various other disciplines. In an economic sense diversity of a portfolio of strategies is a driver for technological and institutional innovation. As Schumpeter [Schumpeter, 1935] already realised diversity in consumer goods is one of the fundamental impulses that set and keep the capitalist engine in motion[10].

Drawing on long-established insights from financial management diversity has recently been rediscovered as offering a resource pool for economic strategies,—refer *e.g.* to [Nelson and Winter, 1982], [Freeman, 1982], [Clark and Juma, 1987], [Anderson, Arrow and Pines, 1988], [Saviotti and Metcalfe, 1991], [Hodgson, 1993] and [Landau, Taylor and Wright, 1996].

10 Schumpeter originally used the term “variety” instead of diversity, but this distinction is not essential here.

Regarding diversity in a broader context social diversity and pluralism are regarded as having a positive impact on institutional and technological innovation—refer *e.g.* to [Norgaard, 1989] and [Mokyr, 1994].

With respect to scientific knowledge Kuhn [Kuhn, 1970] finds that the cross-fertilisation of diverse institutional and technological systems provides a fruitful basis for radical and creative innovations.

Economic diversity has to be regarded in the context of a portfolio of strategies instead of being an attribute of an individual alternative. If diversity is taken into account when selecting projects for a portfolio, also long-term projects whose benefits are inherently more uncertain are included in the portfolio.

In the context of economic diversity the term ignorance is used to describe the completely unforseeable character of the social, political or environmental impacts of innovations. The practicability of techniques based on probability theory for the evaluation of innovation projects is thus limited. Taking the diversity of a portfolio into account is a means to hedge against exposure to ignorance. Hence Stirling [Stirling, 1994] recommends to propagate analytical attempts that characterise the available options instead of trying to define the nature and relative likelihood of all possible future states of the world.

Cowan [Cowan, 1991] however points out that diversity is not a free good. With respect to technological developments scale and transaction benefits can be gained from standardisation, which is in contrast to the concept of diversity. Higher economic diversity is likely to come along with higher transaction costs as more information is required as well as higher production costs due to foregone economies of scale. Allowing for diversity in a project portfolio increases the investment costs necessary to undertake the variety of projects, but reduces the portfolio's risk through diversification.

Among the various approaches to measure diversity, which are mainly taken from ecology—refer to [Magurran, 1988] and [Bobrowski and Ball, 1989]—Hill [Hill, 1973] proposes the famous *t*-Wiener function [Shannon and Weaver, 1949] as a measure for diversity:

$$\Delta = -\sum p_i \ln p_i \tag{5.1}$$

where Δ refers to a particular index of diversity, p_i represents the proportion of the performance of option i with respect to the performance of the whole portfolio. Using this measure diversity reaches a maximum when all the p_i are equal[11].

Besides the economic advantages of diversity there is also an ethic aspect, following Von Foerster's ethical imperative: "Act in such a way that the number of possibilities increases!" [Von Foerster, 1993, p.49].

Mean-Gini Approach

Alternatively to the mean-variance approach another model for portfolio selection derived from financial literature is the mean-Gini approach [Shalit and Yitzhaki, 1984, 1989 and 1994]. The mean-Gini approach is based on the estimation of the mean and a Gini coefficient for each R&D project, where the Gini coefficient is a measure of dispersion in outcomes similar to the variance. The advantage of the method is that efficient portfolios are selected satisfying the necessary

[11] The Shannon-Wiener function as a measure of diversity is of special interest as it is also a measure for the average information content, that will later be used to determine the knowledge content gained within an R&D project, refer to 6.1.2.

conditions for stochastic dominance, regardless of the probability distribution of returns. In terms of stochastic dominance the risky project A is preferred to the risky project B, *i.e.* project A dominates project B, if the cumulative distribution function of B is always greater or equal than the cumulative distribution function of A. In case of cumulative distribution functions that intersect A dominates B if the integral of the cumulative distribution function of B is always greater or equal than the integral of the cumulative distribution function of A for all arguments. For cumulative distribution functions that intersect at most once the mean-Gini approach provides sufficient conditions as well [Graves and Ringuest, 2003]. As another advantage Graves and Ringuest show that the mean-Gini approach can be used to provide an intuitive measure of investment risk.

5.3. Project Interrelations

One important aspect of project portfolio management is the identification of interrelations between projects in order to find out to what extent changes in one project affect other projects [Santhanam and Kyparisis, 1996]. Synergies between the interrelated projects can then be used systematically, which does also involve the transfer of knowledge gained through a project.

Not only projects can have various dimensions contributing to the overall success of the project, as described in chapter one 1.2.1. The same applies to portfolios of R&D projects. Taking interrelations between projects that contribute to the various dimensions of the portfolio into account, the following hierarchy of project interrelations and the according definitions are suggested for this thesis:

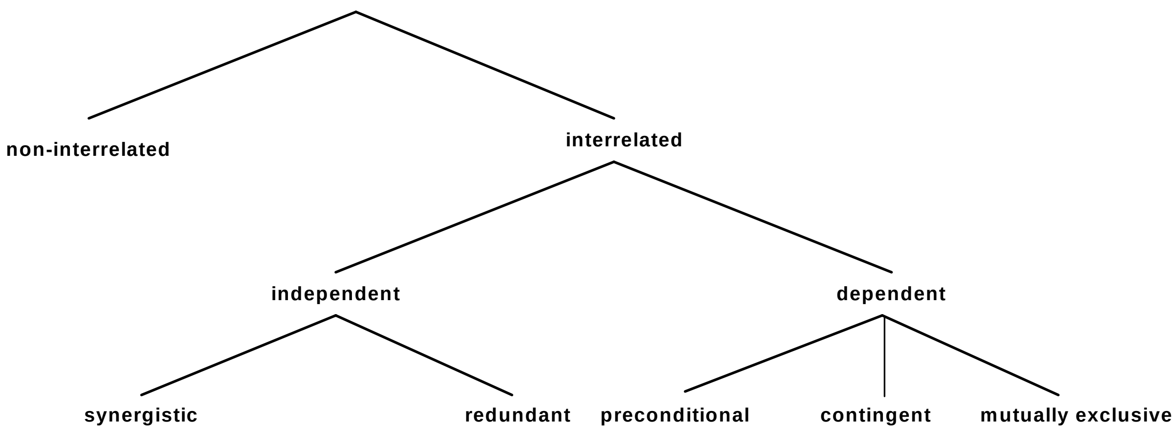


Figure 5.1: "Hierarchy of Project Interrelations"

The total expected value V of a portfolio of n non-interrelated projects is given by:

$$V = \sum_{i=1}^{n} v_i \tag{5.2}$$

5.3.1. Independent Projects

If project π_j is independent of project π_i the probability of project π_j being successful is the same regardless whether project π_i is succesful or not:

$$P(s_j | s_i) = P(s_j)$$

where s_i refers to the success of project π_i[12] and $P(s_i)$ is the probability that project π_i is successful. This definition implies that independence is a symmetric relation:

$$(P(s_j | s_i) = P(s_j)) \Leftrightarrow (P(s_i | s_j) = P(s_i)) \tag{5.3}$$

Independent projects can be processed in parallel, but do not have to. However, if they are processed in parallel, synergies or redundancies can occur within the portfolio.

Synergistic Projects

Synergies between two projects π_i and π_j can be regarded as the additional impact of the projects' utilities to the portfolio [Chien, 2002]. A significant characteristic of synergistic interrelations is that they increase the total utility of a portfolio without increasing the costs. For a description of the integration of synergistic interrelations into the portfolio selection refer to chapter six 6.7.4. Synergistic interrelations are symmetric, transitive and reflexive and thus form an equivalence relation.

Redundant Projects

Due to the uncertainty inherent in the research process, parallel research activities—referred to as redundant projects within this thesis—are of special significance [Klein and Meckling, 1958]. The incentive for undertaking parallel research projects stems from the fact that in the beginning of the research there are many alternative ways of investigation, whereas the less promising are eliminated as information is accumulated [Arrow, 1971].

In contrast to synergies, redundancies in a portfolio reduce its total utility—defined as the sum of the utilities of the selected projects—without reducing the costs. Similar to synergies the relation between redundant projects is symmetric, transitive and reflexive and thus an equivalence relation.

Thus the contribution of redundant projects to the total expected value V of a portfolio as defined in 5.2 is the maximum of the values v_j of the redundant projects π_j.:

$$v_{red} = \sum_{\varphi_i} \max_{j \in \varphi_i} (v_j) \tag{5.4}$$

Where φ_i are the equivalence classes of redundant projects.

5.3.2. Dependent Projects

Dependencies between projects influence the success of a specific project depending on the successes of other projects, thus dependencies also influence the total success of a project portfolio. However, dependencies may also imply constraints on the selection of projects for a

[12] Note that the definition of independency in a statistical context applies to non-interrelated projects as well.

portfolio. Therefore taking dependencies between projects into account is critical for the selection of a portfolio.

Preconditional Dependencies

If project π_j is a precondition for project π_i , π_i can only be a success if π_j turns out to be a success, thus:

$$s_i \Rightarrow s_j \tag{5.5}$$

Note that the success of π_j does by no means guarantee the succees of π_i. Thus a preconditional project is a project whose success is a necessary but not a sufficient condition for the success of the project depending on the preconditional project. Preconditional dependencies are transitive: If π_j is a precondition for π_i and π_i is a precondition for π_k then obviously π_j is also a precondition for π_k. Preconditional dependencies can be represented by a directed acyclic graph. When selecting projects for a portfolio, the portfolio must contain the transitive closure of all selected projects. Preconditional dependencies can be modelled by using a threshold matrix, refer to 5.3.3. If π_j is a precondition for π_i, π_i must not be a precondition for π_j. However, due to statistical reasoning, the covariance of the utilities of the two dependent projects is symmetric. Preconditional projects have to be processed in sequential order, which can be determined by topological sort.

Contingent Dependencies

If two projects π_i and π_j have got a contingent dependency, the success of π_i is a necessary condition for the success of π_j and vice versa, the success of π_j is a necessary condition for the success of π_i . As the contingent relation is transitive, symmetric and reflexive it is an equivalence relation:

$$s_i \equiv s_j \tag{5.6}$$

The correlation coefficient of the utilities of two contingent projects is 1. Contingent projects have to be processed in parallel.

Mutually Exclusive Dependencies

In contrast to a contingent dependency, two projects π_i and π_j are mutually exclusive if π_i can only be successful if π_j is not, and vice versa:[13]

$$s_i \not\equiv s_j \tag{5.7}$$

The correlation coefficient of the utilities of two mutually exclusive projects is -1.

Table 5.1 shows the correspondence between the different kinds of interrelations between two projects π_i and π_j and their successes s_i and s_j respectively. The success s is regarded as a Boolean value and can for example be defined as the project's utility being higher than a certain boundary value.

[13] Weingartner [Weingartner, 1966] defines two projects as mutually exclusive if one may only be selected for the portfolio if the other is not and vice versa. However, within the context of this thesis, in contrast to Weingartner's definition, it is up to the decision makers whether they want to select the two mutually exclusive projects for a portfolio.

Project Interrelations	Logical Relation
independent	$s_i \vee s_j$
preconditional	$s_i \Rightarrow s_j$
contingent	$s_i \equiv s_j$
mutually exclusive	$s_i \not\equiv s_j$

Table 5.1: "Correspondence between Project Interrelations and Logical Relations"

5.3.3. Representing Interrelations

A dependency matrix—compare [Dickinson, Thornton and Graves, 2001])—a threshold matrix or the well-known covariance matrix are suggested for representing the various interrelations among projects.

Dependency Matrix

The dependency matrix is a means to model asymmetric, linear dependencies between projects. In case of a linear dependency between project π_i and project π_j the success of project π_i increases the success s_j of project π_j by an additive amount $d_{ij}*s_i$:

$$s_j = \alpha + d_{ij} * s_i \tag{5.8}$$

with α being the success of project π_j independently of the success of project π_i and thus representing the intrinsic contribution to the success of project π_j. d_{ij} represents the interdependencies between project π_i and project π_j, refer to Figure 5.2.

Linear dependencies do not allow for the modelling of one project's success being a precondition for the success of another project. Non-linear dependencies can be modelled using a threshold matrix, which will be described in the next section.

Linear dependencies between projects can be represented and visualised with a weighted, directed graph, as shown in Figure 5.2.

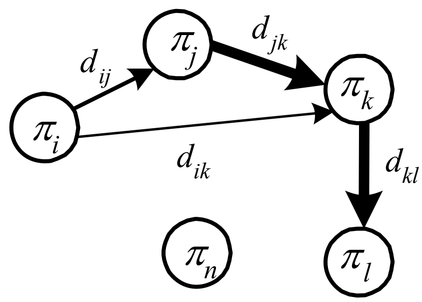


Figure 5.2: "Linear Project Dependencies"

The d_{ij} in Figure 5.2 represent the interdependencies existing between project π_i and project π_j with $d_{ij} \in \Re$. A group of related projects can be described in such a diagram. The different weights of the lines represent the different weights of project dependencies d_{ij}. The various kinds of dependencies between two projects and their weights can be made explicit with a dependency matrix. Each dependency is a directed relationship between one project and another, with

$$d_{ij} \geq 0 \text{ and } d_{ii} = 0 \tag{5.9}$$

As the graph representing the depencies is directed and acyclic, the following is valid for the values d_{ij} of the dependency matrix:

$$d_{ij} \neq 0 \Rightarrow d_{ji} = 0 \tag{5.10}$$

This restriction is necessary to avoid recursive dependencies and thus avoiding recursive success functions.

The sum of the dependency factors of all projects π_i adjacent to a project π_j. represents the extrinsic influence of the success of project π_j. In absolute terms we define the extrinsic contribution s_j^{ex} to the success of project π_j as:

$$s_j^{ex} = \sum_i d_{ij} s_i \tag{5.11}$$

for all projects π_i adjacent to π_j.

The sum of the intrinsic and extrinsic success represents the success s_j of project π_j:

$$s_j = s_j^{in} + s_j^{ex} \tag{5.12}$$

The representation of linear dependencies described above does not take into account the time needed to execute the various projects. In order to include temporal dependencies between the interrelated projects, a dynamic model can be used, that allows for describing the point in time t at which a certain project's success is considered by an additional index. Thus we define the extrinsic contribution s_{jt}^{ex} to the success of project π_j :

$$s_{j,t}^{ex} = \sum_i d_{ij} s_{i,t-1} \tag{5.13}$$

with the total success s_j of project π_j at time t being:

$$s_{j,t} = s_{j,t}^{in} + s_{j,t}^{ex} \tag{5.14}$$

Threshold Matrix

The threshold matrix is a means to model asymmetric, non-linear dependencies between projects. In order to model interrelations between preconditional projects —as defined in 5.3.2. —the performance of project π_j serving as a precondition for the success of project π_i has to exceed a certain threshold θ_{ij}. Otherwise the precondition necessary for undertaking project π_i is not fulfilled and the performance of π_i is zero. The thresholds θ_{ij} are non-negative

$$\theta_{ij} \geq 0 \text{ and } \theta_{ii} = 0 \tag{5.15}$$

A threshold θ_{ij}=0 means that project π_j is not a precondition for π_i.

As preconditional interrelations are anti-symmetric the following condition holds for every i and j:

$$\theta_{ij} \neq 0 \Rightarrow \theta_{ji} = 0 \tag{5.16}$$

Preconditional interrelations are acyclic and non-linear.

Covariance Matrix

Another relation, besides dependencies between projects, is their correlation. If two projects are positively correlated, they are equally successful or unsuccessful. Negative correlation means that the more succesful one project, the less succesful is the other, and vice versa. If two projects are uncorrelated, the success or failure of one project is independent of the success or failure of the other. In contrast to dependency, correlation is a symmetric relation between two projects.

Let us assume that the valuations of the projects' utilities follow a statistical distribution. The correlation can be specified by the covariance matrix *Cov* consisting of the covariances σ_{ij} between the two projects π_i and π_j.. Due to symmetry, the condition $\sigma_{ij} = \sigma_{ji}$ holds for all projects π_i and π_j. in a portfolio. $\sigma_{ij} > 0$ implies that the projects π_i and π_j. are positively correlated. $\sigma_{ij} < 0$ implies that the projects π_i and π_j. are negativey correlated and $\sigma_{ij} = 0$ implies that the projects are uncorrelated.

$$Cov = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1n} \\ \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \sigma_{n1} & \sigma_{n2} & \cdots & \sigma_{nn} \end{pmatrix} \tag{5.17}$$

If two projects π_j and π_k depend on the same project π_i, the projects π_j and π_k are correlated:

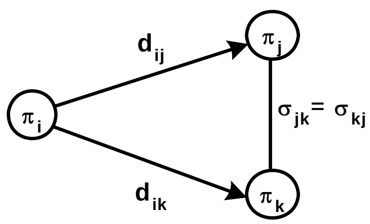


Figure 5.3: "Correlations implied by Dependencies"

5.3.4. Alternative Classifications of Project Interrelations

In addition to the classification of project interrelations described in the previous sections, the following classifications can be found in literature:

Gear and Cowie [Gear and Cowie, 1980] distinguish between internal and external factors that cause interactions between projects. They define external interactions as arising over time from overall social and economic changes which have effects that cut across many, if not all, subsets of a project set. Focusing on internal interrelations, the following classification is common in literature, refer *e.g.* to [Aaker and Tyerbjee, 1978], [Weber, Werners and Zimmermann, 1990] and [Santhanam and Kyparisis, 1996]:

Outcome or Technical Interdependencies

Outcome or technical interdependencies refer to the dependence of the outcome's success of one project on the outcomes successes or failures of other projects. The most common case is that one project has no chance of succeeding without another project being selected for the portfolio and completed successfully. Santhanam and Kyparisis [Santhanam and Kyparisis, 1996] give the example of the aerospace field in which the development of a new engine depends on the successful development of a new fuel, which is also an example of contingency between projects. If projects are contingent one may only be selected for the portfolio if the other project is also part of the portoflio, whereas in case of mutually exclusive projects, one may only be selected for the portfolio if the other project is not [Weingartner, 1966]. The concept of contingent projects does also apply to projects depending on each other with regard to the exchange of knowledge.

Cost or Resource Utilisation Interdependencies

Santhanam and Kyparisis [Santhanam and Kyparisis, 1996] define resource utilisation interdependencies as any instance of two or more projects using the same scarce resource and give lab space as an example for such a scarce resource.

Cost interrelationships are present in a portfolio if the total cost of the portfolio does not correspond to the sum of the costs of the individual projects, which often occurs when various resources are shared by a number of projects. If, for example, the cost of some equipment that is used by many projects but maybe only for a short period, is included in the cost of each project, the total cost of all projects participating in the use of this equipment is overstated by summing the individual costs.

Including human resources into resource utilisation interdependencies, non-additivity can also apply to the same team members working on different projects and providing their knowledge for these projects. For example, employing an expert who can give advice for a number of projects shows that knowledge is a resource which can be shared by projects.

Benefit Interdependencies

Impact or benefit interdependencies can occur if the impacts of the individual projects on *e.g.* returns or costs are not additive. Such projects are called complementary or competitive [Aaker and Tyerbjee, 1978]. For example, for a pharmaceutical research company, it can be reasonable to invest into several competing research projects aiming at designing drugs for the same kind of disease, in order to reduce the risk of the projects failing. If one of the alternative projects and resulting drugs turns out to be more successful than the others, this drug is introduced to the market. However, it can for example happen that one drug is generally better suited to cure the disease, but may not be taken by pregnant women, whereas the other drug creates no problems under these circumstances. Thus both drugs will be produced, but for different market segments. In neither of these cases, are the impacts on returns of the two projects additive.

According to Santhanam and Kyparisis [Santhanam and Kyparisis, 1996] benefit interdependencies occur when there is a synergistic effect between two or more projects. They give the example of two products developed in a pharmaceutical company which make the treatment of a particular disease more efficacious when used together.

Considering knowledge impacts of individual projects on the portfolio, these can be additive and thus independent even if the financial impacts are not. Undertaking two competing research projects, as in the example above, where both turn out to be successful provides the possibility to apply for two patents and thereby roughly doubles the knowledge gained. However, this does not mean that the two projects will achieve twice the financial return.

Present Value Interdependencies

Fox, Baker and Bryant [Fox, Baker and Bryant, 1984] point out that even in the absence of outcome, cost and benefit interactions, this does not imply that the present values of the projects are independent when determing the present value of a portfolio. The reason why independent outcomes, costs and benefits do not necessarily imply independent present values is that the profit function for the whole portfolio is generally not linear with regard to the vector of profit parameters for every period. However, if it were linear, independent outcomes, costs and benefits would imply independent present values.

5.4. *Risk of an R&D Project*

The concept of the Value-at-Risk (VaR)—see *e.g.* [Jorion, 1997]—that has proven a successful way of managing financial risks, can be adapted for measuring the risk of R&D projects and portfolios.

5.4.1. Risk of an Individual Project

Following Jorion we define the risk ϱ_λ of an R&D project as:

$$\rho_\lambda = c - w_\lambda \tag{5.18}$$

with c being the initial investment, w_λ being the VaR, *i.e.* the lowest expected value of the project at confidence level λ. The confidence level $\lambda \in [0,1]$ corresponds to the probability that the performance of the project is higher than w_λ:

$$\Pr\,(w > w_\lambda) = \lambda$$

It is assumed that the probability of the project's performance follows a Normal distribution with mean μ and deviation σ. With

$$1 - \lambda = \int_{-\infty}^{\alpha} \Phi(x)\,dx$$

defining α as the 1-λ percentile of the Standard Normal distribution Φ the risk ϱ_λ of a project at confidence level λ is defined as:

$$\rho_\lambda = c - \mu - \alpha\,\sigma \tag{5.19}$$

referring to the maximum loss at confidence level λ[14].

5.4.2. Risk of a Project with Preconditions

By definition the VaR of a project at confidence level λ corresponds to the 1-λ percentile of the performance's distribution. According to Tibiletti [Tibiletti, 2000] the VaR considering constraints can be defined as the 1-λ percentile of a multi-dimensional distribution. Besides the distribution of the project's performance this multi-dimensional distribution includes an additional dimension modelling the distribution of each constraint. Considering the example of

[14] Note that $\alpha < 0$ for $\lambda > 0.5$ thus increasing σ leads to increasing risk.

project j being a precondition for project i under the constraint that the performance of project j exceeds a given threshold θ_{ij}:

$$w_j > \theta_{ij}$$

the bivariate VaR w_λ of project i is given by:

$$\Pr(w_i \le w_\lambda, w_j > \theta_{ij}) = N_i(w_\lambda) * (1 - N_j(\theta_{ij})) = 1 - \lambda \tag{5.20}$$

with N_i being the cumulative Normal distribution function with mean μ_i and deviation σ_i.

As the threshold θ_{ij} is constant, the probability that the preconditional project π_j exceeds its threshold, given by

$$\Pr(w_j > \theta_{ij}) = 1 - N_j(\theta_{ij}) = \gamma_i \tag{5.21}$$

is also constant.

Thus mean and deviation of the dependent project π_i are transformed to:

$$\mu_i \leftarrow \gamma_i \ \mu_i \tag{5.22}$$

$$\sigma_i \leftarrow \gamma_i \ \sigma_i \tag{5.23}$$

Assuming that project i has got a number of preconditions, the bivariate VaR w_λ of project i is given by:

$$\Pr(w_i \le w_\lambda, \bigwedge_{j\in\tau}(w_j > \theta_{ij})) = N_i(w_\lambda) \prod_{j\in\tau}(1 - N_j(\theta_{ij})) = 1 - \lambda \tag{5.24}$$

where τ refers to the subset of indices of preconditional projects.

The probability that all of the preconditional projects π_j exceed their thresholds becomes

$$\gamma_i = \Pr(\bigwedge_{j\in\tau}(w_j > \theta_{ij})) = \prod_{j\in\tau}(1 - N_j(\theta_{ij})) \tag{5.25}$$

5.5. Risk of an R&D Portfolio

5.5.1. Risk of a Portfolio of Non-Interrelated Projects

Given a portfolio that consists of a set of n non-interrelated projects π_i the performance w of the portfolio is the sum of the respective performances w_i of the projects π_i.

From a statistical point of view the distribution function of the sum of the performances converges to a Normal distribution—regardless of the distribution functions of the performances

$$w = \sum_{i=1}^{n} w_i$$

of the individual projects—with expected value

$$E(X) = \mu = \sum_{i=1}^{n} \mu_i \tag{5.26}$$

and variance

$$Var(X) = \sigma^2 = \sum_{i=1}^{n} \sigma^2{}_i \qquad (5.27)$$

with n being the number of projects, μ_i being the means and σ_i being the deviations of the distribution functions of the performances of these projects.

Along the lines of the definition of the risk of an individual project (equation 5.19) the risk ρ_λ of a portfolio of non-interrelated projects is thus given by:

$$\rho_\lambda = c - \mu \ - \alpha\sigma$$

with α being the 1-λ percentile of the Standard Normal distribution Φ.

As the sum of the squares of the deviations σ_i of the individual projects' performances is always less than the square of their sums, the risk of a portfolio of non-interrelated projects is less than the sum of the risks of its constituent projects, -assuming that more than one of the deviations σ_i >0.

5.5.2. Risk of a Portfolio of Interrelated Projects

In case of interrelated projects the interrelations can be described by the symmetric covariance matrix:

$$Cov = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1n} \\ \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \sigma_{n1} & \sigma_{n2} & \cdots & \sigma_{nn} \end{pmatrix}$$

Accordingly the variance of a portfolio of interrelated projects is given by:

$$Var(X) = \sigma^2 = \sum_{i=1}^{n} \sigma^2{}_i + 2\sum_{i=1}^{n} \sum_{j<i}^{n} \sigma_{ij} \qquad (5.28)$$

Thus the risk

$$\rho_\lambda = c - \mu \ - \alpha\sigma$$

increases if the interrelations and consequently the covariances σ_{ij} increase.

Risk of a Set of Preconditional Projects

As the covariance matrix is symmetric $\sigma_{ij} = \sigma_{ji}$ it is not suited to describe asymmetric interrelations, such as preconditions, μ_i, σ_i^2 and γ_i of the individual projects have to be determined according to equations 5.22, 5.23 and 5.25 using the threshold matrix 5.3.3.

Mean μ and variance σ^2 of the performance of the portfolio are thus given by:

$$E(X) = \mu = \sum_{i=1}^{n} \gamma_i \mu_i \qquad (5.29)$$

$$Var(X) = \sigma^2 = \sum_{i=1}^{n} \gamma_i{}^2 \sigma_i{}^2 \qquad (5.30)$$

leading to the risk ϱ_λ

$$\rho_\lambda = c - \mu \ \ - \alpha\, \sigma$$

Risk of a Set of Contingent Projects

In order to determine the risk of contingent projects, each of the contingent projects can be modelled as a precondition for all other contingent projects. For all contingent projects π_i and π_j ($i \neq j$), this leads to thresholds $\theta_{ij} \neq 0$. μ, σ and ϱ_λ of the set of contingent projects are calculated analogously to preconditional projects. In the case of contingent projects, obviously the condition that the threshold matrix has to be anti-symmetric (equation 5.16) is no longer valid.

Risk of a Set of Synergistic Projects

Synergies are regarded as virtual projects without investments, with the projects causing the synergy serving as preconditions. Thus the additional risk

$$\rho_\lambda = - \mu \ \ - \alpha\, \sigma \tag{5.31}$$

of the virtual synergistic project reduces the risk of the portfolio.

Risk of a Set of Redundant Projects

Concerning redundant projects within a portfolio the value of the set of redundant projects equals the maximum of the values of the redundant projects. Thus the multivariate distribution function of the performance of a set of redundant projects can be expressed as

$$\begin{aligned} &F(w_\lambda) = \Pr\,(\max w_i \leq w_\lambda) = \\ &\Pr\,(w_i \leq w_\lambda, \forall i : 1 \leq i \leq n) = \\ &\prod_{i=1}^{n} N_i\ (w_\lambda) = 1 - \lambda \end{aligned} \tag{5.32}$$

where the distribution function $F(w)$ corresponds to the product copula of the marginal distributions of the values of the redundant projects.

The concept of a copula provides an elegant way to present how a multivariate distribution is influenced by the dependence structure and its marginals. The notion of a copula has been introduced by Sklar [Sklar, 1959] and studied by Kimeldorf and Sampson [Kimeldorf and Sampson, 1975] as well as Deheuvels [Deheuvels, 1978] under the name of uniform representations. A historic overview is provided by Schweizer [Schweizer, 1991]. In recent years the use of copulae has been propagated to various fields including financial modelling and insurance, see *e.g.* [Tibiletti, 1995] and [Embrechts, McNeil and Straumann, 1999].

A copula $\Gamma(p_1,\ldots,p_n)$ maps multivariate distribution functions to the interval [0,1],

$$\Gamma : [0,1]^n \rightarrow [0,1]$$

see [McNeil, Frey and Embrechts, 2005].

Copulae represent the interrelations between the values p_i of the distribution functions. For example the simple product copula is applicable if and only if two projects are independent, which is the case for redundant projects:

$$\Gamma(p_1,...,p_n)=\prod_{i=1}^{n} p_i$$

5.6. R&D Portfolio Selection Methods

The following section gives a brief introduction to the methods used for the selection of projects for a portfolio as can be found in the current literature and also explains if and how they meet the requirements of an R&D project portfolio.

5.6.1. Portfolio Maps

Bubble diagrams, portfolio matrices or portfolio maps plot projects to an X-Y map. Examples for the axes are risk/reward, technical feasibility/market attractiveness, cost/timing, and cost/benefit. The quadrants of the resulting chart are used to classify the various projects [Mikkola, 2001].

These techniques are briefly mentioned here because they are quite popular as the portfolio selection problem is visualised. However, these techniques are more often used in addition and in support of other portfolio selection methods [Cooper, Edgett and Kleinschmidt, 2001a], because they rely on subjective judgements concerning the classification of the projects in the map. Thus, there is no underlying model and the classification scheme is neither objective nor reproducible.

Constraints are not incorporated in the model because there is no way of representing them. Neither are interrelations between projects, as the projects are placed in the map independently of each other. The model could deal with multiple objectives when applying it in an iterative process for various kinds of axes.

5.6.2. Scoring Models Including Checklists

The chapter on project evaluation techniques under risk provides a detailed explanation of scoring models and checklists, refer to 3.2.2. As these models evaluate various aspects or criteria of the projects, they can be used for the evaluation of one project, but also for the evaluation of certain aspects of one project in relation to the same aspects of another project. Therefore, these methods can also be used for the selection of projects for a portfolio and do account for multiple objectives in a portfolio.

Using check lists in order to find out if a project should be part of the portfolio or not, each project must achieve a certain number of yes answers out of a set of yes/no questions.

Scoring models as described in 3.2.2. are used to rank projects against each other, whereas checklists are more often used to make stop/go decisions. According to a study by Cooper, Edgett and Kleinschmidt [Cooper, Edgett and Kleinschmidt, 2001a] the most important criteria for scoring models are strategic fit, financial reward, risk, probability of success and the capabilities to undertake the project commercially and concerning the technology available. The main advantage of scoring models is that they can capture multiple goals. Both quantitative and qualitative criteria can be used to value the projects [Cooper, Edgett and Kleinschmidt, 2001a]. Thus it is possible to also incorporate strategic criteria such as fit with corporate objectives, competitive advantage or market attractiveness. However due to the multiple objectives that can be incorporated the resulting score is dimensionless and might thus be considered as not having such a well-defined meaning like financial numbers like profit or rate of return. The criteria can also be weighted according to their relative importance. The overall project scores are either computed by adding or by multiplying the scores of all criteria [Moore and Baker, 1969a]. To rank the projects according to the criteria they can *e.g.* be scaled as low-medium-high or on a scale of *1* to *5*, *0* to *10 etc.* [Cooper, Edgett and Kleinschmidt, 2001a]. The project candidates can be prioritised against each other. The scores can also be compared to some absolute standards or certain cut-off criteria. If a project gets a zero score on one of these knock-out criteria it gets removed from the list of projcets being candidates for the portfolio.

According to Cooper, Edgett and Kleinschmidt [Cooper, Edgett and Kleinschmidt, 2001a] scoring models are the most favoured ranking methods. They show up the strengths and weaknesses of each project. As in the early stages of an R&D project financial estimates concerning the projects successes are difficult to obtain, scoring models are well suited to evaluate the projects, as they do not focus on financial criteria only. However as scoring models do also account for subjective non-financial criteria, the relevant data have to be provided in form of subjective opinions. Each project has to fulfil a complete set of criteria, which ensures that all critical issues are taken into account for each project. The key issue when applying scoring models to project portfolio selection seems to be the definition of the appropriate scoring criteria and an according procedure to obtain management input. This is especially important as an argument against scoring models is that in case the criteria of the model overlap, a high score concerning one criteria results in high scores in others as well [Cooper, Edgett and Kleinschmidt, 2001b]. Poh, Ang and Bai [Poh, Ang and Bai, 2001] identify scoring models as the most popular R&D project portfolio selection methods due to the availability of data, their simplicity and adaptivity.

Scoring approaches do not account for interrelations between projects. Risk can be taken into account, if it is modelled as one of the aspects for comparison. In the same way constraints can be incorporated into the selection.

The scoring model presented by Cooper, Edgett and Kleinschmidt [Cooper, Edgett and Kleinschmidt, 2001b] consists of six criteria, all of which having sub-criteria. The main criteria comprise:

- Strategic alignment and importance
- Product and competitive advantage
- Market attractiveness
- Leveraging core competencies
- Technical feasibility
- Financial reward versus risk

The overall score for a project is computed by adding the weighted scores for each of these criteria.

Henrikson and Traynor [Henrikson and Traynor, 1999] present a scoring model for R&D project evaluation that uses the criteria relevance, risk, reasonableness, and return. Tradeoffs among the criteria are explicitly incorporated. The value is defined as a function of benefits and costs.

Souder [Souder, 1972] uses a scoring approach in order to determine the suitability of other models for R&D portfolio selection.

5.6.3. Mathematical Optimisation

Every mathematical optimisation model includes the optimisation of an objective function considering constraints concerning resources, technology, strategy, project's dynamics and logic. Among the mathematical optimisation approaches are linear optimisation models, non-linear optimisation models, and stochastic optimisation models.

These models require a mathematical model of a system that includes constraints and relationships between variables [Huchzermeier and Loch, 2001]. However, mathematical optimisation models often require data that research and development is not able to provide, which limits the practical use of such models [Heidenberger and Stummer, 1999].

Mathematical optimisation approaches are methods for the efficient implementation of an algorithm, for example the Simplex algorithm for linear optimisation models or the Knapsack algorithm for certain dynamic optimisation models. Thus, mathematical optimisation models are just tools, but literature does often not distinguish between these tools and the actual algorithms.

Linear Optimisation

Linear optimisation relates to maximising or minimising a linear function of a number of variables subject to a system of linear constraints. These constraints are linear equations or linear inequalities [Balinski and Tucker, 1969].

Definition

Solving a problem with the help of linear optimisation can in the so-called standard form be expressed as follows:

$$\begin{aligned}&\text{minimise/maximise } c^T x\\&\text{subject to} \qquad Ax = b \text{ with } x \geq 0\end{aligned}$$

where x is the vector of variables to be solved for, A is a matrix of known coefficients, and c and b are vectors of known coefficients. cx is called the objective function, and the equations $Ax = b$ are called the constraints. Of course, all these entities must have consistent dimensions, and the matrix A is generally not square. Usually A has more columns than rows, and $Ax = b$ is therefore quite likely to be under-determined, leaving great latitude in the choice of x with which to minimise or maximise $c^T x$. For a more detailed discussion of the concepts of linear optimisation refer *e.g.* to [Dantzig and Thapa, 1997], [Dantzig and Thapa, 2003], [Nash and Sofer, 1996].

The most famous algorithm to solve linear programs is the Simplex method, first proposed by Dantzig in 1947 [Dantzig, 1963]. A Simplex is an n-dimensional convex polytope having $n+1$ vertices. The set of feasible solutions, that satisfies the system of linear equations $Ax = b$ can be regarded as a closed convex polytope. As the function to be optimised is linear and the set of constraints is convex, the maximum—if it does exist—must be achieved for at least one extreme point of the constraint set [Karlin, 2003]. The polytope is defined by the intersection of half-spaces in n-dimensional Euclidian space. Each half-space corresponds to the area lying on one side of a hyperplane. The upper bound of this polytope is given by the number of variables. The objective is to find a point x in the polytope yielding the highest value for the given objective function possible, which corresponds to shifting the hyperplane $c^T x = 0$ as far as possible in the direction of the vector c up until it just still touches the polytope. Then all osculation points are optimal. If the optimization problem is bounded and solvable, it can be shown that there always exists an optimal vertex. Thus the search can be limited to the vertices of the polytope however there can be many of them. An optimum can be found by either moving through the interior of the polytope or by searching on the boundary, which is the approach used when applying the Simplex algorithm. The Simplex method first determines any extreme point. The basic idea is to move stepwise from one vertex of the polytope to the neighbouring vertex yielding a higher value in the objective function, until no more neighbouring vertices yielding higher values in the objective function can be found [Karlin, 2003].

The optimum will be found at a vertex of the polytope and is usually unique, unless it is located on an edge parallel to the hyperplane and thus not unique. The Simplex algorithm is used to determine one optimum even though there might be more than one. Therefore, when searching for the optimum it suffices to search the edges of the polytope, the interior can be ignored.

The Simplex algorithm is called a local search algorithm as it searches for a better solution locally and then proceeds from this solution. Due to the fact that linear optimization is a convex optimization problem, this local optimum is also a global optimum.

The number of a polytope´s vertices can increase exponentially with the number of variables and inequalities. Thus in the worst case the runtime of the Simplex algorithm is exponential. For most practical applications however the runtime is good. For a more detailed introduction to the Simplex algorithm refer *e.g.* to [Dantzig, 1963], [Dantzig and Thapa, 1997], [Dantzig and Thapa, 2003].

According to the duality theorem every linear program can be converted into a dual linear program. The dual of a dual linear program is again the primal linear program. Every feasible solution to a linear optimisation problem provides a bound on the optimal value of its dual linear program´s objective function. Basically the dual linear program results from the primal linear program by exchanging rows and columns. Thus the Simplex algorithm can also be used to solve the dual linear optimisation problem with the help of the dual Simplex algorithm introduced by Lemke [Lemke, 1954].

The Simplex algorithm can for example be used to find the equilibria of a zero-sum game being the solutions to a linear program [Dantzig, 1963], refer also to 3.2.3.

Integer linear optimisation—often simply referred to as integer programming—requires some or all of the variables to take integer values. The advantage of integer optimisation is that for many applications it seems to be more realistic than linear optimisation, at the cost of being much more difficult to solve.

Linear Optimisation for the Creation of an R&D Project Portfolio

The use of linear optimisation for portfolio evaluation yields to the optimisation of expected benefits of a portfolio of R&D projects taking resource constraints into account. Linear optimisation models can be extended to deal with more than one time period. An advantage of the method is that large problems with a number of projects and according resource constraints can be solved by using the Simplex algorithm in order to calculate the optima [Stummer, 1998].

Yet, a major shortcoming of linear optimisation is that the uncertainty surrounding R&D decisions is not covered by the model [Jackson, 1983]. There are approaches to weight each outcome in the linear optimisation model with an expected probability of success instead of using the expected value of the outcome [Asher, 1962]. The drawback of this solution to incorporate uncertainty is that it does not provide information on the range of outcomes which is clearly an important issue for the decision maker.

Linear optimisation models are not able to deal with the types of interrelations existing between projects [Heidenberger and Stummer, 1999]. Thus linear programming models assume additivity, which does not consider interrelations. Assuming additivity implies that the total function or portfolio value can be determined by adding the individual functions of the projects in the portfolio [Chien, 2002]. Efforts to incorporate project interrelations into linear optimisation have not yet been very successful.

Furthermore, fractions of projects can be part of the solution. As projects are non-divisible, and discrete decisions have to be taken when creating a portfolio of R&D projects, integer linear optimisation can be used to avoid the problem of fractional projects in the portfolio [Jackson, 1983].

If one or more of the dimensions of an R&D project should be considered as a probability distribution, non-linear optimisation techniques are required.

Non-linear Optimisation

Non-linear optimisation is used to represent a system mathematically modelled through a series of equations, some of which are non-linear. Quadratic, hyperbolic, or other types of non-linear equations can represent more complex interactions than linear equations. The origins for solving non-linear optimisation problems using non-linear programming were provided in 1939 by Karush [Karush, 1939] and in 1951 by Kuhn and Tucker [Kuhn and Tucker, 1951], now known as the Karush-Kuhn-Tucker conditions. For a discussion of the history of these conditions refer to [Kuhn, 1976]. Non-linear optimisation allows for solving non-linear objective functions subject to non-linear inequality constraints using the Karush-Kuhn-Tucker conditions. Most non-linear optimisation solution processes can only guarantee the generation of a local optimal solution, refer *e.g.* to [Luenberger, 1984].

Non-linear optimisation problems do not exhibit the characteristics of linear optimisation models used by the Simplex algorithm to solve these kinds of problems. The solution space is not necessarily a convex polytope. It does not even have to be convex or connected. In case of a non-linear objective function multiple optimal solutions are not necessarily located on parallel hyperplanes. Thus the optimum solutions do not have to be at the vertices of the solution space, but can also be found in the interior. There is not only a global optimum but also local optima [Zimmermann, 2005].

The method to optimise non-linear utility functions is usually implemented using dynamic programming. That is probably the reason why literature often refers to this problem solving technique as dynamic programming. To be precise, dynamic programming is a universal problem solving technique that can also be applied to a variety of other kinds of optimisation problems. In 1949 Arrow, Blackwell and Girschick solved a generalised version of a statistical decision problem by a functional equation approach as one of the first applications of dynamic programming [Arrow, Blackwell and Girschick, 1949].

Definition

Dynamic programming refers to a recursive method to finding a solution for sequential decision problems. The term dynamic programming was first used by Bellman, who used it to show how solutions for a wide class of sequential decision problems under uncertainty can be found [Bellman, 1957].

Bellman provides a general description of the class of problems that can be solved by dynamic programming techniques [Bellman, 1954]: The economic system under consideration is described by a set of parameters *P*, called the state variables. The optimisation problem consists of multiple stages with a policy decision *D* required at each stage. A finite or infinite number of states can be associated with each stage. The policy decision at each stage has the effect of transforming the current state into a state associated with the next stage, whereby the transformation may be deterministic or stochastic. The decisions are taken with the aim to maximise a function of the final state variables. Knowing the values of the state variables and the possible decisions at that stage, the task is to find a strategy that will yield the optimal decision at each stage. Bellman defines a function for the general problem [Bellman 1954, p.47]:

$F(P)$ = the function of the final state variables obtained using an optimal policy starting with the initial variables represented by *P*

Furthermore the transformation effect by a choice is described by $P' = T_k(P)$ with *k* being the parameters that describe a particular choice.

Given a current state, an optimal policy for the remaining stages is independent of the policy adopted in the previous stages. This is the so-called "Principle of Optimality" or the "Markovian Property". The principle of optimality according to Bellman states that "an optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision" [Bellman, 2003, p.83]. Dynamic programming is thus suited for optimisation problems characterised by an optimal substructure, which means that an optimal solution can be composed in an efficient way by finding optimal solutions to the related subproblems.

This can be expressed by the following equation [Bellman, 1954, p.47]:

$$f(P) = \max_k f(T_k(P)) \tag{5.33}$$

Making suitable assumptions about $T_k(P)$ this equation can be used to find optimal strategies.

Usually finding the optimal policy for each stage begins at the last stage, thus dynamic problems are typically solved by using a backward solution technique; although, in some cases, a forward procedure makes more sense, see for example [Bellman, 1957].

In game theory the concept of dynamic programming is known as backward induction. Backward induction can be used to identify optimal decision rules for agents playing against nature. With respect to dynamic games of a number of agents the method is employed to find subgame perfect equilibria [Von Neumann and Morgenstern, 1944]. For dynamic economic models, backward induction aids in finding competitive equilibria. Backward induction results in a decision strategy which is optimal for every possible subgame because at every node of the game tree the agent chooses the alternative yielding the highest expected payoff for all possible further stages of the game. Regarding a dynamic two-agent game, backward induction results in a pair of strategies. These strategies are mutual best responses and constitute a Nash equilibrium, refer also to 3.2.3. The strategies resulting from backward induction are also subgame-perfect [Selten, 1965] as they are Nash equilibrium strategies in every possible subgame.

A key assumption of backward induction is that the decision strategies are time consistent, meaning that an agent has no incentive to *ex post* deviate from a strategy that was provided *ex ante* by backward induction. The validity of backward induction is based on assuming that agents maximise expected utility. However in many cases decision making under uncertainty is not consistent with the concept of expected utility maximisation and preferences should thus be represented as non-linear functions of the probabilities which represent the uncertainty, refer *e.g.* to [MacCrimmon and Larsson, 1979], [Machina, 1983], [Weber and Camerer, 1987], [Fishburn, 1988].

Non-linear Optimisation for the Creation of an R&D Project Portfolio

When applying non-linear optimisation to the selection of R&D projects for a portfolio, decisions about a project made in one time period affect the environment in which decisions will be taken in the next period. That means that the probability for success of the project in the last time period depends on the resources available for that project in the last and all previous periods. Thus, the model can be used to find the optimal path of actions for a set of sequentially made decisions.

Non-linear optimisation is capable of treating the relation between resource inputs and the probability of the project's success through a non-linear function. A powerful feature of these models is their ability to include interactions among projects such as competition for the same resource pool, system level interactions through mutual incompatibilities, synergistic enhancements or market interactions if the market criteria are not separable and additive [Jackson, 1983].

A shortcoming of non-linear optimisation models is that only one resource to be allocated over a project's life can be constrained [Heidenberger and Stummer, 1999].

Applying dynamic programming to the non-linear optimisation of a number of projects over various stages can be expressed as finding an optimal resource allocation strategy for each project in each period. Using a backward procedure, the aim is to determine the amount of support the project has to be given in the present period under the assumption that all subsequent decisions have been optimally made, compare [Jackson, 1983]. Working backwards the last decision for the portfolio selection is to maximise expected benefits minus costs:

$$F_{i,1} = B_{i,1} \times P_{i,1} - X_{i,1} \tag{5.34}$$

where the index i is the number of the project, and 1 refers to the last period in the project's life. $F_{i,1}$ are the net benefits gained from project i, if it is successful in the last period. $B_{i,1}$ are the total benefits gained from project i, if it is successful in the last period. $P_{i,1}$ is the probability that project i is successful in the last period and $X_{i,1}$ are the investments for project i, in the last period. The probability for success of a project in period 1 depends on the investments made for the project in period 1 and the investments in all the previous periods.

Having determined the optimal level of support for each project in the last period, the procedure is repeated for the previous stage. For all the (j–1) periods left the problem is to maximise:

$$F_{i,j} = B_{i,j} \times P_{i,j} - X_{i,j} + (1 - P_{i,j})\, F_{i,j-1} \tag{5.35}$$

where j is the number of the current period. $B_{i,j} \times P_{i,j} - X_{i,j}$ are the expected benefits of research from each project for each of the remaining periods and $(1-P_{i,j})F_{j-1}$ is the expected net benefit of research in the next period if it occurs.

Stochastic Optimisation

The early roots of stochastic optimisation were provided by Dantzig in 1955 referring to optimisation models for activities that consist of two or more stages. The quantities relating to the activities during the first stage have to be determined, the ones needed during the following stages cannot be determined in advance as they depend on the uncertain demand in the earlier stages [Dantzig, 2004]. Also in 1955 Beale presented algorithms for the solution of stochastic optimisation models [Beale, 1955].

In stochastic optimisation models at least one input is uncertain and can vary. Therefore, these models seem to be especially suitable for R&D project selection, as they allow for a high degree of uncertainty. In practice, the lack of information concerning the distribution of stochastic variables limits the use of stochastic programming [Stummer, 1998]. Most of the existing models use chance-constrained programming where resource limitations are random variables rather than constant parameter [Heidenberger and Stummer, 1999]. Thus chance-constrained programming is capable of taking breakthroughs in research into account and resource plans and funding can be revised after such breakthroughs.

A major problem of the method is that data requirements such as estimating the responses to breakthroughs in each R&D project are usually very demanding [Jackson, 1983].

Note that stochastic optimisation refers to mathematical optimisation under uncertainty, and thus comprises any mathematical optimisation where one or more of the variables are not precisely known when decision-making occurs. Thus, stochastic optimisation defines a class of problems and can be solved by, for example, stochastic dynamic programming, which is a solution procedure and not a problem class. Therefore, stochastic optimisation is not a counterpart of linear and non-linear optimisation, but the counterpart of deterministic optimisation [Kall and Wallace, 1994]. There are a number of methods to solve stochastic programs, including stochastic linear optimisation, stochastic non-linear optimisation and stochastic dynamic optimisation, so most of these methods are adjustments of methods known from deterministic optimisation. This is the reason why stochastic optimisation is not listed as a separate method for the selection of projects for a portfolio in Table 5.2.

5.6.4. Comparison of the Methods

	Inter-relations	**Risk and Uncertainty**	**Multiple Objectives**	**Constraints**	**Algorithm**
Portfolio Maps	not covered	optional	optional	not covered	visual comparison
Scoring Models	not covered	optional	covered	optional	linear mapping
Linear Optimisation	not covered	limited	not covered	multiple constraints	*e.g.* Simplex algorithm
Non-linear Optimisation	covered	covered	not covered	depending on the algorithm (one constraint in case of dyn. progr.)	*e.g.* Dynamic programming

Table 5.2: "Comparison of Portfolio Selection Models"

Interrelations

Interrelations include interdependencies, synergies and redundancies as defined in 5.3.

Risk and Uncertainty

In the case of mathematical optimisation models, the possibility to cover risk refers to the ability of these models to incorporate probability distributions for one or more of the parameters, thus describing the risk inherent to these parameters. Considering scoring models and portfolio maps, the uncertainty caused by various aspects of the project or the project as a whole, can only be incorporated into the portfolio selection process as a criterion for comparison.

Multiple Objectives

Note that multiple objectives in the context of a portfolio of R&D projects are defined as a number of goals that should be achieved by creating a portfolio. These objectives can be orthogonal, meaning that one objective is completely independent of the other. In case of ambiguous objectives, priorities have to be assigned to the various goals.

Constraints

Constraints refer to resource constraints, including maximum costs that must not be exceeded. Mathematical optimisation techniques include constraints onto the calculation, whereas regarding scoring models and portfolio maps projects that do not conform to the constraints must be excluded from the portfolio selection process "manually".

Algorithm

An algorithm describes a procedure to select projects for a portfolio. For mathematical optimisation models this is, as the name suggests a mathematical algorithm. Regarding scoring models, projects for the portfolio are selected by linear mapping. Portfolio maps, as a heuristic method, just provide a way of visually comparing the projects according to their position on the map [Cooper, Edgett and Kleinschmidt, 2001a].

Chapter 6 — An Evaluation Framework for R&D Portfolios

The aim of the model presented within this thesis is to develop a framework for the evaluation of R&D projects accounting for the multiple aspects or dimensions that contribute to the success of R&D projects and providing a measure for the risk surrounding these aspects.

The real options method is used for the valuation of the various dimensions of an R&D project. Traditional options valuation focuses on the financial dimension of a project. Especially with R&D projects, there are often other dimensions that contribute to the success of the project, and therefore the possibility for taking these dimensions into account should exist. The presented framework tries to do this by performing the same valuation for the budgetary dimension of the project as well as for *e.g.* gaining knowledge or the environmental impacts of a project.

The valuations of the various dimensions of a project are then consolidated using multi-attribute utility analysis. After having determined utility values for sets of projects, these values are used for the selection of the optimum set of projects as a portfolio. The portfolio selection maximises the utility of the portfolio under resource constraints and limited risk considering interdependencies, synergies and redundancies between the selected projects.

The presented framework is implemented as a prototype. In order to illustrate the concepts, this chapter includes screenshots of the implementation using data from sample projects. Chapter seven presents the application of the framework in the context of several case studies. For a detailed explanation of how to use the prototype refer to the manual presented in the appendix.

6.1. Aspects Considered

6.1.1. Multi-Dimensionality

One of the main aims of the presented framework is to take the multi-dimensionality of R&D projects into account. Evaluating a project thus involves identifying the aspects that determine the success of the project. As already mentioned in 1.2.1. a distinction between conventional projects and R&D projects is that the latter are not only conducted for the financial return but for gaining knowledge and experience in an emerging or completely new field.

Undertaking research projects also has benefits and drawbacks other than the mere gaining of knowledge, for example the development of new drugs or ways of treating diseases, which enhances the social situation, or the development of new technologies that have effects on the environment. Such effects can have a direct financial impact and thus be measured in monetary units. For example, some new production technology has to be developed because the technology in use does not meet the environmental regulations any more and continuing to use the old technology would involve high payments to compensate for the environmental damage caused. The effects of other research results have more long-term character, and are thus probably not appropriately measurable in monetary units.

Even though, in some cases, it is probably hard to estimate the potential effects of R&D, it is nevertheless important to take these factors into account, because they might justify conducting an R&D project that is not a success, when success is defined only in terms of short-term financial return.

Thus an R&D project is modelled by decomposing it into the dimensions that are critical for the success of the project. Critical success factors do not only comprise factors contributing to the success of the project, but also aspects that can cause the project's failure, because, for example, governmental regulations are no longer met if the contribution of that aspect to the project exceeds or falls below a certain threshold.

The presented framework allows for a separated valuation of the various dimensions of a project to make explicit in which respects the project is a potential success and in which respects it is a potential failure. In order to provide a measure of the risk surrounding the outcome of the project with regard to the various dimensions, the Value-at-Risk (VaR) of each of these critical dimensions is calculated, refer to 5.5., 6.3. respectively.

Apart from the monetary dimension of an R&D project, the knowledge gained is used as an example dimension throughout this chapter. Obviously, other dimensions can be taken into account, such as social or environmental impacts. Within the formulas, whenever it is convenient, multi-dimensional values are represented by vectors for the sake of universality.

The dimensions chosen for the evaluation of the projects should fulfil a number of conditions in order to allow for a consistent comparison of various projects, which are also mandatory for the portfolio selection process: The dimensions should be comprehensive, which means that the decision maker can understand to what extent this dimension contributes to the specified project success at a given point in time. The dimensions are also supposed to be measurable, which makes a rank ordering possible, and allows for a comparison of the dimensions' values, before, during and after the project. If there are no commonly accepted objective measurement scales for a dimension, subjective indexes must be constructed, for example point ordered scales [Keeney and Raiffa, 1976]. Apart from the financial dimension, the remaining dimensions should be mutually independent, which implies that these dimensions ought to be orthogonal, refer to 6.5.

Furthermore, there are desirable properties for the dimensions: The dimensions for the evaluation of a project should be complete, meaning that all of the aspects that are critical for the project's success are represented by the dimensions. Non-redundancy is required in order to avoid double counting of impacts, which can easily happen if there are dependencies between the various dimensions, or if one dimension includes the other in contributing to the overall success. Non-redundancy, combined with the coverage of all the relevant dimensions, leads to a set of dimensions minimum in size [Keeney and Raiffa, 1976].

6.1.2. A Note on Measuring Intellectual Capital

When trying to estimate the value of knowledge gained within an R&D project, some special characteristics of the value of knowledge have to be taken into account:

- Knowledge is bound to an individual or an organisation. Thus it follows that knowledge per se does not exist.
- The level of knowledge of an individual or organisation[15] only increases and never decreases, not even if the relevant information is given away to other individuals or organisations. This implies that one has also gained knowledge within a project if it turns out that it is not possible to develop a certain technology, that a method is not applicable to the specific field of research or that it is generally impossible to solve a problem in the way suggested. Thus the research team can only know more after the project.
- The "dissemination of knowledge" is relatively cheap in comparison to the value of knowledge.
- The convertibility of knowledge is a special issue and there are cases in which knowledge can be "bought", *e.g.* by hiring people or paying licenses, and there are cases in which this is not possible, because the necessary information does not exist. Arrow [Arrow, 1971] points out that—given there is some kind of market for information—the value of information is not known to the purchaser until the information is obtained. Thus the buying decision is based on non-optimal criteria.
- The process of gaining knowledge can be time consuming, and it is possible that this process cannot be accelerated through the addition of extra resources.
- Information, originating knowledge, is both, the product of research activities, but also the input necessary to undertake research [Arrow, 1971].

Definitions

Human capital is defined by the OECD [OECD, 1999] as:

„The knowledge, skills, competences and other attributes embodied in individuals that are relevant to economic activity".

According to Machlup [Machlup, 1980] there are two kinds of knowledge important for the transfer of innovations, which the author refers to as "knowing that" and "knowing how". Machlup describes "knowing that" as propositional knowledge about factual or decriptive data. Whereas "knowing how" refers to knowledge about how to achieve certain desired outcomes, which does not necessarily require understanding the specific details of the components involved in achieving the desired effects.

Stewart [Stewart, 1997] classifies intellectual capital into human capital, organisational capital and customer or external capital. Human capital is the knowledge of the employees, while organisational capital comprises the procedures, databases, systems and solutions and external capital refers to the information that is exchanged between the company and its customers, also including reputation and customer loyalty. This definition of intellectual capital in essence conforms with many other existing classifications, which only differ concerning the naming conventions.

Measurement Techniques

When trying to measure the knowledge gained when undertaking a project, one actually aims at comparing the intellectual capital of a company or, more specifically, a team of researchers before and after the project.

[15] A definition of individual and organisational knowledge is provided in the following section.

There are two general methods for measuring intellectual capital. One method aims at performing a component-by-component evaluation. This of course requires finding measurement units that are appropriate for each component. Regarding, for example, the value of patents or the number of work-related competencies, different ways and thus different units of measurement have to be determined. Furthermore, one has to take the various levels in an organisation into account, because different measures have different relevance and usefulness concerning the organisational structure of a company. According to Luthy [Luthy, 1998] measuring quantities is usually more relevant at the work unit level, and financial measures are usually more relevant at the organisation level. Nevertheless, all of the values measured have to be finally aligned to guarantee a common valuation of intellectual capital.

An example method for the measurement of intellectual capital on a component-by-component level is called the "Brooking Approach – Dream Ticket or Intellectual Capital Audit Example", see [Brooking, Board and Jones, 1997]. The business literature contains several other performance evaluation models that relate to the measurement of intellectual capital, including the "Balanced Scorecard" developed by Kaplan and Norton [Kaplan and Norton, 1996].

The other approach—the financial approach—is to measure the value of intellectual assets in financial terms at an organisational level, without referencing to individual components of intellectual capital.

In order to classify the financial methods for the valuation of intellectual capital Stewart [Stewart, 1997] suggests three measures of intellectual capital at an organisational level. These are market-to-book ratio, Tobin's *q*—the ratio of the value of an asset to its replacement cost, developed by Nobel Prize winner James Tobin—and calculated intangible value. Without describing the approaches in detail, the general idea of these measures is to determine the value given to the company by the stock market, compared to the value indicated on the company's balance sheet. The differences between these two values are then defined as the intangible value of intellectual capital that is not captured by traditional accounting systems.

Regarding the debate whether intellectual capital should be measured with financial or non-financial tools, the argument in favour of financial valuation is that non-financial methods are not strong enough to influence managerial actions. For a more detailed discussion of the use of financial or non-financial methods for the valuation of intellectual capital refer to Ferec [Ferec, 2000].

Information, Knowledge and Innovation

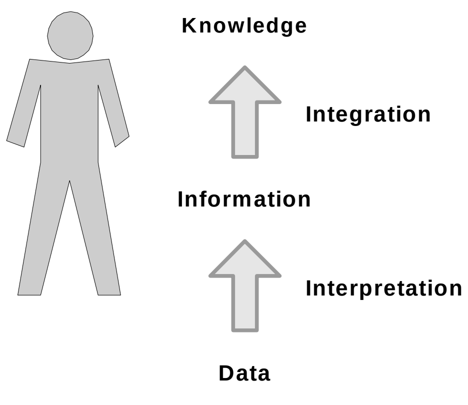


Figure 6.1: "From Data to Knowledge"

Data are objective and can be stored, transferred and measured easily *e.g.* in Bytes, kiloBytes, gigaBytes. For example a certain stock price is represented and transmitted as data. The information that can be gained from the data depends on how humans interpret the data and on their current level of information. Thus information is subjective and the same data can provide different information for different humans. The stock price for example can be interpreted as surprisingly high or low depending on the expectations of the shareholder. Furthermore information is independent of its representation. It does not matter whether the value of a share is represented in a table, in a graph or transmitted via voice mail. Knowledge is even more abstract, because it involves the processing of information within the context of knowledge the human has already obtained. Therefore it follows that knowledge can neither be shared nor stored.[16] It is thus not possible to talk about measuring knowledge as intellectual capital, because knowledge itself does not exist in measurable or any other reified form [Stacey, 2000]. Again referring to the example of the stock price, the knowledge gained by the information of the stock price can *e.g.* be combined with the knowledge the shareholder has already obtained through experience and the economic environment and thus be used as a basis for the decision whether to sell or keep the stock.

Shannon's Information Theory

Information content as defined by Shannon and Wiener [Shannon and Weaver, 1949] refers to the transfer of information from a sender to a receiver, by a message.

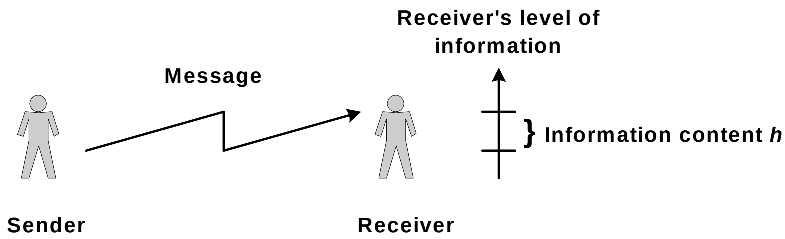


Figure 6.2: "Information Transfer"

As can be seen in figure 6.2. the aim is to measure how much the receiver's level of information is increased by the information content *h*, independent of the receiver's total level of information. The information content *h* has got the following characteristics:

- It is independent of the information's representation by the message, *i.e.* the way of encoding the information is irrelevant.
- It cannot become negative.
- The information content *h* is supposed to be a monotonic function of the reciprocal value of the expected value that this information will occur. This has got the obvious effect of expected information having a low information content *h* and unexpected information having a high information content *h*.

[16] To be precise one has to distinguish between explicit and so-called tacit knowledge. Explicit knowledge is systematic and easily transmitted from one person to another in the form of language. Tacit knowledge takes the form of mental models below the level of awareness and is displayed as skill or knowhow [Nonaka and Takeuchi, 1995].

- Given monotonicity and independence of representation, it follows that if the information is split up and transferred via two messages, the sum of the information contents of the two messages is equal to the total information content.

Using the independency of phases of projects and expected values, the probability of the total information content is the product of the individual probabilities. Combined with the concept of additivity h is best described by a logarithmic function of the individual expected values, because only then $h(x * y) = h(x) + h(y)$. Thus the information content h is given by:

$$h = ld\frac{1}{p} \tag{6.1}$$

where p refers to the probability of expecting the information and the binary logarithm scales the information content, that becomes 1 for p=0.5. The information content is measured in bits.

Note that h also defines the minimum length of a binary code that can be used to encode the information. The difference between a code that is used in practice and h corresponds to redundancy.

Considering the two cases of p =1 and p =0, information content that is expected with certainty has got a probability of occurrence of 1, from which the obvious result of h = 0 follows. In case the occurrence of certain information is nearly impossible and thus having a probability of $p \rightarrow 0$, this leads to h approaching infinity, which shows that there is no upper limit for the information content.

If a limited number of different information is expected with probability p_i for each occurrence, the average information content H is given by:

$$H = \sum_i p_i \, h_i = \sum_i p_i \, ld\frac{1}{p_i} \tag{6.2}$$

with $\sum p_i = 1$.

The average information content H has got a maximum, when all the probabilities p_i are equal, *i.e.* every piece of information occurs with equal probability.

The concepts introduced above can also be applied to knowledge replacing information. The subjective character of knowledge can be expressed by using expected values of relevant information, which themselves refer to expectations of individuals. Referring to the value of knowledge it is important to mention that the information content does not say anything about how useful the information is, but should rather be regarded as a measure of complexity.

Considering research projects the main goal is to gain knowledge. When it comes to the evaluation of projects, the value of the knowledge gained can either be measured in monetary units or regarded as the average information content, which itself can be seen as a measure of innovation. Following this distinction between the monetary value and the information content, the financial dimension and the dimension knowledge are orthogonal in the sense that neither of the two can be substituted by the other.

6.1.3. A Note on Measuring Environmental Impacts, Costs and Benefits

Environmental accounting, as a quantitative measurement technique in monetary values or physical units, aims at accurately identifying and measuring investments and benefits related to environmental conservation activities. Environmental conservation refers to the prevention, reduction and avoidance of environmental impacts or the removal thereof. Environmental accounting comprises the following three kinds of measures:

- Environmental conservation cost—monetary value
- Environmental conservation benefit—physical units
- Economic benefit resulting from environmental conservation activities—monetary value

There is a tendency of management control systems that take environmental concerns into account to use non-financial measures. However financial values have always been "accountancy's strongest weapon". Thus, as Cope and James [Cope and James, 1990] point out, capturing internal environmental considerations in terms of financial consequences and attempting to measure financially external impacts from the organisation on the environment is a major challenge for the further development of environmental accounting. For a more detailed introduction to environmental accounting refer *e.g.* to [Bailey, 1991] or [White, Becker and Savage, 1993].

There are a number of valuation tools for various kinds of environmental liabilities—such as compliance obligations, punitive damages or fines and penalties—a company has to face. For a definition of an environmental liability refer to 6.4.2. Bailey *et alii* provide a brief description and comparison of techniques, that derive monetary values for the various environmental liabilities [Bailey et al., 1996].

6.2. The Model

The functionality of the presented framework for R&D portfolios is to support decision makers with objective criteria for selecting R&D projects under limited resources, limited risk and arbitrary interrelations between projects. Input parameters are estimates, *e.g.* based on experts' estimates or other suitable data sources, on the projects' successes $s_{i,k}$ concerning the various dimensions k, the necessary investment costs $c_{i,k}$ as well as the available resources $C_{max,k}$ and project interdependencies as well as synergies and redundancies. Interrelated projects are grouped into clusters τ by the portfolio selection module. The presented framework selects a portfolio that maximises the expected utility U considering dependencies and constraints, such as limited risk and resources. Total risks $\varrho_{\lambda,k}$ of the selected projects are computed simultaneously. Although the evaluation and interrelations of the projects refer to the various dimensions, the selection process is based on a scalar utility measure. The utility itself is determined by the call values $v_{i,k}$ for every dimension of the single projects π_i. These call values are computed based on the real options model (RO) using the statistical means $\mu_{i,k}$ and deviations $\sigma_{i,k}$ of the estimated projects' successes. For each portfolio the call values V_k of the various dimensions are calculated and the portfolio's utility is determined using multi-attribute utility analysis (MAUA), thus delivering the portfolio's utility measure U.

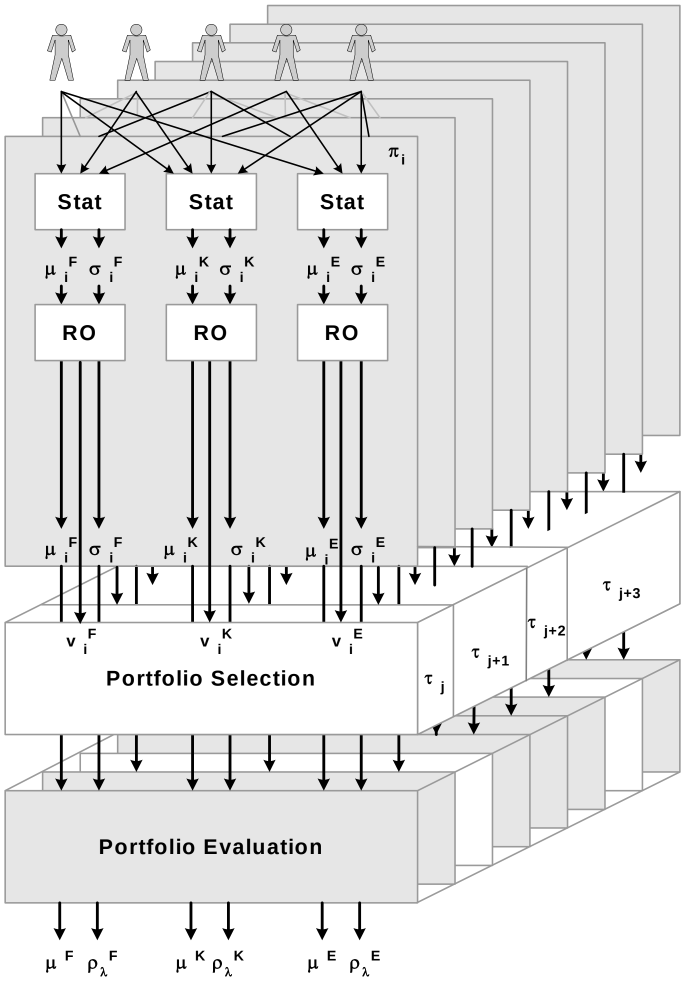


Figure 6.3: "Design of the Evaluation Framework for R&D Portfolios"

Abbreviation	Description
π_i	Project *i*
$\mu_{i,k}$	Mean of success estimates for dimension *k* of project π_i
$\sigma_{i,k}$	Deviation of success estimates for dimension *k* of project π_i
$v_{i,k}$	Call value of dimension *k* of project π_i
$\varrho_{\lambda,k}$	Risk of dimension *k* at confidence level λ of selected portfolio
F	Dimension finance
K	Dimension knowledge
E	Dimension environment
τ_j	Cluster *j* of interrelated projects

Table 6.1: "Legend" for Figure 6.3.

6.2.1. Applying Statistics

Estimates on the outcomes of each dimension of the various projects are input to a basic statistic module (Stat) delivering the mean $\mu_{i,k}$ and deviation $\sigma_{i,k}$ of the success estimates for each dimension k.

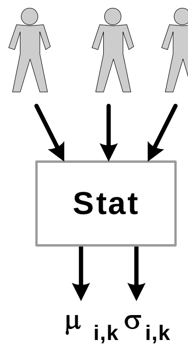


Figure 6.4: "Statistics Module"

6.2.2. Real Options Valuation

For each dimension k of every project π_i the call values $v_{i,k}$ are computed, using the Black-Scholes formula as described in 6.4.1. with means $\mu_{i,k}$ and deviations $\sigma_{i,k}$ as input parameters. The call values $v_{i,k}$ are used for the evaluation of the projects' dimensions.

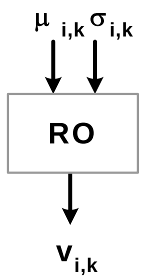


Figure 6.5: "Real Options Module"

Note that the call values are computed separately for every dimension, thus correlations between the dimensions are not taken into account.

Figure 6.6. gives an overview of the process of determining a project's call values:

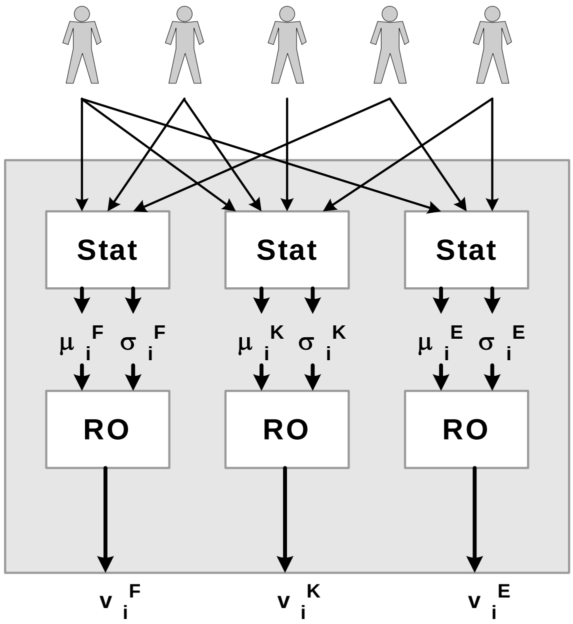


Figure 6.6: "Determining a Project's Call Values"

6.2.3. Selecting the Portfolio

In order to take interrelations between projects into account, projects are grouped into clusters τ_j. Note that by definition there are no interrelations among the clusters. In addition to the call values $v_{i,k}$ the limitation of resources, *i.e.* the capacity C_{max} is another input parameter that has to be provided by the decision maker, as well as the investments $c_{i,k}$ needed for each project. The selection of the optimum portfolio is based on the solution of the Knapsack problem maximising the portfolio's utility U as described in 6.6. and 6.7.

Determining a Portfolio's Utility

The call values $v_{i,k}$ of the selected projects π_i are accumulated (Acc) to a single utility value U using multi-attribute utility analysis (MAUA) as described in 6.5.2.

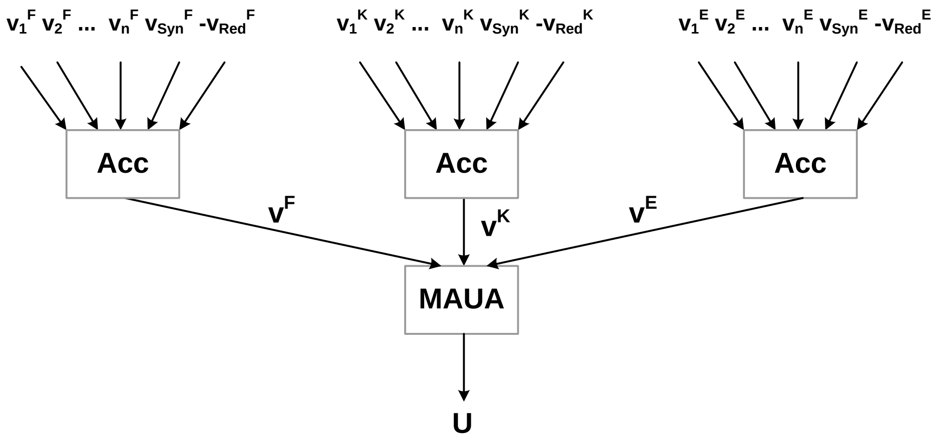


Figure 6.7: "Determining the Utility of a Portfolio"

In addition to the call values $v_{i,k}$ of the various projects π_i the decision maker's preferences regarding the scaling—linear or multiplicative—of the dimensions k have to be determined as an input to the multi-attribute utility analysis module. This input can be provided as weights or best and worst case patterns respectively, see 6.5.2. Note that the scaling constants have to be the same for all sets of projects in order to guarantee for comparability of the sets of projects' utility values. It is important to mention that the resulting utility values U_i are used for the portfolio selection only, but do not reflect the portfolios' performances in absolute figures.

6.2.4. Evaluating the Portfolio

Once the portfolio is selected, its evaluation is based on the original estimates considering synergies and redundancies. Output of the evaluation process is the expected total success of the portfolio μ_k for each dimension accompanied by the measure of risk $\varrho_{\lambda,k}$.

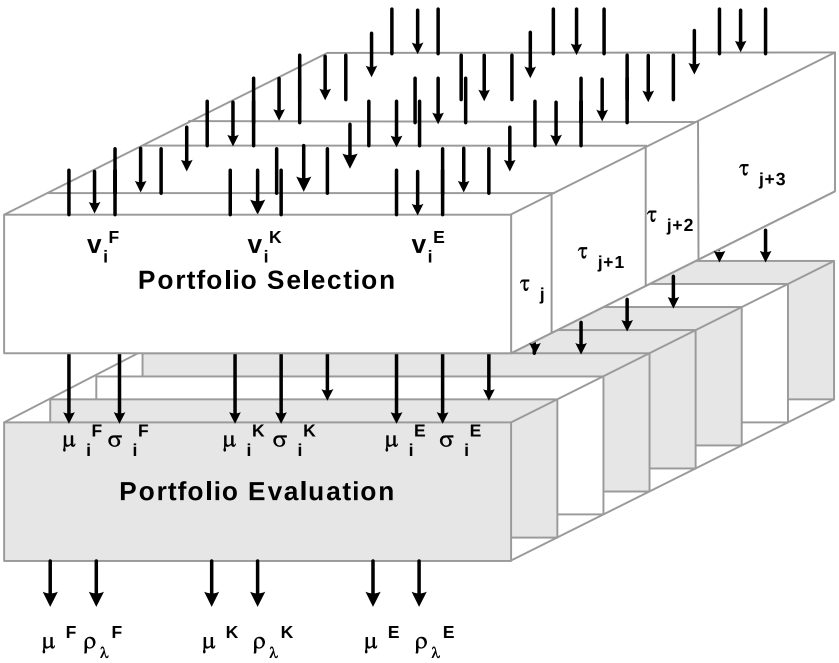


Figure 6.8: "Portfolio Selection and Evaluation"

6.3. *Calculation of Risk*

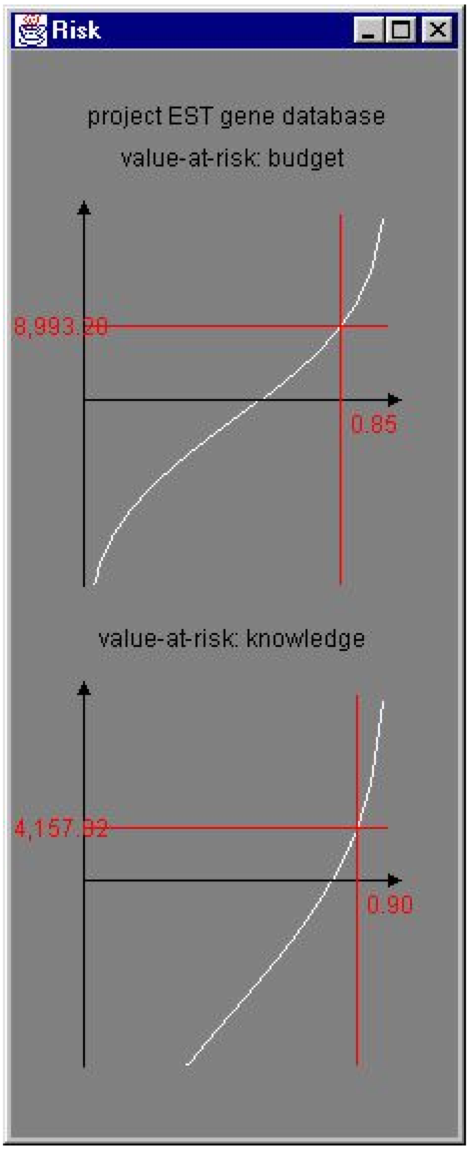
Referring to equation 5.19 the risk ϱ of an individual project is given by:

$$\rho_\lambda = c - \mu - \alpha\sigma$$

with α being the 1-λ percentile of the Standard Normal distribution Φ, c referring to the initial investment, μ being the mean and σ being the deviation of the distribution of the project's expected performance. The risk ϱ_λ corresponds to the Value-at-Risk (VaR), *i.e.* the highest possible loss of the project at confidence level λ. A negative VaR implies that the risk is so low that a minimum profit can be expected from the project instead of a maximum loss. Obviously the unit of measurement of the project's risk is the same as the units of measurement for the project's investment, performance respectively.

Taking various dimensions of a project into account there is a different risk for each of the dimensions k.

$$\rho_{\lambda k} = c_k - \mu_k - \alpha \sigma_k \tag{6.3}$$



Screenshot 6.1: "Value-at-Risk for various Dimensions of a Project"

Screenshot 6.1 shows the Value-at-Risk for various dimensions of a project depending on the confidence level λ.

Considering preconditional interrelations between projects the distribution function the VaR is based on, has to take into account that the thresholds θ_{jk} of the preconditional project π_j are exceeded in every dimension k.

According to equations 5.22 and 5.23 mean and deviation of the dependent project π_i are transformed to:

$$\mu_i \leftarrow \gamma_i \ \mu_i$$

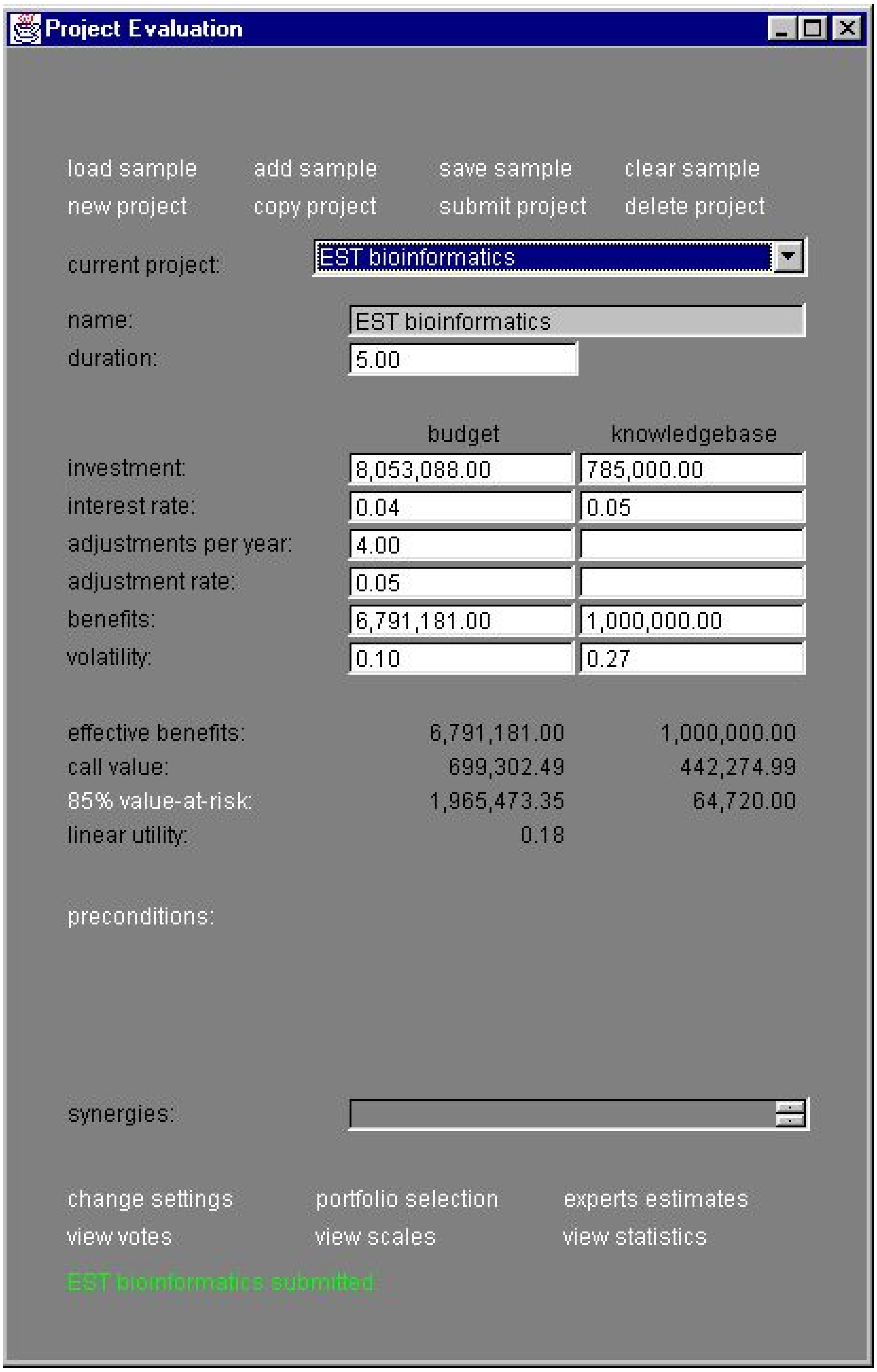
$$\sigma_i \leftarrow \gamma_i \ \sigma_i$$

Thus the probability that all of the thresholds of the preconditional project π_j are exceeded, becomes

$$\gamma_i = \prod_k (1 - F_{jk}(\theta_{ijk})) \tag{6.4}$$

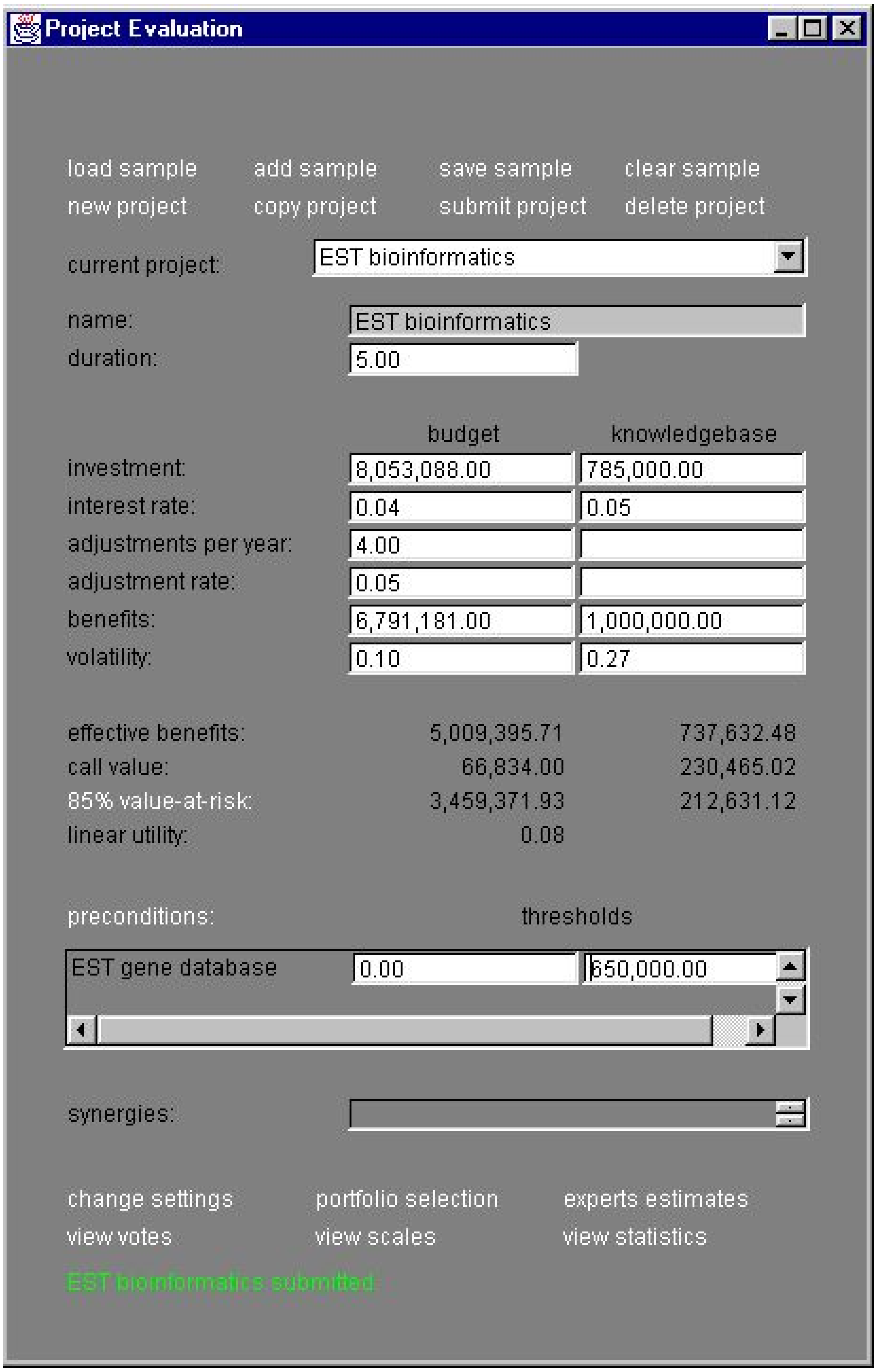
with F_{jk} being the cumulative distribution function[17] of the performance of the preconditional project π_j with respect to dimension k and θ_{ijk} being the threshold of the preconditional project π_j with respect to dimension k regarding the dependent project π_i.

[17] In most cases the cumulative Normal distribution function $N_{jk}(v)$ is used for $F_{jk}(v)$.



Screenshot 6.2: "Risks of a Sample Project without Preconditions"

Screenshot 6.2. shows the data and valuation of the sample project "EST bioinformatics" —refer to the case study in 7.1—without any preconditions.



Screenshot 6.3: "Comparison of Risks of a Sample Project Taking Preconditions into Account"

Taking into account that the project "EST gene database" serves as a precondition for "EST bioinformatics" shows that the effective benefits are reduced and the Value-at-Risk increases. Note that although the threshold affects only the dimension "knowledgebase" of "EST gene database" the effective benefits in both dimensions of "EST bioinformatics" are reduced.

In case of several preconditional projects equation 6.4 expands to:

$$\gamma_i = \prod_{j \in \tau} \prod_k (1 - F_{jk}(\theta_{ijk})) \tag{6.5}$$

where τ refers to the subset of indices of preconditional projects.

According to 5.5.2. the risk of a portfolio of non-interrelated projects $\varrho_{\lambda k}$ with respect to dimension k is given by:

$$\rho_{\lambda k} = \sum_{i=1}^{n} c_{ik} - \sum_{i=1}^{n} \mu_{ik} - \alpha \sqrt{\sum_{i=1}^{n} \sigma_{ik}^{2}} \tag{6.6}$$

with c_{ik} referring to the initial investment, μ_{ik} being the mean and σ_{ik} being the deviation of the distribution of the expected performance of project π_i with respect to dimension k.

Analogously to the results of section 5.5.2. the risk of a portfolio consisting of preconditional projects becomes

$$\rho_{\lambda k} = \sum_{i=1}^{n} c_{ik} - \sum_{i=1}^{n} \gamma_i \mu_{ik} - \alpha \sqrt{\sum_{i=1}^{n} \gamma_i^{2} \sigma_{ik}^{2}} \tag{6.7}$$

with γ_i being the probability that all thresholds of the preconditional projects for project π_i are exceeded, refer to equation 6.5.

Note that the calculation of a portfolio's risk including contingent, synergistic and redundant projects requires a special treatment as described in 5.5.2.

6.4. Real Options Valuation

6.4.1. Black-Scholes Model

The Black-Scholes formula for option pricing has already been derived in 4.3.2. It has been chosen for the calculation of the options' values in the presented framework following the arguments of Brealey and Myers [Brealey and Myers, 1988], who recommend using the Black-Scholes formula for the valuation of proposed R&D investments, because of the major advantage of the Black-Scholes formula namely that the option's value can be expressed in a closed formula solution.

An obvious shortcoming of the traditional options approach when applied to R&D projects is that normally there is no market for R&D projects, and therefore no volatility can be observed. The presented framework's option valuation tries to overcome this by using experts' judgements for the valuation of the various project dimensions and thereby getting a mean value for *e.g.* the expected cash flows and the according volatility. This process can be repeated for the other dimensions of the project (*e.g.* knowledge gained, or environmental impacts of the project).

The outcomes of the real options valuation are call values for the various dimensions of the project. These call values correspond to the virtual current value of the project, measured in the same units as the according dimension. For convenience the Black-Scholes formula is presented here again, adapted to the context of the project evaluation framework:

$$v_{i,k} = \mu_{i,k}\, e^{-yt} N(d_1) - c_{i,k}\, e^{-rt} * N(d_2) \qquad (6.8)$$

with
$$d_1 = \frac{\ln \frac{\mu_{i,k}}{c_{i,k}} + \left(r - y + \frac{\sigma_{i,k}^{2}}{2} \right) t}{\sigma_{i,k}\sqrt{t}}$$

$$d_2 = d_1 - \sigma_{i,k}\sqrt{t}$$

with the variables defined as described in Table 6.2. and **N**(.) being the cumulative Normal density function

The Black-Scholes model is based on Brownian Motions describing the price movements of the underlying stock. This assumption may be valid for financial options R&D projects however reflect a different behaviour. Changes of the state of a project do not occur continously but at certain points in time when the project is evaluated and decisions are taken or breakthroughs in research take place. Furthermore the amount of the change can vary. Given that the probability of the occurrence of project relevant events in the future is independent of the probability of occurrence of such events in the past, the time intervals between these events are exponentially distributed with parameter θ. This implies that the number of such events while undertaking a project is Poisson distributed with mean $1/\theta$. The amount of the change follows a Weibull distribution with mean γ and shape parameter 2. According to Pennings and Lint [Pennings and Lint, 1997] the call value of a project in analogy to the Black-Scholes formula is given by:

$$v_{i,k} = \mu_{i,k} * N\left(d + \sqrt{\frac{t}{\theta_{i,k}}}\,\gamma_{i,k}\right) - c_{i,k}\, e^{-rt} N(d) \qquad (6.9)$$

with
$$d = \frac{\ln\left(\frac{\mu_{i,k}}{c_{i,k}}\right) + \left(r - \frac{\gamma_{i,k}^{2}}{2\theta_{i,k}} \right) t}{\sqrt{\frac{t}{\theta_{i,k}}}\,\gamma_{i,k}}$$

Further investment decision models including jump processes are presented by [Merton, 1976], [McDonald and Siegel, 1986] and [Baldwin and Meyer, 1979]. Technological uncertainty in research is also modeled as a Poisson process in [Loury, 1979], [Dasgupta and Stiglitz, 1980], [Lee and Wilde, 1980], [Reinganum, 1983] and [Dixit, 1988].

6.4.2. Input Parameters

After having defined the various dimensions being important for the success of the project, the option value of these dimensions is calculated. In order to regard the various dimensions contributing to the project's success as an option, the "investment" that was made for this dimension has to be determined. Furthermore the return potentially gained from this investment has to be estimated, which is done using experts' judgements, as explained in the next section. The option value of the dimensions is determined with the Black-Scholes formula, introduced in 4.3.2. The input variables to the Black-Scholes formula are summarised in Table 6.2.

	Input Variables to the Black-Scholes Formula		Corresponding Values for R&D Projects
S	Current value of the underlying asset	$\mu_{i,k}$	Mean of experts' estimates for success of dimension *k*
K	Strike price of the option	$c_{i,k}$	Present value of investment costs for dimension *k*
t	Life to expiration of the option	t	Project duration
r	Riskless interest rate corresponding to the life of the option	r	Riskless interest rate
y	Dividends/current value of the asset	y	Payments lost through waiting to invest
σ	Deviation of the underlying asset	$\sigma_{i,k}$	Deviation of experts' estimates for success of dimension *k*

Table 6.2: "Input Variables to the Black-Scholes Formula and Corresponding Project Values"

Chapter four 4.4.2. provides a detailed discussion of how the necessary input parameters of an R&D project can be determined when treating the project as a real option. These guidelines do, of course, focus on a monetary valuation, or in terms of the presented framework, they only take the financial dimension of an R&D project into account.

Therefore, the next sections show how other than financial aspects of an R&D project can be modelled as options and the option characteristics of these aspects are explained.

Increasing Knowledge Regarded as an Option

As already discussed in 6.1.1. gaining know-how can be one of the main reasons for undertaking a research project. The assumption that there is a discount rate for knowledge is realistic, as knowledge becomes out-of-date, and especially for R&D projects it can make a crucial difference whether pieces of new information are obtained earlier or later. Taking competition into account this issue becomes even more important, but also in the absence of competitive activities, and regarding the research investments, it makes a big difference, if one finds out that the project will be a failure today, or after having invested in *n* years of research. This does not necessarily mean that the whole research efforts are worthless, but can have important consequences for follow-up projects. The same obviously applies to major breakthroughs in research, which can *e.g.* be modelled with jump processes as described by Pennings and Lint [Pennings and Lint, 1997]. The consequences of the timing of research breakthroughs are not only a monetary issue, but can also have major social or environmental impacts. Discovering ways to heal diseases earlier or later in time makes a difference that can in some cases be measured in saved human lives.

The presented framework measures the existing knowledge and the knowledge gained as described in section 6.1.2. explicitly trying not to convert all of the values for the project's success criteria into monetary values.

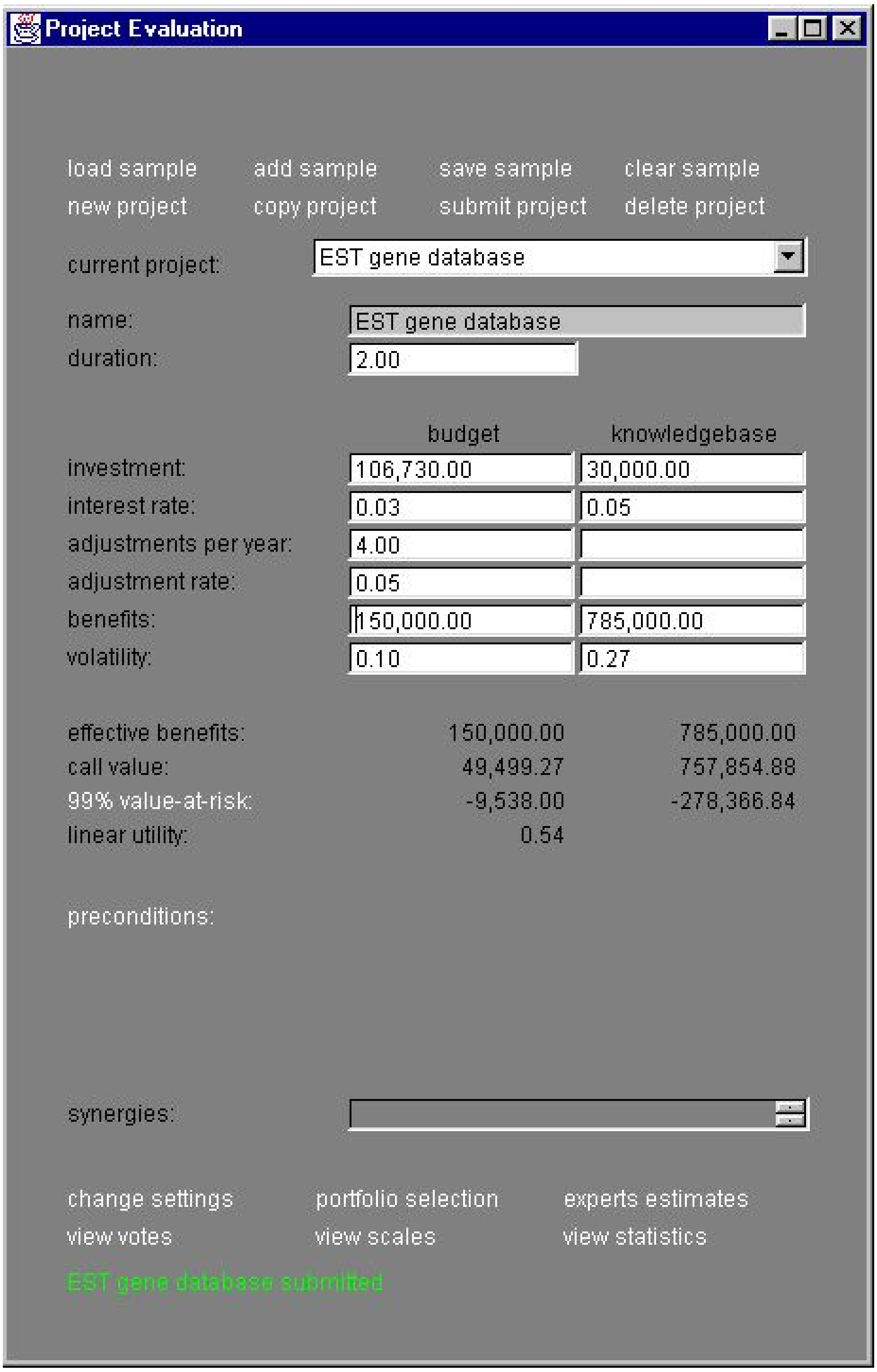
Environmental Impacts Regarded as Options

If a project has significant positive or negative environmental impacts, a metrics to measure the quality of the environment before and after the project has to be defined. For example air pollution can be measured before and estimated for the time after the project.

Note that an R&D project can have positive and negative consequences for the environment. While the dimension knowledge can only increase, the level of the environmental situation can become better or worse through the implementation of the project, or more specific the technologies, methods and processes developed within the project. Thus the measure for the environmental benefits/damages can increase or decrease.

Finding a discount rate for the environmental impacts, can be achieved by estimating the percentage of the increase in, for example, pollution given the project is not undertaken. This implies that the discount rate could also become negative. Alternatively the measure for the environmental impacts can be inverted so that the undesired effect leads to a high measure, *e.g.* measuring pollution instead of clean air. This leads to a situation where the transformation function for the multi-attribute utility analysis has to be inverted as well, refer to 6.5.1. In any case it has to be guaranteed that an increase of desired environmental effects leads to a higher utility value.

Bailey *et alii* [Bailey et al., 1996] define an environmental liability of a company or organisation as an obligation to make a future expenditure due to the past or ongoing manufacture, use, release, or threatened release of a particular substance, or other activities that adversely affect the environment. Consequently a potential environmental liability refers to a potential obligation depending on future events or law regulations that are not yet in effect. The difference between an "environmental liability" and a "potential environmental liability" is that in case of the latter the organisation has got the option to prevent the liability from occurring by altering its own practices or adopting new practices in order to avoid or reduce adverse environmental impacts.



Screenshot 6.4: "Valuation of a Sample Project"

Screenshot 6.4 shows the valuation of the sample project "EST gene database", refer to the case study in 7.1. The duration, investment and interest rate for the various dimensions of the project have to be entered. With the help of the data gained by the experts' estimates the benefits of the dimensions are determined. Following the model presented by Pennings and Lint [Pennings and Lint, 1997] in case of the dimension "budget" the volatility is calculated using "adjustments per year" and "adjustment rate", which have to be entered as well. For the dimension "knowledgebase" the volatility is taken from the deviation of the experts' estimates. In this case the unit of measurement for the dimension "knowledgebase" refers to database entries of an Expressed Sequence Tags (EST) gene database. Values for the risk of the project's dimensions as well as an aggregated value for the project's overall utility are calculated, as described in 6.3. and 6.5.2. respectively.

6.4.3. Experts' Estimates

The use of experts' estimates is threefold in the presented project evaluation framework. First, experts are asked to judge the various aspects of a project including their future potentials, in order to simulate a market for R&D projects. Secondly, the deviation of the different opinions of the experts is used as an input to the real options model as well as the calculation of a project's risk. Furthermore, the experts have to define possible interrelations between the projects, which will have an effect on the performance of the portfolio if these projects are selected together. Section 6.7.4. describes this process in detail.

Trying to classify the expert interviews, as needed for the portfolio evaluation framework, within the definitions provided in literature—refer *e.g.* to [Bogner, Littig, Menz, 2002]—the technique to obtain the necessary input data could be referred to as a so-called systematic expert interview. The aim of this kind of interview is to gain information systematically and completely. The expert is regarded as an advisor who can provide specific knowledge about a specific field of research. This kind of interview technique is also used for Delphi surveys as described in 3.1.2. In contrast to the explorative expert interview, the systematic expert interview aims at providing comparable data from various experts.

The knowledge provided by experts can be classified into technical knowledge, process knowledge and prediction knowledge [Bogner and Menz, 2002]. Technical knowledge, which is characterised as being very systematic and specific, comprises knowledge about production possibilities, usage of operations and technical procedures and specific application routines. Process knowledge is based mainly on experience gained through practice, and includes knowledge about workflows, interaction routines and organisational constellations. Prediction knowledge means using the experts' knowledge in order to make forecasts for possible future developments and thus gaining data. The forecast is made by extrapolating observed developments into the future. Referring to this classification, the experts' prediction knowledge is of interest for the expert interview, being part of the presented framework to gain input data for the model but can of course not be provided without the other kinds of knowledge serving as a basis for the forecast.

Furthermore, the experts can help exploring a certain problem proposition, because experts in the field of interest often recognise possible future difficulties and risks *in statu nascendi*.

Choosing the Experts

Before discussing who could be chosen as an expert for the framework's project evaluation process, the term "expert" will be defined as being used in the context of this thesis. The term expert in the present framework refers to an expert from a methodological point of view, which means that a person becomes an expert because it is assumed that this person obtains knowledge that is not obtained by everybody in the field of interest. Thus the term expert includes persons who:

- are responsible for the design, implementation or controlling of a process,
- have got a privileged access to information concerning relevant fields of science, groups of people and decision processes [Meuser and Nagel, 2002].

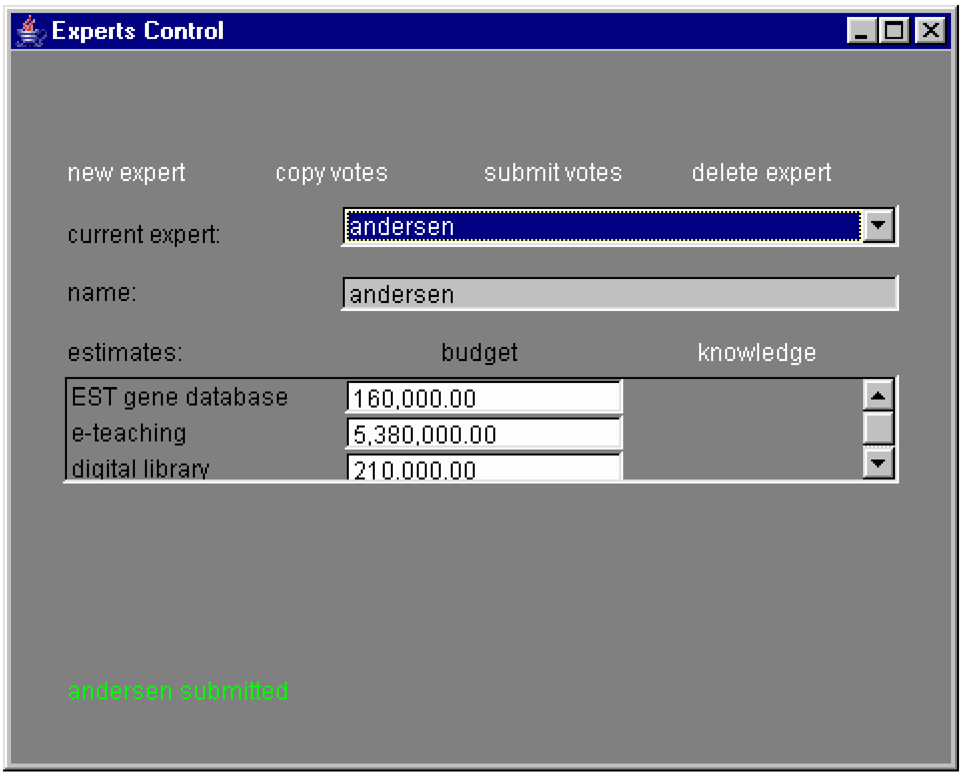
In practice, the experts might include team members, who know details about the various projects as well as independent, external experts, such as people from universities *etc.* who can provide information about general trends and developments, in order to estimate the future potential of the technology to be developed.

Simulation of a Market

The options model is based on the assumption that there is a market for the underlying stocks that delivers the stock course and consequently the volatility necessary for the options valuation. As there is no such market for R&D projects, the necessary input data is gained by the experts' estimates concerning the expected outcomes of the projects' dimensions. Note that, instead of a time series of market data, the experts' estimates occur simultaneously, and thus represent a snapshot at a certain point in time. Fortunately, the real options model does not take dependencies over time into account.

Influence on Risk

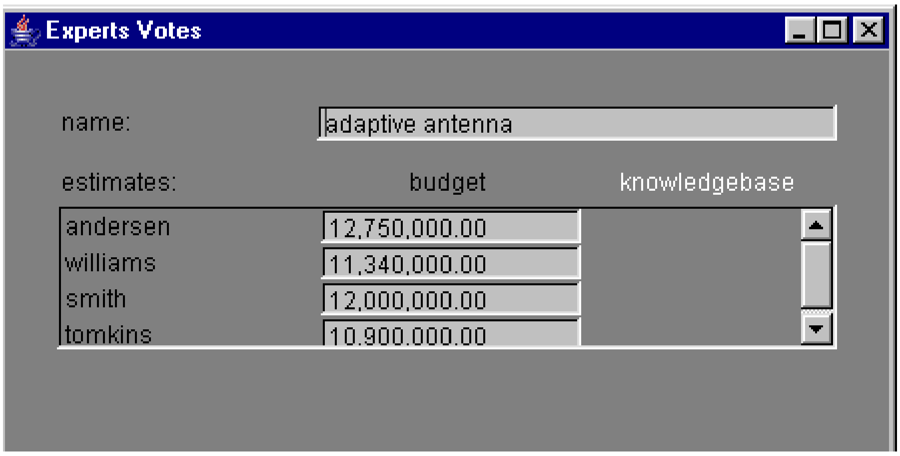
Other than the group decision techniques described in 3.1.2. the use of experts' estimates in the present framework explicitly does not aim at finding consensus. By conducting Delphi surveys, one also gets information concerning the deviation of the various opinions from the consensus, but usually this information is not used, whereas here the deviations of the estimates of the various experts are used in order to determine the risks for the project's dimensions—refer to 6.3.



Screenshot 6.5: "Experts Control"

Screenshot 6.5. shows the “Experts Control” where the experts can enter their estimates for each project’s benefits in the dimension of their expertise. The number and identity of experts can vary with respect to the various dimensions.

Note that every expert has to value every project, but there can be finance experts, knowledge experts *etc.* with respect to the various dimensions, and their number can vary.



Screenshot 6.6: “Experts Estimates View”

In Screenshot 6.6. the estimates of all of the experts for one dimension of a specific project can be compared. Thus one can get an impression of the range and volatility of the estimates.

6.5. Multiple Objectives

In order to incorporate various dimensions of an R&D project into the evaluation, objective functions can be created that represent multiple objectives. This process includes defining the dimensions under which projects can be evaluated as multiple objectives. These correspond to the various dimensions of the R&D project’s success function. Project outcomes can then be evaluated on separate scales. The results are combined into a single scalar measure of project utility that reflects the decision maker’s preferences over outcomes.

In order to define a multi-attribute utility function the decision makers must provide information about the relative importance of each of the project’s aspects and the importance of that aspect in comparison to the other aspects.

Keefer [Keefer, 1978] defined conditions under which multi-attribute objective functions can be used for R&D project management. It is assumed that decision makers are rational, and aim at maximising the expected utilities by properly allocating resources among research activities. This involves making the following two assumptions about the decision maker’s preferences over project outcomes:

Utility independence—which means that the decision maker’s preferences for lotteries over one attribute are independent of the fixed level of the remaining attributes. For the presented framework this means that the dimensions have to be orthogonal.

Preferential independence—which means that the decision maker's preference over variations in two particular attributes does not depend on the level of the remaining attributes as long as they remain fixed.

Monotonicity

Monotonicity is a common—and in many cases reasonable—characteristic of utility functions [Keeney and Raiffa, 1976]. A monotonically increasing (or decreasing) utility function u, implies that a higher (or lower) level of a certain aspect x_1, of a project is preferred to lower (higher) level x_2:

$[x_1 < x_2] \leftrightarrow [u(x_1) < u(x_2)]$ for increasing utility functions and

$[x_1 < x_2] \leftrightarrow [u(x_1) > u(x_2)]$ for decreasing utility functions respectively.

Considering the monetary dimension, as well as knowledge, the utility function is monotonic, because more financial return is generally preferred to less, and from a scientific point of view, knowing more is also preferred to knowing less. However, there can also be cases where the utility function is not monotonic. Considering environmental aspects of a project, there is a certain optimum amount of nitrogen in the air and the utility function is monotonically increasing up to the desired level of nitrogen and monotonically decreasing afterwards. Such a function is called unimodular.

Note that monotonicity only implies that a higher or lower level of a dimension yields a better overall result, but it does not give any information on how much better the result is. Thus a 10% higher utility value of one result in comparison to another result does not imply that the decision maker prefers this result by 10% to the other. As a consequence, monotonicity is sufficient for the selection of a portfolio.

If all of the assumptions described above are satisfied the decision maker's multi-attribute utility function can be expressed in an additive or general form (see 6.5.2. equations 6.16 and 6.17).

In order to allow arbitrary non-negative call values as inputs to the utility function, it is appropriate to transform the range [0..∞] of the call values to the interval [0..1] with the help of a monotonic scaling function $f(v)$.

6.5.1. Basic Transformation

A simple monotonic function f that transforms the interval [0..∞] to the interval [0..1] is given by:

$$f(v) = \frac{v}{v+c} \tag{6.10}$$

with v referring to the dimension' s call value and c referring to the dimension' s investment costs. Note that it is assumed that the call values v as well as the investment costs c are non-negative, which seems to be realistic. Thus $f(v)$ maps the call values from the interval [0..∞] to the range [0..1], scaling $f(v)$ to 0.5 for the special case of $v = c$ with a return on investment of zero:

$$f(v) = \begin{cases} 0 & for\ v = 0 \\ 0.5 & for\ v = c \\ 1 & for\ v \to \infty \end{cases}$$

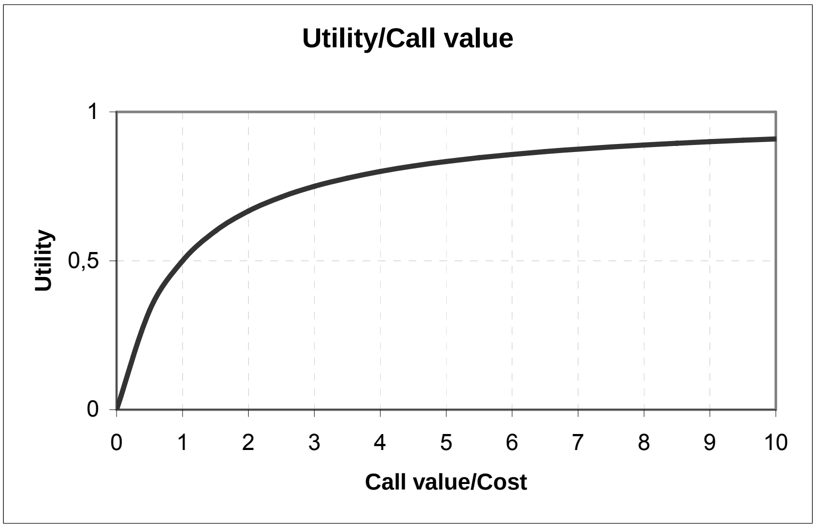


Figure 6.9: "Transformation of Call Values: $f(v) = \frac{v}{v+c}$"

Another transformation function worth considering, is:

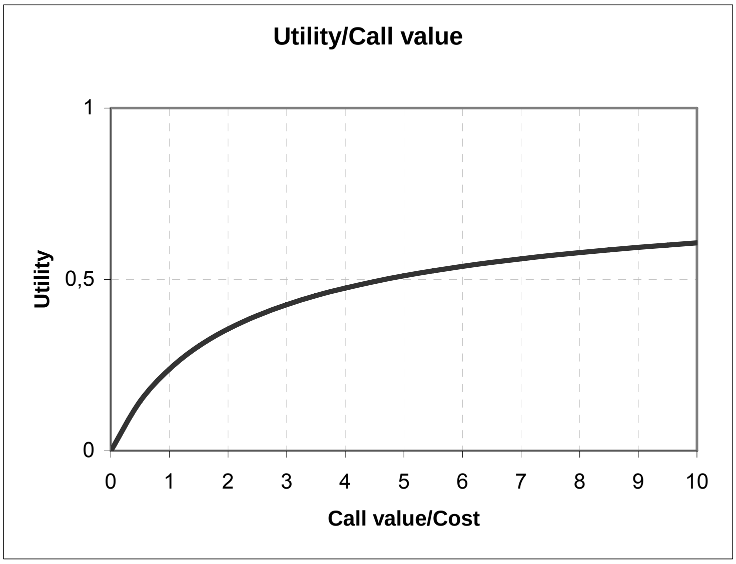


Figure 6.10: "Transformation of Call Values: $f(v) = 1 - \frac{1}{\ln\left(\frac{v}{c} + e\right)}$"

Note that the transformation functions described so far are non-linear. Consequently the function applied to a sum of call values is not necessarily equal to the sum of the functions applied to the individual call values. This has to be taken into account when selecting projects for a portfolio, see 6.6.

The fact that the slope of the two transformation functions presented so far depends on the call values is irrelevant for the portfolio selection because the demanded monotonicity is given and consequently the order relation of the call values and their corresponding function values remains the same.

Obviously, if a scaling of the dimension's utility from [0..100] to [0..1] is needed, because the original valuation of the dimension is measured in percent, the following linear function could be used:

$$f(v) = \frac{v}{100} \tag{6.11}$$

with $f(0) = 0$ and $f(100) = 1$.

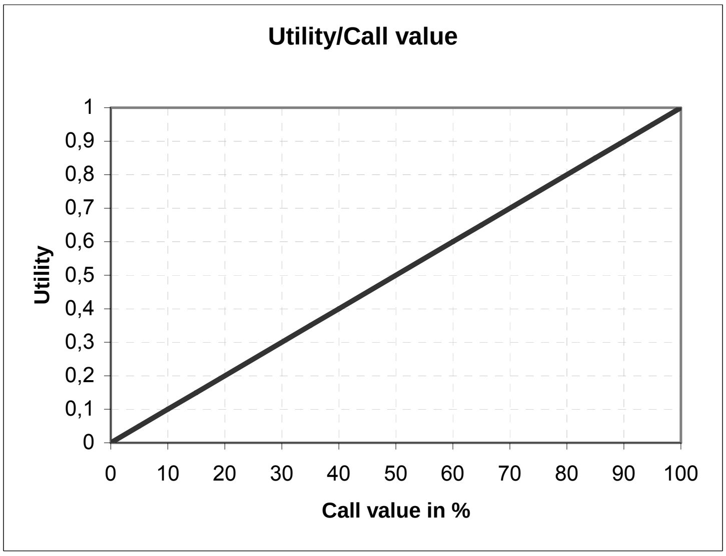


Figure 6.11: "Transformation of Call Values: $f(v) = \frac{v}{100}$"

All the functions that have been given as examples for the transformation so far are based on the assumption that higher values of each of the dimensions valuations are preferred to lower values, but that does not necessarily have to be the case. In practice, it can very well be that the dimension environmental impacts of the project is measured by determining the level of pollution before and after the project. Of course lower levels of pollution are commonly preferred to higher ones. Thus a transformation function is needed that maps $f(0)$ to 1 and $f(\infty)$ to 0. Such a function can easily be derived by substituting *f(v)* by 1-*f(v)*. For example:

$$f(v) = \frac{c}{v+c} \tag{6.12}$$

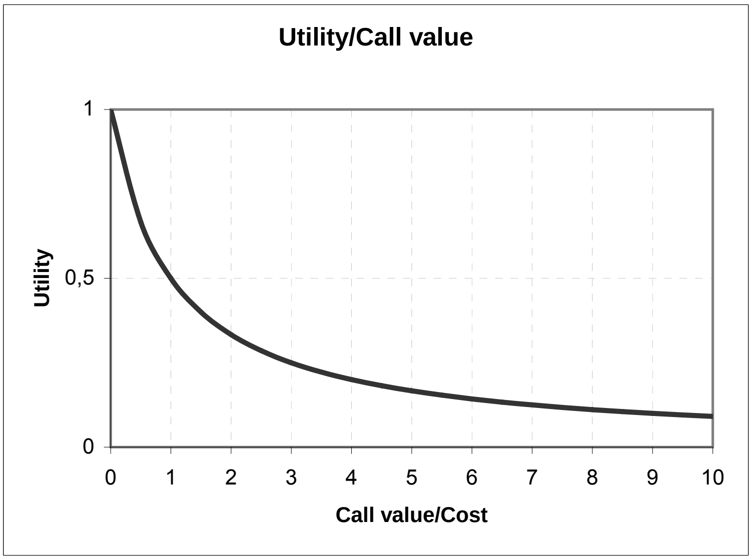


Figure 6.12: "Transformation of Call Values: $f(v) = \frac{c}{v+c}$ **"**

In the case of a dimension's values being measured in percent, *i.e.* scaling the interval [0..100] to [0..1] the following function could be used:

$$f(v) = 1 - \frac{v}{100} \tag{6.13}$$

Or again the more general case scaling the interval [0..a] to [0..1] with *f*(0) leading to 1 and *f*(a) leading to 0:

$$f(v) = 1 - \frac{v}{a} \tag{6.14}$$

6.5.2. Multi-Attribute Utility Analysis

Multi-attribute utility analysis (MAUA) combines the values of the various dimensions to a single scalar utility measure. Such a utility measure is needed for the comparison of alternative project sets in order to maximise their utility values. The preferences concerning the various dimensions can be determined by the decision maker by defining sampling points of the utility function or best and worst case analysis. Multi-attribute utility analysis allows for additive utility functions as the weighted sum of its arguments as well as for multiplicative utility functions. The latter provides the possibility to define limits on the measures of certain dimensions in order to achieve non-zero total utility values. Whereas the additive utility function allows compensating for small measures in one dimension by higher results in other dimensions.

The call values of the various dimensions have to be scaled to the interval [0..1] by a monotonic scaling function *f*(*v*), before the consolidation with MAUA. Thus the utility function also delivers values within the interval [0..1].

Additive Utility Function

The additive utility function for three attributes as defined by Keeney and Raiffa [18][Keeney and Raiffa, 1976] is given by:

$$u(v^F, v^K, v^E) = a^F f^F(v^F) + a^K f^K(v^K) + a^E f^E(v^E) \qquad (6.15)$$

where the a^F, a^K, a^E are the scaling constants that are assigned as weights to the various project dimensions with

$$a^F + a^K + a^E = 1$$

In general terms

$$u(\bar{v}) = \sum_k a_k f_k(v_k) \qquad (6.16)$$

with

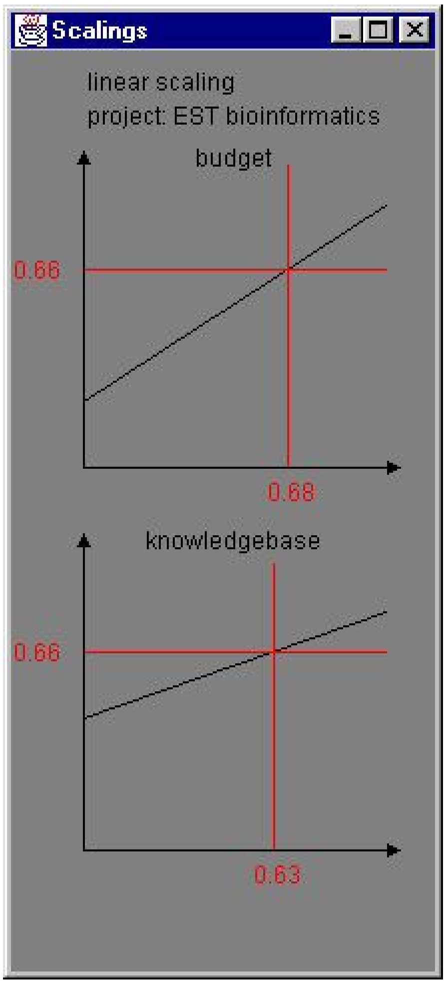
$$\sum_k a_k = 1$$

Arbitrary values for the a_k can be chosen, although the restriction $a_k \geq 0$ seems to be appropriate in most cases[19]. The a_k can be determined using multiple linear regression over an arbitrary number of monotonic sampling points.

Alternatively the a_k can be defined by determining the slope of the utility function with respect to a specific dimension, with the call values for the other dimensions being constant. In other words the a_k can be calculated by solving the system of linear equations given by the partial derivations of the utility function.

[18] For additive utility functions also refer to [Debreu, 1960], [Arrow, 1971] and [Vincke, 1992].

[19] $a_k \geq 0$ means that the slope of the utility function with respect to dimension *k* must not decrease, which implies that a higher call value of dimension *k* is preferred to a lower one.



Screenshot 6.7: "Slopes of the Additive Utility Function of a Sample Project"

Screenshot 6.7. shows the slopes of the additive or linear utility function for a sample project with respect to the various dimensions. The ordinate corresponds to the utility and the abscissa to the transformed call value of the according dimension. The red figures reflect the transformed call values and the utility of the underlying project.

General Utility Function

If v^K and v^E are utility independent of their respective complements $\{v^F, v^E\}$ and $\{v^F, v^K\}$ the general utility function for three attributes as defined by Keeney and Raiffa[20] [Keeney and Raiffa, 1976] is given by:

$$u(v^F,v^K,v^E)=a^F f^F(v^F)+g^K(v^F)f^K(v^K)+g^E(v^F)f^E(v^E)+g^{KE}(v^F)f^K(v^K)f^E(v^E) \qquad (6.17)$$

where a^F refers to the scaling constant of the additive utility function and

[20] Further multiplicative utility functions are used by Keefer [Keefer, 1978] as well as by Keefer and Kirkwood [Keefer and Kirkwood, 1978].

$$g^{K}(v^{F}) = u(v^{F}, v_{+}^{K}, v_{-}^{E}) - u(v^{F}, v_{-}^{K}, v_{-}^{E})$$
$$g^{E}(v^{F}) = u(v^{F}, v_{-}^{K}, v_{+}^{E}) - u(v^{F}, v_{-}^{K}, v_{-}^{E})$$
$$g^{KE}(v^{F}) = u(v^{F}, v_{+}^{K}, v_{+}^{E}) - u(v^{F}, v_{+}^{K}, v_{-}^{E}) - u(v^{F}, v_{-}^{K}, v_{+}^{E}) + u(v^{F}, v_{-}^{K}, v_{-}^{E})$$

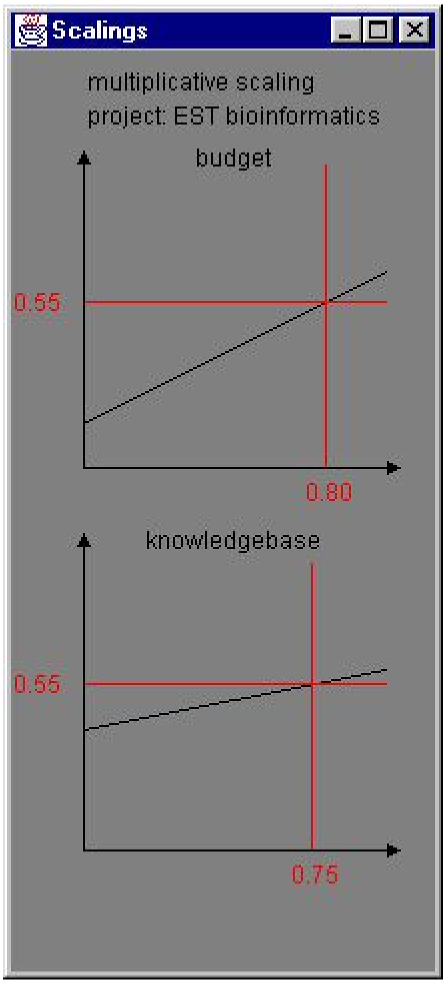
Again each of the utility functions is scaled from 0 to 1, with (v_+^F, v_+^K, v_+^E) being the best consequence and (v_-^F, v_-^K, v_-^E) the worst. The best and worst cases as well as the according utility values have to be determined by the decision maker.

Note that utility independence as stated above implies that the estimated knowledge gained within the projects is independent of the estimated financial successes and the estimated environmental impacts are independent of the estimated financial successes and the estimated knowledge gained. However, the financial successes may very well depend on the knowledge gained as well as on the environmental impacts of the projects. This restriction is consistent with the practical evidence that the financial aspects of a project is influenced by all the other aspects.

In the case of two attributes *F* and *K* the general utility function becomes:

$$u(v^{F}, v^{K}) = u(v^{F}, v_{-}^{K}) + u(v_{-}^{F}, v^{K}) + ku(v^{F}, v_{-}^{K})\,u(v_{-}^{F}, v^{K}) \tag{6.18}$$

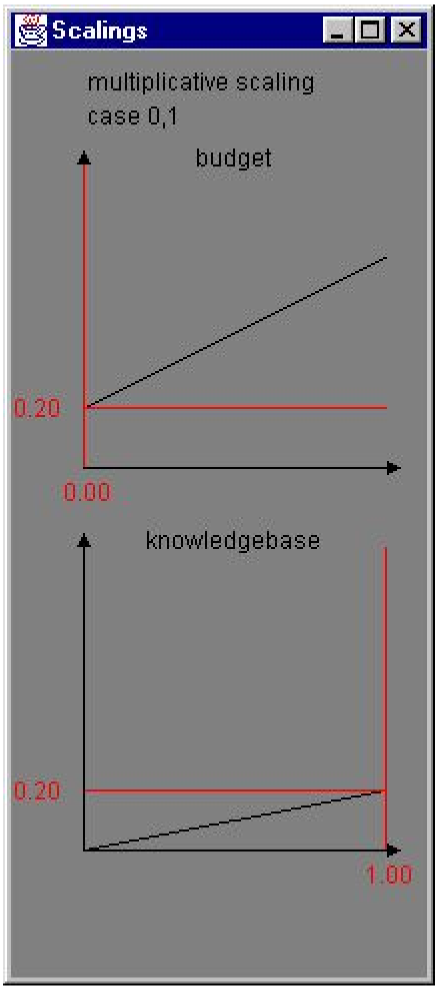
This corresponds to the general utility function for three attributes (equation 6.17) with g^E and g^{KE} being zero.



Screenshot 6.8: "Slopes of the General Utility Function of a Sample Project"

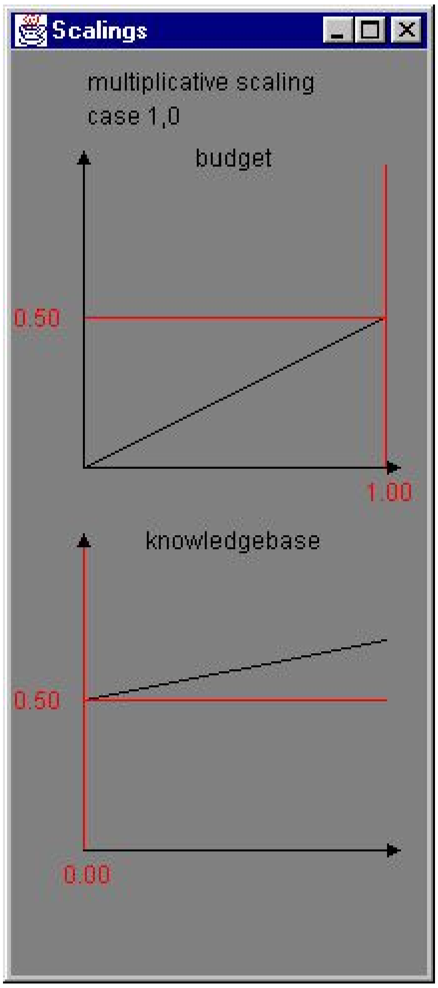
Screenshot 6.8. shows the slopes of the general or multiplicative utility function for a sample project with respect to the various dimensions. The ordinate corresponds to the utility and the abscissa to the transformed call value of the according dimension. The red figures reflect the transformed call values, which correspond to the values in screenshot 6.7. and the utility of the underlying project.

The following screenshots show the scaling of the utility function based on the best and worst case scenarios.



Screenshot 6.9: "Slopes of the General Utility Function for Worst/Best Case Scenario"

Screenshot 6.9. shows the slope of the utility function for the worst/best case scenario with the call value for the dimension "budget" being minimal (zero) and the call value for the dimension "knowledgebase" being maximal (one).

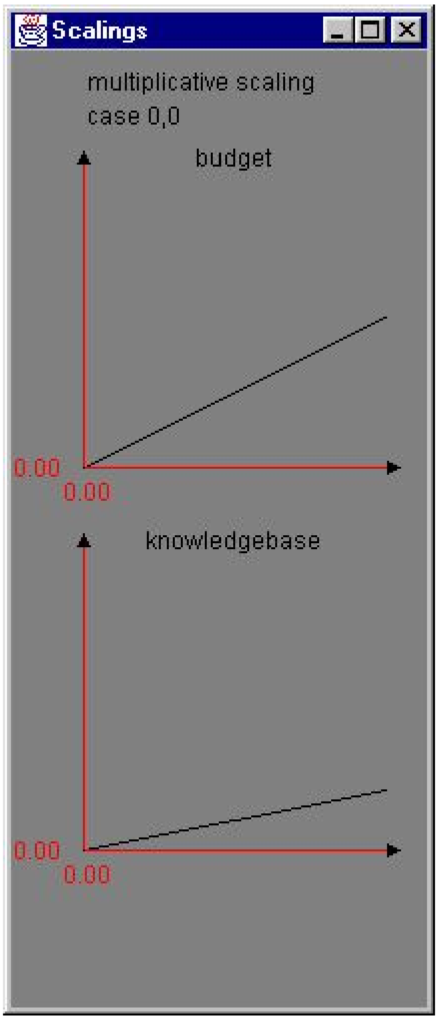


Screenshot 6.10: "Slopes of the General Utility Function for Best/Worst Case Scenario"

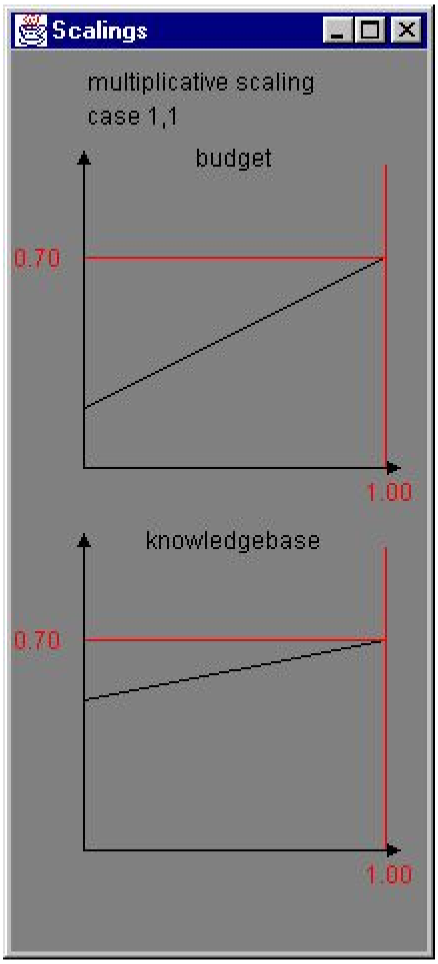
Screenshot 6.10. shows the slope of the utility function for the best/worst case scenario with the call value for the dimension "budget" being maximal (one) and the call value for the dimension "knowledgebase" being minimal (zero).

The resulting utility for the special cases described above can be defined by the decision maker.

The utility resulting from the two following special cases (worst/worst and best/best case scenarios) is zero, one respectively and must not be altered because of the standardised scaling of the utility from zero to one.



Screenshot 6.11: "Slopes of the General Utility Function for Worst/Worst Case Scenario"



Screenshot 6.12: "Slopes of the General Utility Function for Best/Best Case Scenario"

6.6. *Portfolio Selection of Non-Interrelated Projects*

Based on the call values that have been determined for a number of research projects, the presented framework provides a selection method to find out which of these projects should be chosen for the project portfolio given that only a limited amount of resources is available to be invested.

The total multi-dimensional call value $\vec{V}_\tau$ of a portfolio consisting of non-interrelated projects is defined as the sum of the call values of the selected projects $\vec{v}_i$.

$$\vec{V}_\tau = \sum_{i \in \tau} \vec{v}_i \tag{6.19}$$

$$U_\tau = u(\vec{V}_\tau) \tag{6.20}$$

The selection τ of the portfolio is based on a utility function U_τ that is determined by the total call value $\vec{V}_\tau$.[21] Furthermore, the selection mechanism is based on the assumption that the valuation of the various aspects is consistent throughout all the included projects. Thus a transparent and objective selection mechanism is guaranteed and projects cannot be favoured with the help of additional parameters of the tool.

6.6.1. Knapsack Problem for Non-Interrelated Projects

The optimal selection of projects for a portfolio can be mapped to the well-known Knapsack problem, being defined as follows:

Given a Knapsack of capacity $C_{max} > 0$ and n objects with sizes $c_1,..., c_n$ with $c_i > 0$ for $i = 1,…, n$ and benefits $s_1,..., s_n$ with $s_i > 0$ for $i = 1,…, n$ −find the largest total benefit of any subset of these objects that fits in the Knapsack, and find the subset that achieves the maximum benefit.

The specific case of the so-called 0/1 Knapsack does not allow for fractions of objects, *i.e.* objects can either be included in the Knapsack, or not.

In the case of portfolio selection the objects correspond to the projects π_i, the total benefits are the portfolios' utilities, the sizes are the costs c_i and the capacity C_{max} corresponds to the resources available for the portfolio, *e.g.* financial resources or man power; with $c_i > 0$ for $i = 1,…, n,$ where n refers to the number of projects.[22]

The selection task is to determine a subset τ of {1, 2, …, n} that defines a portfolio of projects π_i with $i \in \tau$ maximising $U(\vec{V})$ where

$$\sum_{i \in \tau} c_i \leq C_{\max} \tag{6.21}$$

for every dimension, with $U(\vec{V})$ being the total call value of the portfolio and U being the according utility function.

The solution of the classic Knapsack problem adapted to portfolio selection can be described recursively by the following algorithm:

```
select (i) {
if i ≤ n {
        select (i+1)
τ ← τ ⋃ [i]
if (Cτ ≤ Cmax) select (i+1)
τ ← τ \ [i]
        } else {
                if Uτ > Uopt {
                Uopt ← Uτ
                τopt ← τ
        }
}
```

"Algorithm for the Solution of the Classic 0/1 Knapsack Problem"

[21] Note that the utility functions as defined in 6.5.2. are not additive with respect to the call values. It is therefore essential to calculate the total utility as a function of the total call values and not as the sum of utilities of the projects.

[22] Note that the costs c_i as well as the capacity C_{max} may very well be multi-dimensional values. Thus the limit given by the capacities must not be exceeded by any of the dimensions.

Note that i is the index of the project considered to be selected, τ is the set of indices of the projects selected so far, C_τ refers to the total costs of this set of projects and U_τ to the total utility of this set of projects.

Before the algorithm starts τ and τ_{opt} are initialised with the empty set, U_{opt} is set to zero. The initial call

```
select(1)
```

starts the selection of the first project and subsequent calls check the remaining projects recursively. The algorithm delivers results for τ_{opt} being the optimum set of selected projects and U_{opt} being the maximum utility achieved.

The algorithm described above can easily be extended to multiple dimensions by substituting the condition $C_\tau \leq C_{max}$ by a conjunction of the corresponding conditions for each dimension:

$$\bigwedge_k \left(C_{k\tau} \leq C_{k\,\max} \right) \tag{6.22}$$

This multi-dimensional restriction can be extended to take dependencies between projects such as preconditions (refer to 5.3.2.) into account, see 6.7.1. Furthermore synergies and redundancies can easily be included into the utility function, see equation 6.25.

The algorithm for the Knapsack problem is NP-complete with a complexity of $O(2^n)$[23]. Therefore, it is only reasonable for a small number of projects n. Fortunately, there is a dynamic programming solution to the Knapsack problem which reduces the complexity to $O(n{*}C_{max})$ under the assumption of non-negative integer costs c_i and a non-negative integer capacity C_{max}. Obviously the restriction of costs and capacity being integers is irrelevant for project portfolio selection purposes.

6.6.2. Dynamic Programming Solution for the Portfolio Selection of Non-Interrelated Projects

Dynamic programming is a systematic, iterative mathematical procedure for determining the optimal combination in a sequence of interrelated decisions. In contrast to linear programming, as briefly introduced in 5.6.3. there does not exist a standard mathematical formulation of "the" dynamic programming program. Dynamic programming should rather be regarded as a general approach to problem solving.

Using a dynamic programming optimisation procedure a large, complicated optimisation problem is decomposed into a series of smaller ones. These reduced optimisation problems are interconnected and contain only a few variables. The result provided by the dynamic optimisation is a series of partial optimisations that require only a reduced effort to find the optimum. In order to find the optimum for the entire optimisation problem the connected partial optimisations are combined.

The dynamic programming approach for the portfolio selection can be described as follows:
Assume a subproblem in which the set of projects is restricted to $\{\pi_1,\ldots,\pi_i\}$ where $i \leq n$, and the capacity of the portfolio is c, where $0 \leq c \leq C_{max}$.

Let $V_{i,c}$ denote the optimum call value and $U(V_{i,c})$ denote the maximum utility achieved for this problem. Due to c being used as an index, the values of c are restricted to integers.

[23] The complexity is of $O(2^n)$ because basically the power set of all 2^n sets of projects has to be considered. The effort can be reduced by omitting the bundles of subsets which are obviously too expensive. Thus the effort is decreased by a factor but the complexity of $O(2^n)$ remains unchanged by definition.

The aim is to compute the maximum utility of the original problem $U(V_{n,Cmax})$.

The original problem is solved by computing $V_{i,c}$ for $i = 0, 1, \ldots, n$ and for $c = 0, 1, \ldots, C_{max}$.

If there are no projects in the portfolio—or the capacity of the portfolio is 0—the call value is 0:

$$V_{i,c} \leftarrow 0 \qquad \text{for } i = 0 \text{ or } c = 0.$$

Considering project π_i there are two possible cases:

If the costs of project π_i exceed the capacity c of the portfolio, project π_i cannot be included in the portfolio and the optimum call value is:

$$V_{i,c} \leftarrow V_{i-1,c} \qquad \text{if } c_i > c$$

Otherwise, the call value is the optimum achieved by either including project π_i or by not including project π_i:

$$V_{i,c} \longleftarrow \begin{cases} V_{i-1,\, c-ci} + v_i & \text{if } U(V_{i-1,\, c-ci} + v_i) > U(V_{i-1,c}) \\ V_{i-1,c} & \textit{otherwise} \end{cases}$$

In terms of the Knapsack problem instead of packing only one Knapsack of capacity C_{max}, in the dynamic programming solution all Knapsacks with integer capacities c are packed simultaneously. For each object that fits into one of the Knapsacks a decision has to be taken whether the Knapsack should contain the object or not. If so, the remaining capacity of the Knapsack is filled with a smaller Knapsack of size c-c_i.Otherwise the Knapsack remains unchanged.

The algorithm of the dynamic programming solution for the portfolio selection can be expressed in pseudo-code as follows:

```
for all capacities c = 0,1,2,…, Cmax {
τ0,c ← [ ]
V0,c ← 0
}
for all indices of projects i = 1,2,…, n {
for all capacities c = ci,ci +1,…, Cmax {
                        if U(Vi-1,c-ci + vi) > U(Vi-1,c)
                        then {
τi,c ← τi-1, c-ci ⋃ [i]
Vi,c ← Vi-1, c-ci + vi
                        } else {
τi,c ← τi-1, c
Vi,c ← Vi-1, c
            }
            }
}
```

"Dynamic Programming Solution for the Portfolio Selection of Non-Interrelated Projects"

The result is the selection $\tau_{n,Cmax}$ of indices of projects π_j which provide maximum utility for a given capacity c of the portfolio.

Proof:

Assume that project i is in the optimum subset that costs at most C_{max}. If project i is removed from this subset, the remaining subset must be the optimum subset costing at most $C_{max} - c_i$ of the $n - 1$ remaining projects after excluding project i. If the remaining subset after excluding project i was not the optimum one costing at most $C_{max} - c_i$ of the $n - 1$ remaining projects, we could find a better solution for this problem and improve the optimal solution. As this is impossible the remaining subset must be the optimum subset costing at most $C_{max} - c_i$.

Note that in the pseudo-code algorithm the order in which the capacities c are traversed is irrelevant. This is due to the fact that the algorithm relies on a matrix V holding all $n*C_{max}$ call values of the partial optimisations. For the sake of efficiency the matrix V can be substituted by a vector representing only the current row of the matrix and thus eliminating the first index of the matrix. However, if the matrix V is substituted by a vector, the order in which the capacities c are traversed becomes extremely relevant: Traversing the capacities c in increasing order can result in multiple occurrences of identical projects in the selection. In order to avoid these multiple occurrences the capacities c ought to be traversed in decreasing order from C_{max} to c_i. The order of the projects is irrelevant in any case as long as there are no interdependencies—and thus no preconditions—between them.

The optimised algorithm for the dynamic programming solution for the selection of non-interrelated projects for a portfolio substituting the matrices V and τ by vectors and reversing the order by which the Knapsacks are traversed can be described in pseudo-code like follows:

```
for all capacities c = 0,1,2,…, Cmax {
τc ← [ ]
Vc ← 0
}
for all indices of projects i = 1,2,…, n  {
for all capacities c = Cmax, Cmax –1, …, ci+1, ci  {
                    if U(Vc - ci  + vi) > U(Vc)
                    then {
τc  ← τc - ci ⋃ [i]
Vc  ← Vc - ci  + vi
                    } else {
τc  ← τc
Vc  ← Vc
          }
          }
}
```

"Optimised Dynamic Programming Solution for the Portfolio Selection of Non-Interrelated Projects"

In case of interrelations between projects the dynamic programming approach for the selection of a portfolio has to be modified to guarantee maximum utility.

6.7. Portfolio Selection of Interrelated Projects

The modelling of interrelations between projects is based on the definition of the various kinds of interrelations, which have already been presented in 5.3.

6.7.1. Modelling of Dependencies

Dependencies between projects as defined in 5.3.2. can be determined with respect to the aspects of certain dimensions; for example, the knowledge gained within one project may be a necessary prerequisite for another project. Therefore, the experts have to agree upon sets of projects $\omega_{i,k}$ fulfilling the preconditions for project π_i in dimension k. Regarding the selection of a portfolio, the union of these sets has to be included in the portfolio Ω.

$$\pi_i \in \Omega \Rightarrow \bigcup_k \omega_{i,k} \subset \Omega \tag{6.23}$$

with $\omega_{i,k}$ being the set of projects which are preconditions for project π_i with respect to dimension k. Note that the probability that the thresholds (refer to 5.3.3.) of the preconditional projects are exceeded is reflected in the call value of the project under consideration.

Condition 6.23 does also have to hold for contingent projects with $\omega_{i,k}$ being the set of projects contingent with π_i. Note that contingencies are by definition symmetric and thus cause circular dependencies, while preconditions must not be cyclic.

6.7.2. Knapsack Problem for Interrelated Projects

Taking preconditions between projects into account leads to additional constraints apart from the maximal capacity C_{max}. The following algorithm reflects this additional constraint and delivers the optimum selection τ_{opt} of a portfolio with maximal utility U_{opt}.

```
select (i) {
if i ≤ n {
        select (i+1)
τ ← τ ∪ [i]
if (Cτ ≤ Cmax) ∧( ∀_{j∈ωi} j ∈ τ ) select (i+1)
τ ← τ \ [i]
        } else {
                if Uτ > Uopt {
                Uopt ← Uτ
                τopt ← τ
        }
}
```

"Algorithm for the Solution of the Extended 0/1 Knapsack Problem Considering Interdependencies between Projects"

This algorithm differs from the solution of the classic 0/1 Knapsack problem only in that it considers a project π_i if the indices of all of its preconditions ω_i are already members of the subset τ. In order to allow the indices of all preconditions ω_i to be members of the subset τ the projects have to be traversed in topological order. This guarantees that for all projects all preconditions are checked before the project itself is considered for the portfolio.

$$\forall_i \forall_{j \in \omega_i} j < i \tag{6.24}$$

The initial call of the algorithm is now preceded by a topological sort:

```
topSort of all projects
        select(1)
```

The drawback of the algorithm being NP-complete and of complexity $O(2^n)$ has not been affected by taking interdependencies into account. This is why a dynamic programming solution for the 0/1 Knapsack problem considering interdependencies between projects is proposed.

6.7.3. Dynamic Programming Solution for the Portfolio Selection of Interrelated Projects

The problem with interrelated projects is that the optimum selection of the remaining subset fitting to project *i* may depend on project *i* and thus cannot be determined in advance. Fortunately the interrelations between projects usually form clusters, which themselves are independent of each other.

Taking into account the various kinds of interrelations as defined in 5.3. the projects and their interrelations can be mapped to a graph, with nodes corresponding to the projects and edges corresponding to the interrelations between them. Clusters of interrelated projects correspond to connected components of the graph. Determining these clusters of interrelated projects is equivalent to identifying the connected components of this graph. The following algorithm allows for the identification of the independent clusters:

```
for all indices of projects i = 1,2,…, n unmark project πi
j ← 0
for all indices of projects i = 1,2,…, n
if (project πi is unmarked) {
        j ← j + 1
        τj ← [ ]
        add project πi to cluster τj
}
```

"Identification of Independent Clusters (Main-Program)"

Note that the following recursive procedure "add project π_i to cluster τ_j" corresponds to a depth first traversal of the graph:

```
add project πi to cluster τj {
        mark project πi
        τj ← τj ∪ [i]
        for all unmarked projects πk interrelated[24] with πi {
                add πk to cluster τj
        }
}
```

"Identification of Independent Clusters (Sub-Program)"

Note that this algorithm does not check for circular preconditions, which thus allows to treat contingent dependencies in the same way as preconditions. Concerning the implementation of the model, checking for circular preconditions immediately takes places when preconditions for the projects are entered. Even if there were circular dependencies, as in the case of contingent dependencies, marking the nodes guarantees that the algorithm terminates.

The complexity of the algorithm to determine the clusters is of order $O(l+n)$ with l being the number of interrelations and n being the number of projects.

[24] Two projects π_k and π_i are regarded as interrelated, if π_k is interrelated with π_i or π_i is interrelated with π_k.

Each non-interrelated project is represented by a cluster of size 1 containing only this project. This allows for a classification of interrelated and non-interrelated projects. The non-interrelated projects are preselected by the dynamic Knapsack algorithm described in 6.6.2.

In a next step we consider all subsets of the set of interrelated projects with the total investments not exceeding C_{max}. Each of these subsets is treated as if it was a single project in the context of the dynamic programming solution.

The final step is to regard each of these subsets as a potential candidate for the Knapsack with capacity C_{max}. One by one each of these candidates is packed into the Knapsack and the remaining capacity is filled with the optimum set of non-interrelated projects that were calculated in the preselection process. Searching for maximum utility this process is repeated for all potential candidates of the subsets of interrelated projects whose investments do not exceed C_{max}.

The extended dynamic programming solution can be described in pseudo-code as follows, with:

ψ_j being the *jth* potential candidate of the subsets of interrelated projects whose investments do not exceed C_{max}

m being the number of these candidates

n being the number of non-interrelated projects

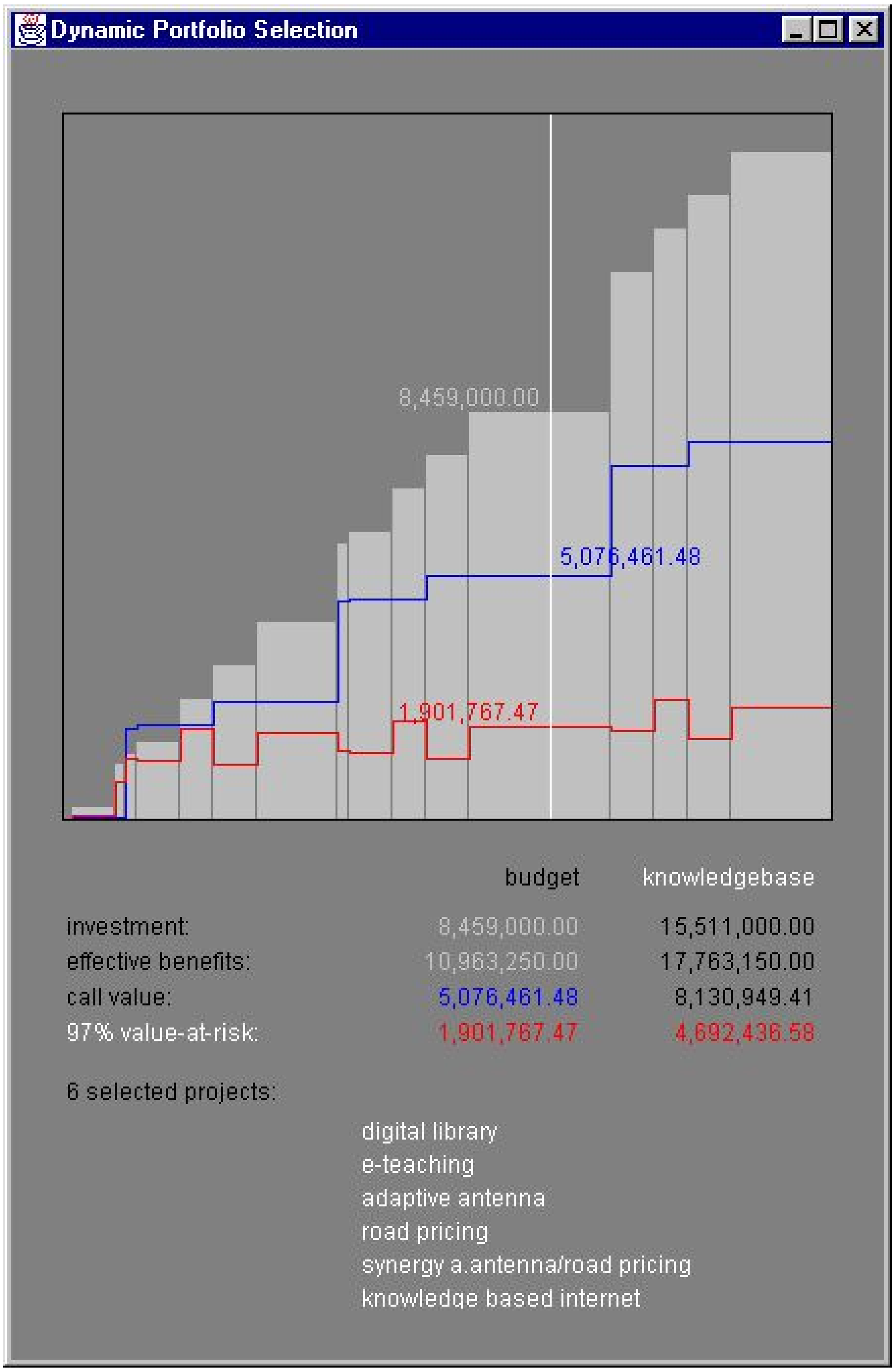
c_j being the total investment for candidate *j*

v_j being the total call value for candidate *j*

```
for all capacities c = 0,1,2,…, Cmax {
τc ← [ ]
Vc ← 0
}
for all indices of projects i = 1,2,…, n  {
for all capacities c = Cmax, Cmax –1, …, ci+1, ci  {
                        if u(Vc - ci  + vi)  > u(Vc)
                        then {
τc  ← τc - ci ⋃ [i]
Vc  ← Vc - ci  + vi
                        } else {
τc  ← τc
Vc  ← Vc
            }
            }
}
for all indices of candidates j= 1,2,…, m
if u(VCmax – cj + vj)  > u(VCmax)
then       {
τCmax ← τCmax- cj ⋃ ψj
VCmax ← u(VCmax – cj + vj)
}
```

"Extended Algorithm for the Dynamic Programming Solution for the Portfolio Selection of Interrelated Projects"

Note that the complexity of the algorithm increases by an additive term 2^m with m being the number of dependent projects. Thus the complexity of the dynamic programming solution for the selection of interrelated projects is $O(n*C_{max}+2^m)$, with n being the number of non-interrelated projects. In contrast to the classic Knapsack algorithm, with a complexity of $O(2^{n+m})$, the advantage of this modified dynamic programming approach is that for practical applications m is much smaller than the total number of projects $n+m$, because usually the number of interrelated projects is limited.



Screenshot 6.13: "Portfolio Selection using a Dynamic Programming Solution to the 0/1 Knapsack Algorithm"

Screenshot 6.13. shows the selection of six interrelated projects for the portfolio calculated with the dynamic programming solution of the 0/1 Knapsack algorithm depending on the chosen value for the current financial investment. The Value-at-Risk of the portfolio is calculated according to the formulas specified in 6.3. In the example the project "digital library" is a precondition for "e-teaching". "road pricing" and "adaptive antenna" serve as preconditions for the synergy "synergy a.antenna/road pricing". The diagram shows the portfolio's total call value (blue line), the total financial investment (grey bars) and the total Value-at-Risk (red line) for various limits of the total financial investment.

6.7.4. Modelling of Synergies and Redundancies

Synergies and redundancies between R&D projects as defined in 5.3.1. have to be determined before the portfolio selection process, as they alter the portfolio's performance.

In order to model the possible synergies and redundancies, the decision maker has to define the projects where possible synergies or redundancies might occur. First the experts have to estimate the possible outcomes for each of the projects separately and then the additional benefits of synergies have to be quantified. The synergies are valued similar to actual projects, but the investments are set to zero, because they are already included in the valuation of the synergistic projects.

The total multi-dimensional call value $\vec{V}_\tau$ of a portfolio considering interrelations is defined as the sum of the call values of the selected projects v_i plus synergistic contributions minus redundancies fulfilling the constraints caused by interdependencies between the projects. Note that the amendments to the call values caused by synergies $\vec{V}_{\tau syn}$ as well as the subtrahends caused by redundancies $\vec{V}_{\tau red}$ are multi-dimensional too. Interpreting the multi-dimensional call values as vectors, the total call value $\vec{V}_\tau$ of a portfolio of projects π_i with $i \in \tau$ is given by:

$$\vec{V}_\tau = \sum_{i \in \tau} \vec{v}_i + \vec{V}_{\tau\, syn} - \vec{V}_{\tau\, red} \tag{6.25}$$

with

$$\vec{V}_{\tau\, syn} = \sum_{\varphi_{syn\ i} \subseteq \tau} \vec{v}_i \tag{6.26}$$

and

$$\vec{V}_{\tau\, red} = \sum_i \Big(\sum_{j \in \varphi_{red\ i} \cap \tau} \vec{v}_j - \max_{j \in \varphi_{red\ i} \cap \tau} (\vec{v}_j) \Big) \tag{6.27}$$

$\vec{V}_{\tau syn}$ is the additional call value caused by the synergistic effects of the selection τ and $\varphi_{syn\, i}$ is the set of indices of projects causing synergy i. v_i refers to the call value
equivalent of synergy i.

The additional call value $\vec{V}_{\tau syn}$ caused by the synergistic effects of the selection τ is the sum of the call value equivalents of synergies of those projects being a subset of τ.

$\vec{V}_{\tau red}$ is the redundant call value equivalent caused by the redundant projects of the selection τ. From all the projects π_j which are members of the selection τ and members of one of the sets of redundant projects $\varphi_{red\, i}$ simultaneously, all projects are redundant apart from the one with the maximum call value.

In order to integrate synergies and redundancies into the 0/1 Knapsack as well as into the extended 0/1 Knapsack algorithm as described in 6.6.1. and 6.7.2. it is sufficient to alter the calculation of the utility of a selection U_τ

$$U_\tau = u(\vec{V}_\tau)$$

according to the call value defined in equation 6.25.

The same applies to the dynamic programming solution for the Knapsack problem 6.7.3. However it is important to treat projects causing synergies or redundancies just like projects with preconditions.

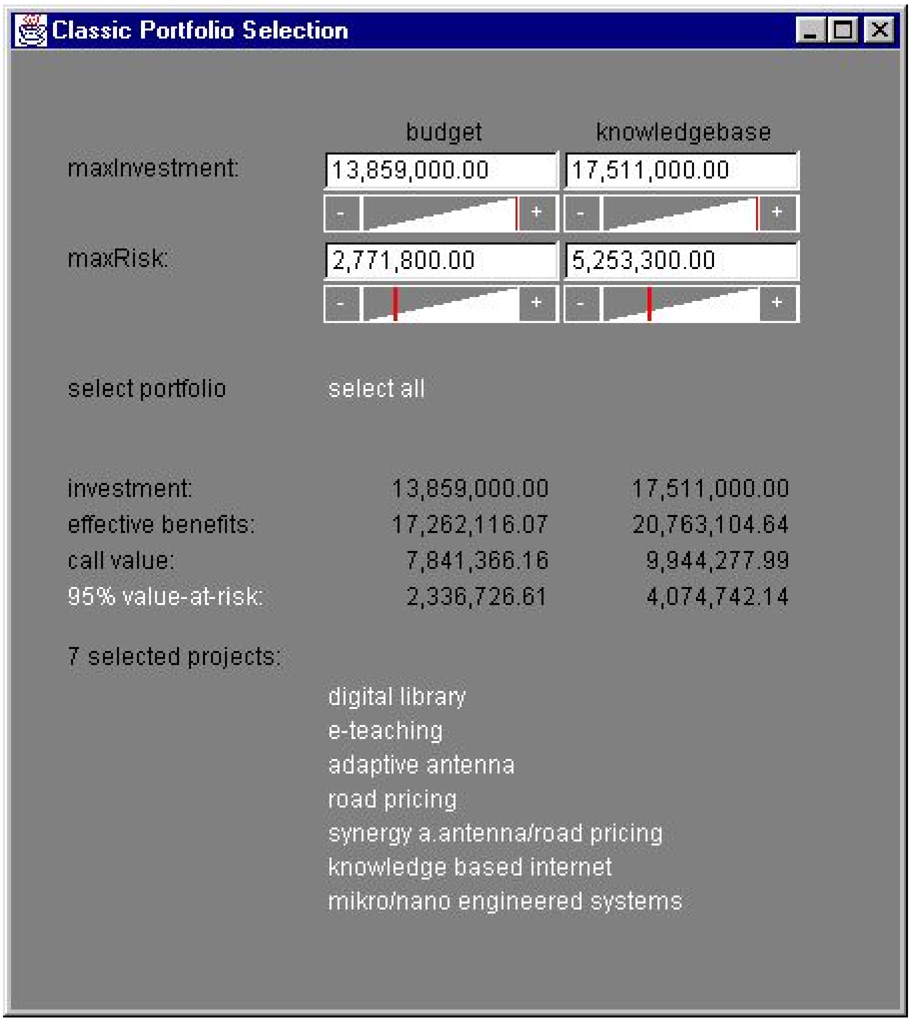
6.8. Portfolio Selection with Limited Risk

In many cases it is desirable not only to limit the total investment available for the portfolio but in addition to set a limit for the risk in selected dimensions. The risk at confidence level λ as defined in 6.3. is well suited to specify the risk limit. The following algorithm extends the classic 0/1 Knapsack algorithm as introduced in 6.7.2. to take the risk limit into account:

```
select (i) {
if i ≤ n {
        select (i+ 1)
τ ← τ ⋃ [i]
if (Cτ ≤ Cmax) ∧( ∀_{j∈ωi} j ∈ τ ) select (i+ 1)
τ ← τ \ [i]
        } else {
          for all dimensions k
                if ρτ,k > ρmax,k then return
                if Uτ > Uopt {
                Uopt ← Uτ
                τopt ← τ
        }
}
```

"Algorithm for the Solution of the Extended 0/1 Knapsack Problem Considering Interdependencies and Limited Risk"

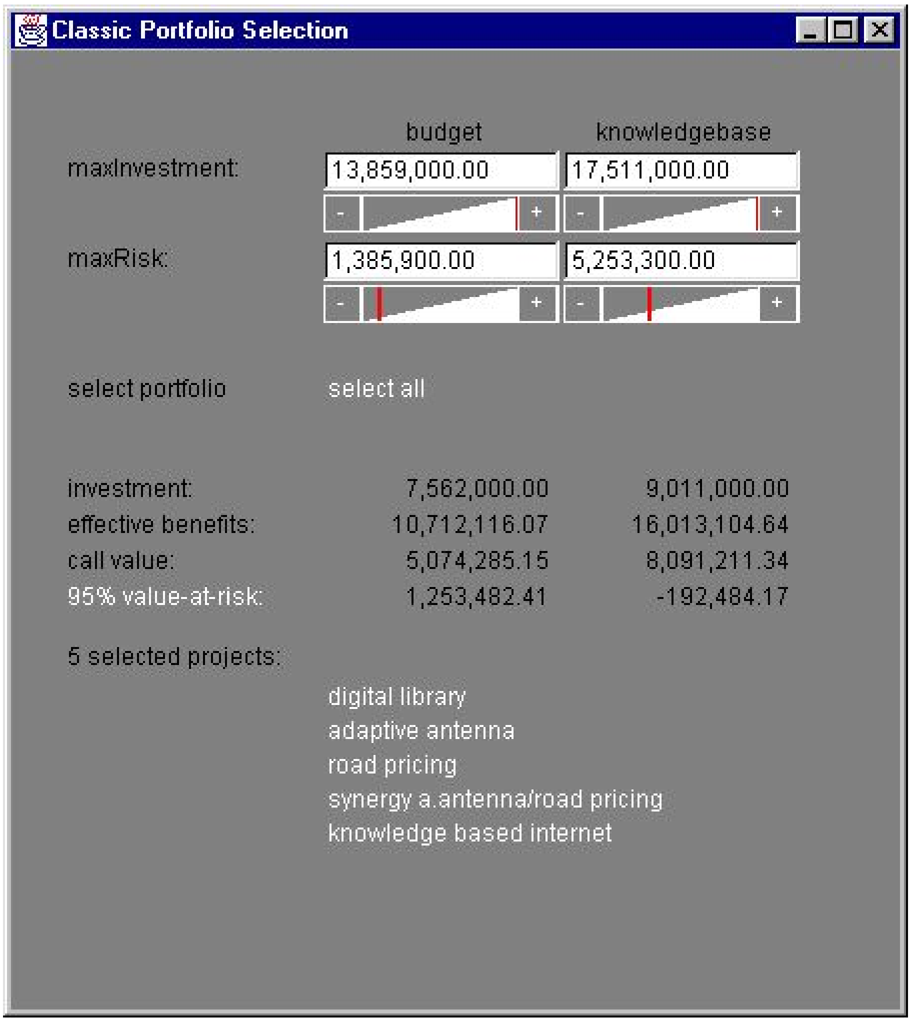
The algorithm presented above checks the risk of the selection τ with respect to dimension k, $\varrho_{\tau,k}$, against the risk limit $\varrho_{max,k}$. If for any dimension k, $\varrho_{\tau,k}$ exceeds the risk limit $\varrho_{max,k}$ the recursive procedure `select(i)` returns before the selection becomes a candidate for optimisation.



Screenshot 6.14: "Portfolio Selection Framework with Limited Risks"

In additional to the maximum investment the maximum risk, *i.e.* the maximum loss to be expected with a confidence level of 95%, can be entered as a limit as well.

Reducing the maximum risk can change the selection significantly:



Screenshot 6.15: "Change of the Portfolio Selection after Reducing the Maximal Risk Limit"

Screenshot 6.15. shows that reducing the maximal financial risk results in a different selection with reduced total investment and consequently reduced call value. The negative VaR of the dimension "knowledgebase" implies that the risk is so low that a minimum profit can be expected from the project instead of a maximum loss.

Note that the limitation of risk is beyond the scope of the dynamic programming solution of the 0/1 Knapsack, because the risk ϱ_τ of a selection τ is by no means additive with respect to the selected projects. Furthermore the complexity of the algorithm increases by the factor n, with n being the number of non-interrelated projects.

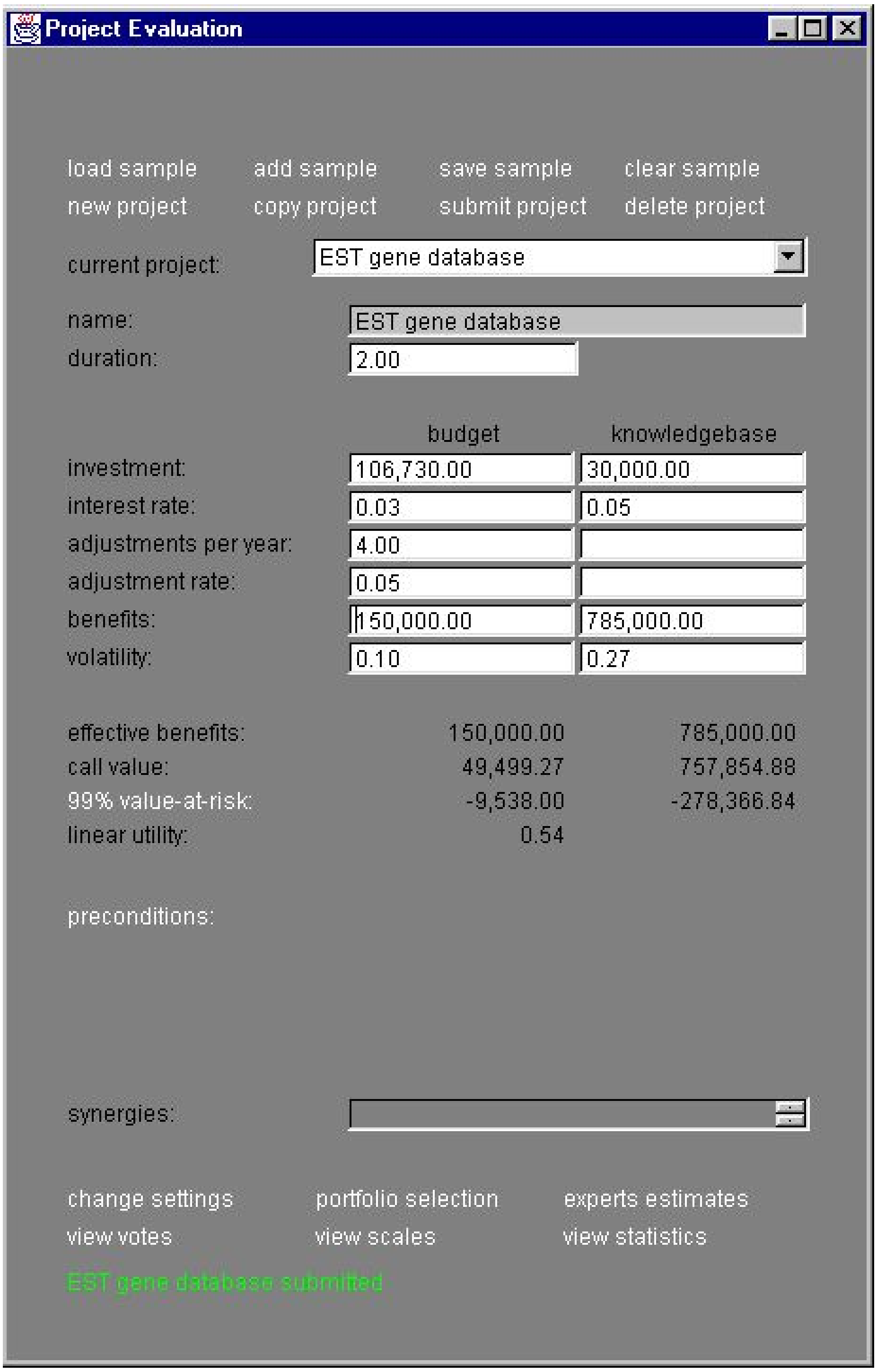
Chapter 7 — Case Studies

The present case studies are based on a sample of research projects undertaken within the Innovation Labs of the Austrian Research Centers (ARC) [1].

7.1. EST Bioinformatics

Functional and comparative genomics promises to be a valuable field of research for the near future. Understanding the plants' gene functions will be crucial for future crop improvement programs in order to exploit their full potential of functional diversity.

ARC Seibersdorf Research plans to establish an EST (Expressed Sequence Tags) database for the forestry and plant genome community. The aim of the project is to offer a microarray spotting service that allows access to various EST clones from a single institution. Prerequisite is a huge database and genebank containing sequenced EST clones as well as the necessary information on function and literature [3].



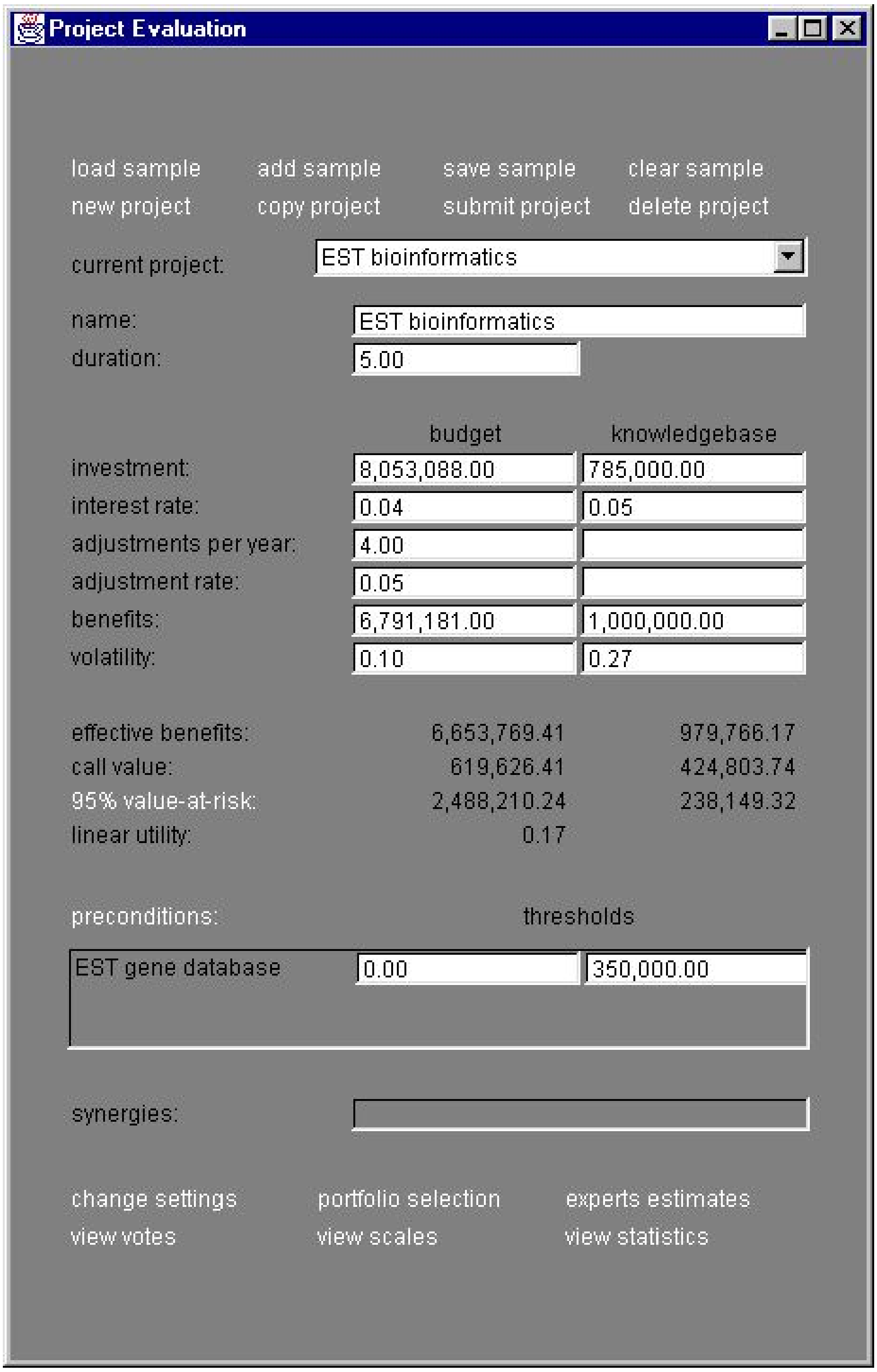
Screenshot 7.1: "Case Study EST Gene Database"

Screenshot 7.1 shows the results provided by the presented framework using data of the sample project "EST gene database". The database for the forestry and plant genome community developed within the project is a necessary precondition for the project "EST bioinformatics". Apart from a dimension "budget" covering the financial aspects of the project, there is a second dimension "knowledgebase" that refers to the content of the database. The project lasts for two years. Investment, interest rate, the number of adjustments per year (*e.g.* project reviews) and the amount of change of the project's value per review (in %), as well as an estimation of the project's benefits have to be specified for each dimension. The interest rate for the dimension "knowledgebase" reflects the relevance of time for the knowledge gained.

The project's volatility for the dimension "budget" is derived using the number of adjustments per year and the according adjustment rate. Alternatively, if there are no adjustments and according adjustment rate for the according dimension the volatility can be derived using the deviation of the experts' estimates.

While the unit of measurement for the dimension "budget" is Euros, the content of the knowledgebase is measured in EST gene database entries. Initially there were about 30,000 database entries. Experts' estimates for the content of the database at the end of the project range between 500,000 and 1,000,000. The result of these estimates is a "benefit" value of 785,000 database entries and a volatility of 0.27.

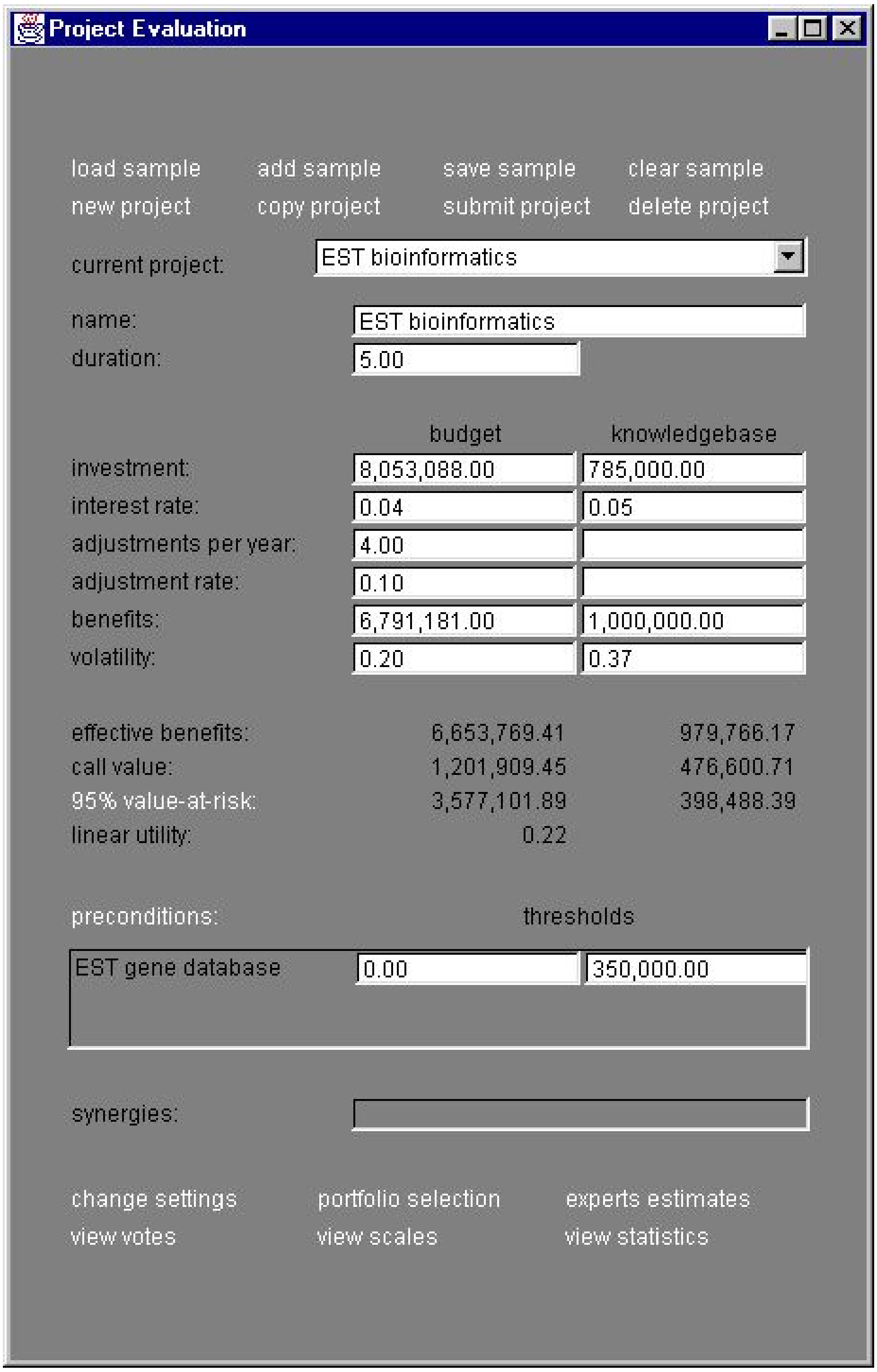
The results of the evaluation are the project's dimensions' call values, the Value-at-Risk (VaR) at a confidence level of 99%, as well as a utility value aggregating the valuations of the project's dimensions. The Value-at-Risk refers to the maximum loss to be expected in each dimension at a confidence level of 99%. A negative VaR, as in this case, implies that the risk is so low that a minimum profit can be expected from the project instead of a maximum loss



Screenshot 7.2: "Case Study EST Bioinformatics"

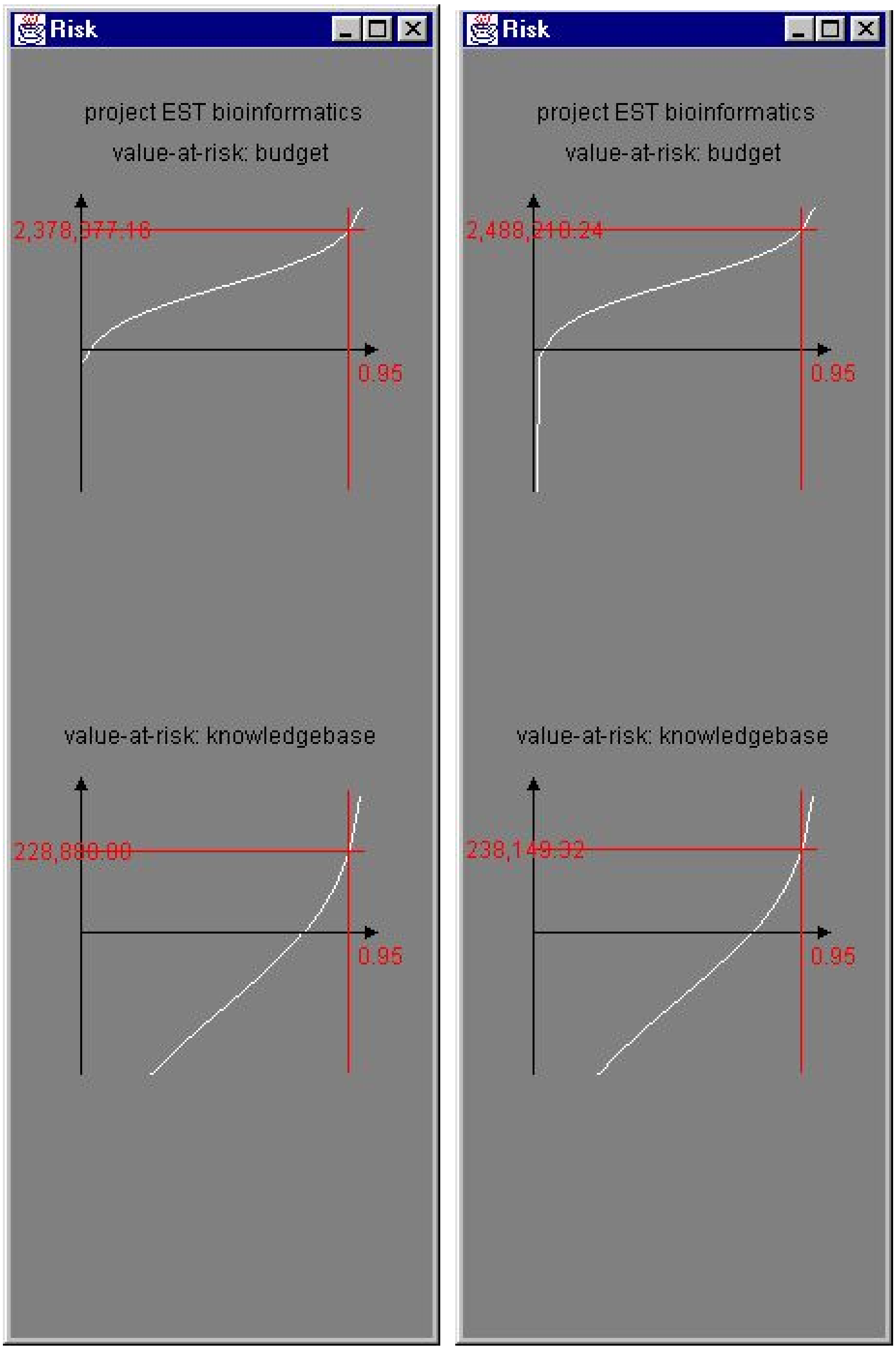
Screenshot 7.2 shows the valuation of the actual project "EST bioinformatics", for which the project "EST gene database" serves as a precondition. At least 350,000 entries in the gene database are necessary for a successful implementation of the project "EST bioinformatics". Note that the effective benefits (6,653,769.41 EUR) of "EST bioinformatics" are lower than the estimated benefits (6,791,181.00 EUR) because effective benefits take the probability of success of the preconditional project "EST gene database" into account. The effective benefits of the dimension "budget" decrease with the preconditional project even though the threshold in this dimension is set to 0.00. At least 350,000 database entries are necessary for the success of the project "EST bioinformatics", but the financial success of the database project does not affect the performance of the follow-up bioinformatics project. Nevertheless the minimum number of 350,000 database entries is crucial for the financial success of "EST bioinformatics" as well.

While the project "EST bioinformatics" obviously has got a negative net present value and would thus be rejected when using standard discounted cash flow techniques as decision support, the call value is positive. The call value takes the volatility and thus the project's "upside" potential into account. If the project develops unfavourably the option is not exercised and it will not be invested in the next stage of the project. Consequently the project's call value increases with a higher volatility as can be seen in screenshot 7.3. If the adjustment rate of the project's financial benefits rises from 5% to 10% per review, the volatility increases from 0.1 to 0.2, which causes an increase of the call value from 619,626.41 EUR to 1,201,909.45 EUR. The same effect can be observed for the dimension "knowledgebase". Obviously the VaR increases as well with increasing volatility.



Screenshot 7.3: "Higher Volatility Increases Call Value"

Screenshot 7.4 below shows that adding preconditions to a project increases its Value-at-Risk, defined as the maximum loss to be expected in each dimension at confidence level λ. In the example λ corresponds to 95%. The left screenshot shows that – given the project "EST gene database" was not a necessary precondition for the project "EST bioinformatics" – the maximum expected loss of the project "EST bioinformatics" would with a probability of 0.95 be 2,378,377.16 EUR and 228,880 knowledgebase entries. However, if the success of "EST gene database" is added as a necessary precondition for "EST bioinformatics" the maximum loss to be expected with a probability of 0.95 increases to 2,488,210.24 EUR and 238,149.32 knowledgebase entries.



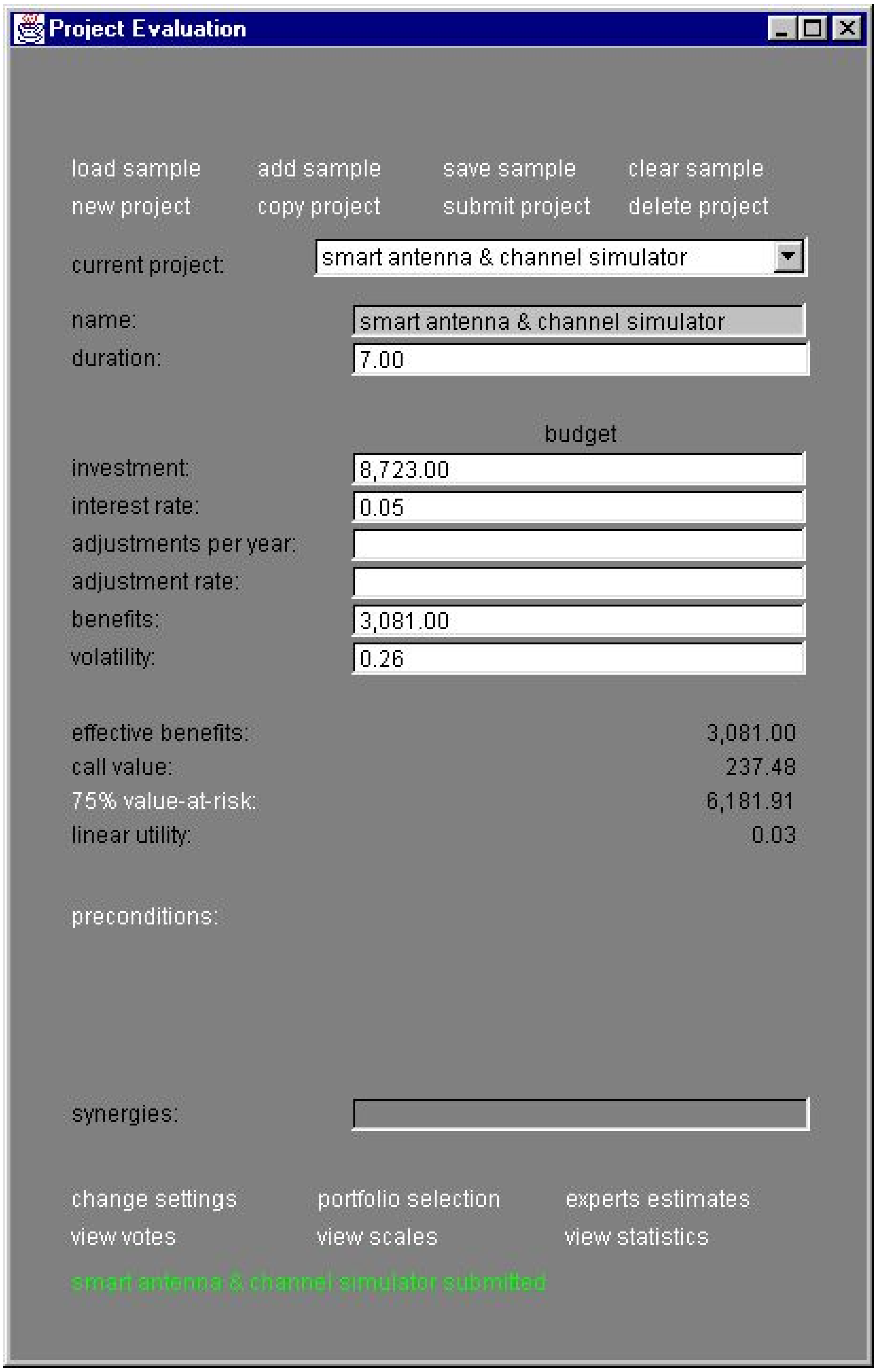
Screenshot 7.4: "Increase in Project's Value-at-Risk with Preconditions"

7.2. Smart Antenna

The steadily increasing number of mobile telecommunication users is accompanied by a growing need for transmission channels for mobile language and data communications. Smart antennas promise an increase in the overall capacity of the entire mobile telecommunications system by separating several users by means of spatial filtering and thus reducing power consumption for the same coverage resulting in longer active speaking time per battery-recharging,

Smart antennas comprise a group of single antennas that are driven by digital signal processors and are thus able to both compensate interference and optimise the transmission channel automatically. Smart antennas require vast amounts of computer power. Nevertheless they are regarded as one of the key technologies for the next generation of multimedia-enabled mobile telecom stations. Smart antennas use the combination of array technologies with digital signal interpretations in order to automatically compensate the negative effects of multi-path propagation in the mobile telecom channel, thus providing better transmission quality, higher data transfer rates and multi-media compatibility. Smart antennas have been well researched for basis stations, however, the results cannot yet be applied to mobile telecom stations. A hardware real-time channel simulator is developed jointly with the smart antenna technology in order to provide realistic conditions to test and optimise the functionality of smart antennas for mobile telecom stations and the required basis band signal-processing for GSM (and later UMTS).

Based on these ideas, ARC Seibersdorf Research launched a research project on smart antennas in 2002 [4].

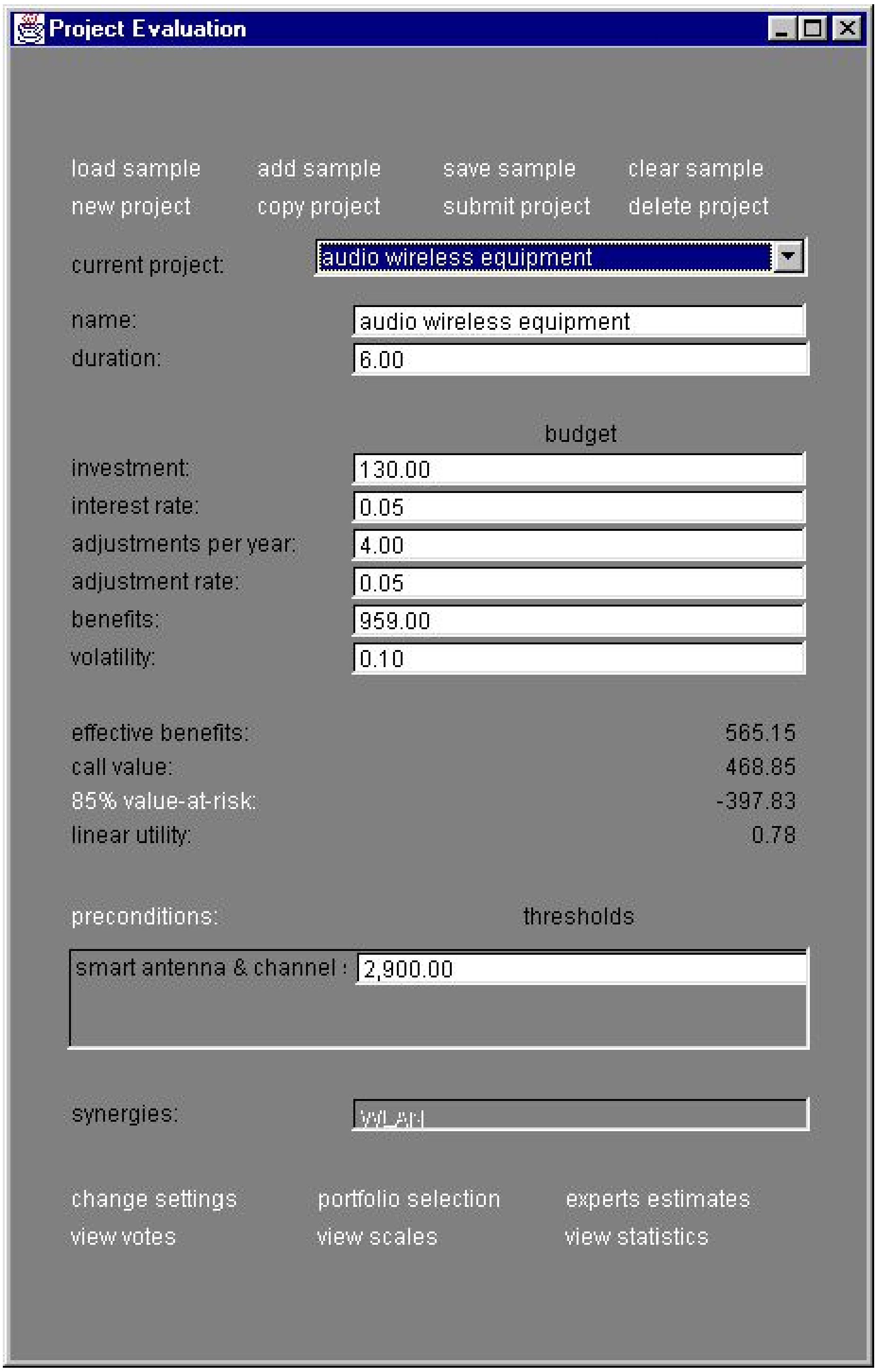


Screenshot 7.5: "Case Study Smart Antenna"

Screenshot 7.5 shows the evaluation of the "smart antenna and channel simulator" development project. Obviously the project would have a negative net present value due to the high investment costs (8,723 kEUR) compared to the relatively low expected revenues (3,081 kEUR). However, the project's call value takes the volatility and thus the project's "upside" potential into account. If the project develops unfavourably the option is not exercised and it will not be invested in the next stage of the project.

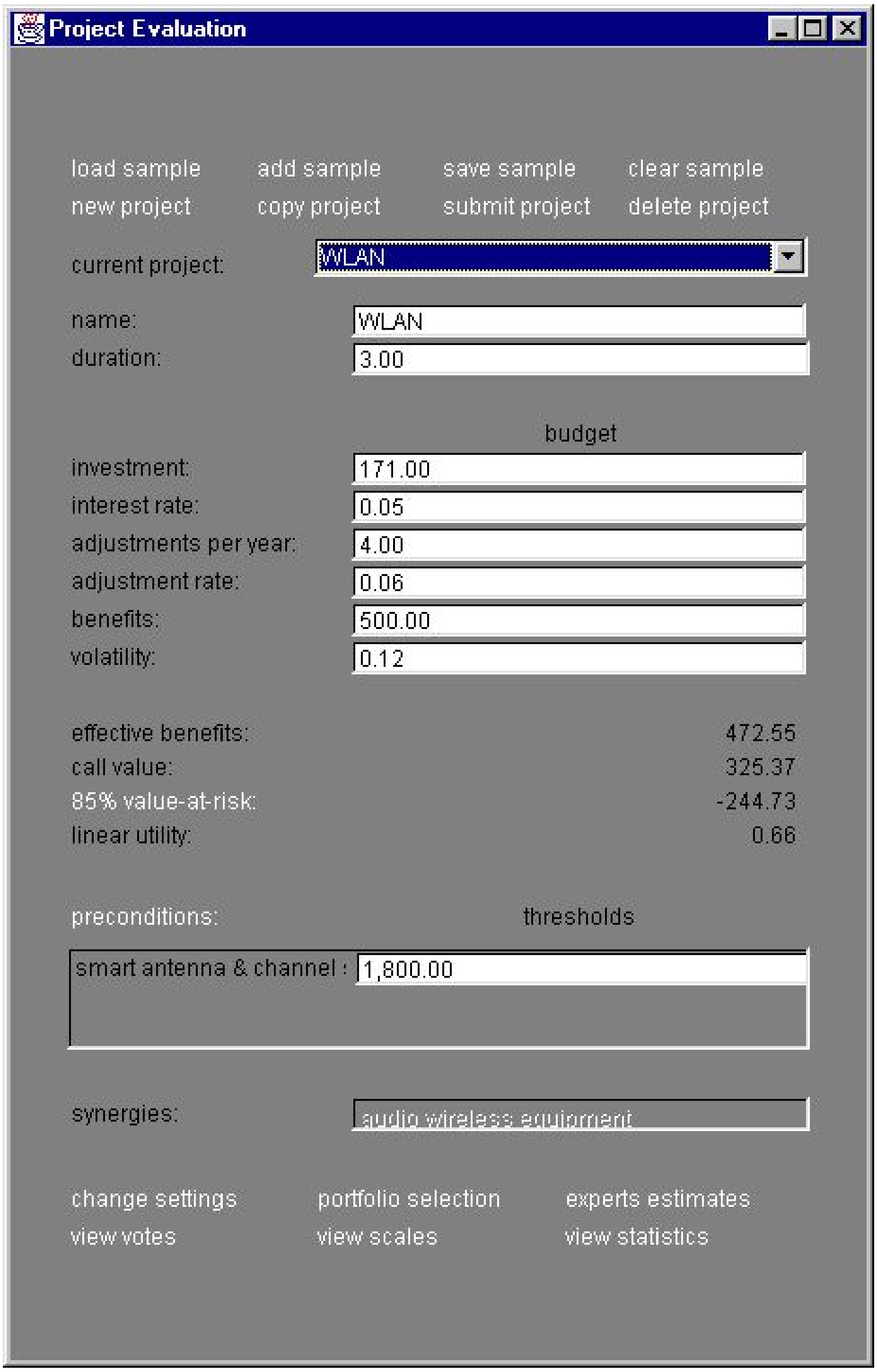
The development of the smart antennas allows for a number of follow-up applications. These include "Software Defined Radio" (SDR), a new and emerging area of research and development where market introduction is expected to take place from 2006 onwards. Furthermore the technology can be used for GPRS, audio wireless equipment and wireless LAN applications.

The project's Value-at-Risk (6,181.91) at a confidence level of 75% indicates that with a probability of λ=0.75 the project's expected loss will not be more than 6,181.91 kEUR.



Screenshot 7.6: "Case Study Audio Wireless Equipment"

Screenshot 7.6 shows the evaluation of the development of the “audio wireless equipment” project based on the technology provided by the “smart antennas and channel simulator”. Thus the successful implementation of the initial smart antenna project serves as a necessary precondition for the “audio wireless equipment”. The “smart antenna” project is regarded as a success if the project revenues exceed a threshold of at least 2,900 kEUR.

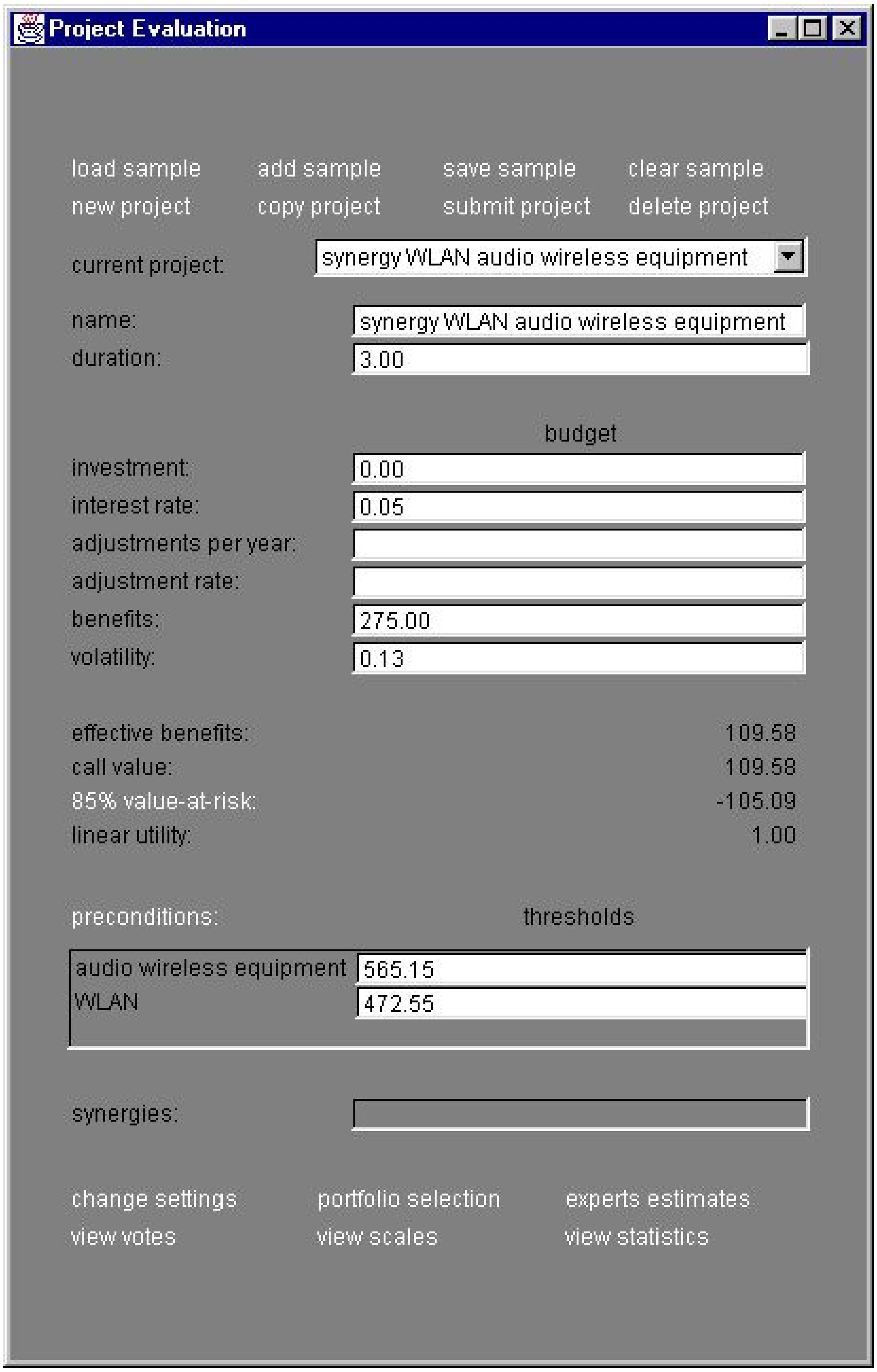


Screenshot 7.7: “Case Study Wireless LAN”

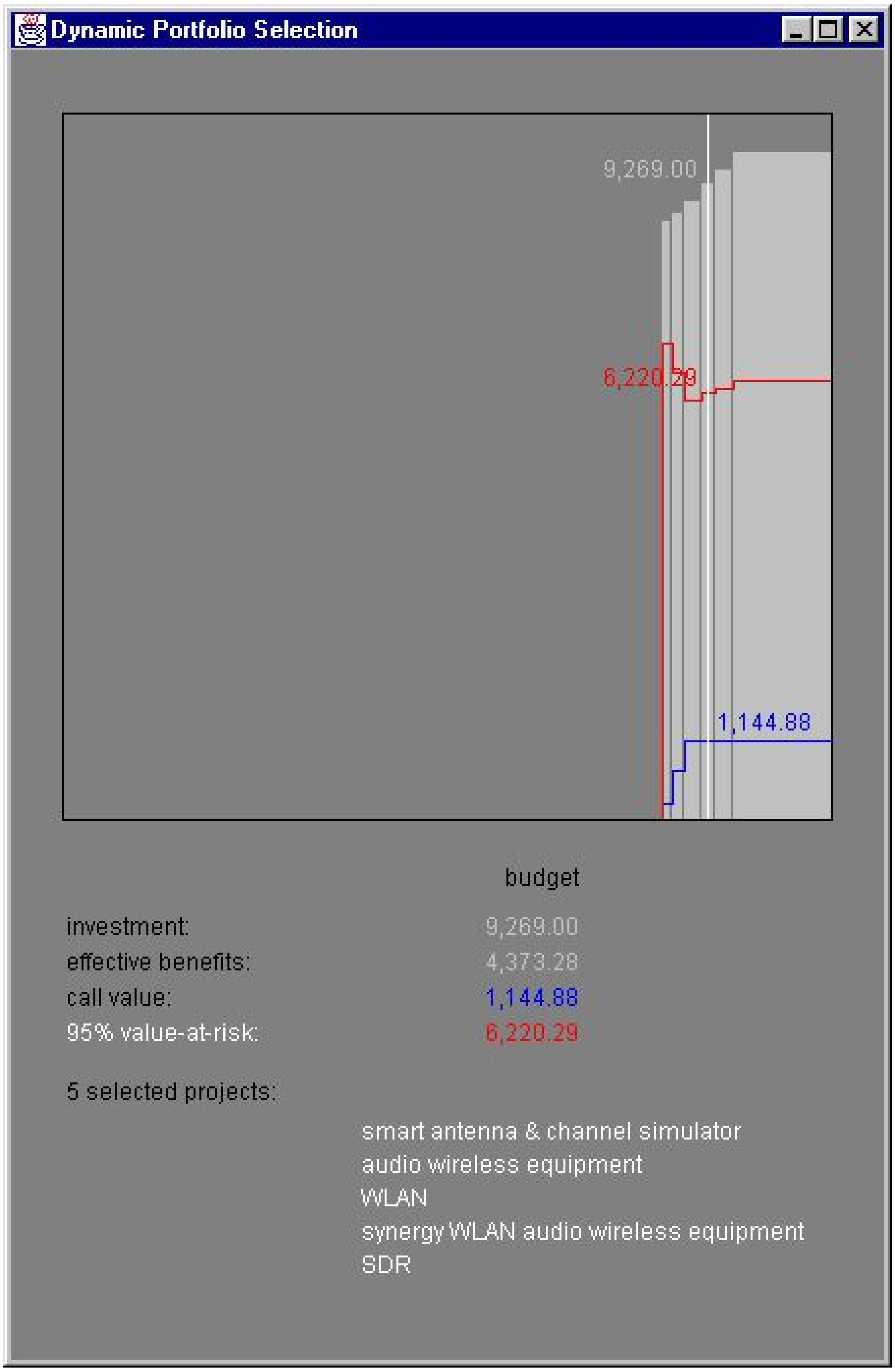
Just like “audio wireless equipment”, also the “wireless LAN” applications require a successful implementation of the smart antennas as a precondition. The thresholds indicating a successful implementation of the initial smart antenna project do not have to be the same for all of the follow-up projects.

If both projects, “audio wireless equipment” as well as the “wireless LAN” applications are successfully implemented, there are synergistic effects, *i.e.* additional benefits resulting from the implementation of the two projects together. Using the electronic equipment together with the competence gained within the two projects *e.g.* additional services for usability checks could be offered. Therefore “audio wireless equipment” is listed as a synergy for the “WLAN” project and vice versa.

In order to quantify the synergistic contributions of “WLAN” and “audio wireless euipment” for the portfolio, they are regarded as a virtual project without investments but additional benefits, see screenshot 7.8 The successful implementations exceeding specified thresholds (565.15 kEUR, 472.55 kEUR respectively) of the projects causing the synergy serve as necessary preconditions for the synergy. Obviously the call value as well as the utility of the synergistic project are very high, as the project causes additional benefits without costs. Again the effective benefits (109.58 kEUR) are lower than the estimated benefits (275 kEUR) as the probabilities of a successful implementation of the preconditional projects have to be taken into account.



Screenshot 7.8: "Case Study Synergy Wireless LAN and Audio Wireless Equipment"



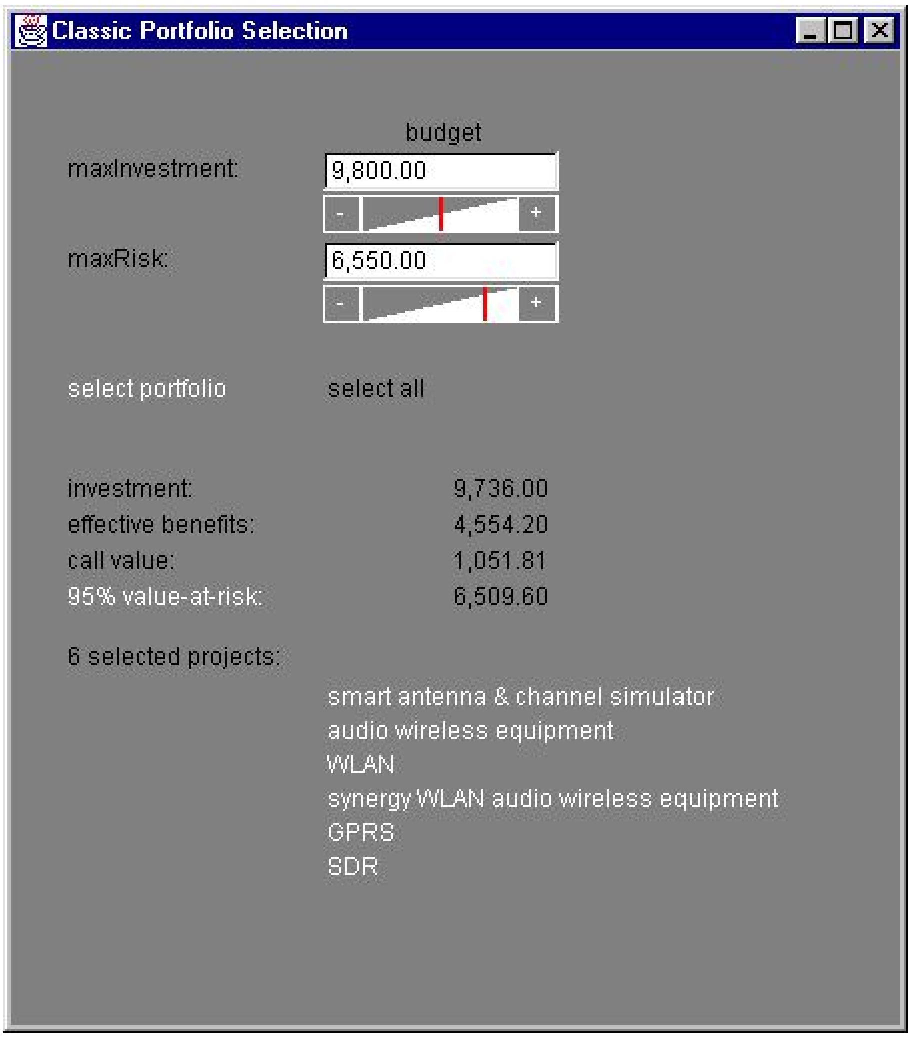
Screenshot 7.9: "Dynamic Portfolio Selection for Smart Antenna and Follow-Up Projects"

Screenshot 7.9 shows the implementation of the portfolio selection module for the smart antenna project and the according follow-up developments. Five interrelated projects are selected for the portfolio by the dynamic programming solution of the 0/1 Knapsack algorithm depending on the chosen value for the current financial investment. The chosen investment level (white line) corresponds to a percentage of the maximum investment, that would be necessary to select all candidate projects and can be altered by dragging the white vertical line. The graph of the dynamic programming solution to the 0/1 Knapsack algorithm allows the comparison of financial call values and the Value-at-Risk at a confidence level of 95% for various financial investments (grey bars). The portfolio's call value corresponds to 1,144.88 kEUR for the chosen investment of 9,269 kEUR.

The financial Value-at-Risk is 6,220.29 kEUR at a confidence level of 95%, meaning that with a probability of 0.95 the portfolio's loss will not exceed 6,220.29 kEUR.

The reason for the bunching of the data to the right of the chart is that a relatively high initial investment is necessary to start the "smart antenna and channel simulator" project. As this project serves as a precondition for all the other projects, no follow-up project can be selected for the portfolio without investing in smart antennas. As soon as "WLAN" and "audio wireless equipment" are selected for the portfolio, the according synergy augments the value of the portfolio without incresing the necessary investments.

Screenshot 7.10 shows that using the classic 0/1 Knapsack algorithm for portfolio selection the investments as well as the Value-at-Risk of the portfolio can be limited. Limits can be set in each dimension, but for the present case study there is only a one dimension covering the financial aspects of the "smart antenna" and follow-up projects. The following screenshot shows a selection of six projects for limited investments and limited Value-at-Risk.



Screenshot 7.10: "Classic Portfolio Selection for Smart Antenna and Follow-Up Projects"

Chapter 8 — Conclusions & Further Research

The framework presented in this thesis provides the evaluation of R&D projects considering multi-dimensional aspects combined with an estimation of the projects´ risk. The valuations of a number of R&D projects being candidates for an R&D portfolio are used to select projects for the portfolio considering interrelations between these projects. The portfolio selection allows for specifying limits for the total investment and the risk of the portfolio. The focus of the framework is on the integration of these requirements. Therefore, in order to limit the scope of this thesis, well-known concepts were used for the valuation of real options, the integration of the valuations of the projects´ multiple dimensions and for the calculation of a single project`s as well as the portfolio´s risk.

Using the Black-Scholes formula for valuing projects as real options, might be regarded as an oversimplifying approach to the complex issue of option pricing. Especially as it is argued in literature that real projects do not entirely resemble financial options and consequently the necessary input data for the real options valuation can in many cases not be provided, refer *e.g.* to [Perlitz, Peske and Schrank, 1999]. However the framework would allow for substituting the real options valuation using the Black-Scholes formula by more complex option valuation methods specially suited to deal with specific kinds of R&D projects. It is also possible to use specific kinds of option pricing models for specific project dimensions, such as the discontinuous jump model proposed by Pennings and Lint [Pennings and Lint, 1997] for the valuation of the dimension knowledge, as the knowledge gained during a project can only increase and never decrease even though the project might not be successful.

Due to the multi-dimensional valuation approach it is recommendable to use a multi-dimensional distribution function as the basis for the real options model. Further research could involve deriving a general solution of the Black-Scholes model based on a multi-dimensional Normal distribution function. With respect to the projects´ risk the multi-dimensional distribution function would require finding adequate copulae to describe the risk.

Analysing a project with decision trees allows for a more detailed modelling of the project than analysing it with real options using the Black-Scholes formula. On the other hand, in order to use decision trees accurately, one has to define consequences of decision and assign subjective probabilities to the outcomes possible. This might be difficult in practice and becomes more difficult for periods lying far in the future.

Real options, in general, provide a much less detailed view on projects, and do not account for interrelations between projects as long as compound options are not taken into account.

The presented framework analyses projects on a higher level of granularity than standard real options, because various aspects of a project are evaluated and the focus is not on the financial aspects only. Furthermore, various kinds of interrelations between projects are taken into account and the impacts of these interrelations on the performance of the portfolio are considered within the portfolio selection. Nevertheless the various stages of a project and the according decisions are not modelled explicitly, as with the decision tree approach. By asking a number of experts to judge the possible outcomes of the various aspects of a project, the estimation of the project's results is simplified. Instead of assigning probabilities to the outcomes of decisions, the experts only have to give an approximate estimation of the value of the project's results. Due to the incorporation of a number of experts into the valuation process, the framework supports a democratic decision process Consequently the resulting selection of projects relies mainly on the quality of the experts' estimates.

The task of valuing the knowledge gained within a project is somewhat critical as it can not be measured directly, like financial numbers. Therefore a proxy representing the gain in knowledge has to be found in order to include this important aspect into the projects´ valuation. These could be database entries where each entry represents an essential bit of knowledge for the whole project such as in the case study Bioinformatics described in 7.1. The "correct" valuation of knowledge and whether it can be evaluated at all is disputed, but on the other hand more and more required as can *e.g.* be evidenced by the advancing deployment of intellectual capital statements. In order to facilitate an arbitrary way of taking the knowledge gained within a project into account, the presented framework does not specify how knowledge has to be valuated but allows for various kinds of valuations to be used as input data for the valuation of a project´s knowledge dimension.

Some studies comparing evaluation models for R&D projects—refer for example to [Neely, 1998] or [Frenkel, Hommel and Rudolf, 2000]—conclude that financial approaches including real options are not suitable for basic research projects. This conclusion is based on the obvious lack of financial input data for research that is not yet related to any kind of product development. The presented framework provides a way to evaluate such projects with the real options approach in non-monetary terms by simply not including the financial dimension into the valuation, but focusing on the aspects of gaining knowledge or other potential benefits from the project. If the basic research turns out to be promising, and results into the development of new products or processes the financial dimension can be included into the evaluation at a later point in time. Thus the presented framework provides a flexible way of evaluating projects in an iterative process, based on the information that is available at that stage of the project. The same evaluation tool can be used for the whole life of the project and adapted to the main focus of the current stage of research or development.

There is little practical experience concerning the measurement of non-monetary aspects like the knowledge gained within a research project or social, environmental impacts of a project respectively. Consequently the acceptance of the valuation process by the users might be difficult to achieve. Another problem is the recruiting of qualified experts for these domains. Despite of these difficulties taking non-monetary aspects of research projects into account will be a challenge for the endevoured future integration of knowledge and human resource management into project management.

The practical application of the framework showed that the model has got high stability with respect to changes of the scales of the multi-attribute utility analysis. Therefore the decision maker who is responsible for specifying the scales for the various dimensions has only got a minor influence on the portfolio selection process. Thus managers can only marginally influence the selection process and the preference of certain projects favourised by managers is not possible.

The classic 0/1 Knapsack algorithm for the portfolio selection allows for resource and risk limits in the different dimensions, as well as taking various kinds of interrelations into account. The shortcoming of the algorithm is that it is NP-complete. As a consequence of the exponential complexity of the classic 0/1 Knapsack algorithm the dynamic programming solution to the Knapsack problem is suggested as an alternative. Inherent to the dynamic programming approach only one limit can be specified for the optimisation and the investments have to be integers. The latter is irrelevant for practical applications. The simultaneous calculation of all portfolios for smaller investment limits, which is inevitable for the dynamic programming algorithm, turned out to be an additional benefit of the dynamic programming solution, as all solutions can be displayed in parallel, which provides the decision maker with a better overview.

The portfolio selection provides optimal choices at single points in time. However, it is not possible to simulate the effects of starting a project at a later point in time, which would allow for optimising the resource investments over time. Thus the scheduling of resource allocations over time could be a desirable feature of future extensions of the portfolio evaluation framework.

Glossary

Additivity[25]	Additivity in the context of projects contributing to a portfolio means that the contributions of the projects to the portfolio are non-interrelated and can thus simply be added when determining the value of the portfolio.
American option	An option that can be exercised any time until its expiration date.
Arbitrage	The purchase of securities on one market for immediate resale on another market in order to profit from a price or currency discrepancy.
Attributes	Measurable values of a specific dimension.
Beta	Beta is defined as the ratio between the covariance of the rate of return of the asset and the rate of return of the market portfolio, and the variance of the market portfolio. It measures the systematic risk of the asset, *i.e.* the risk that cannot be diversified away.
Best/worst cases	Estimations of best and worst cases for the weights of the various dimensions needed for the calculation of the general utility values.
Binomial distribution	Binomial distributions model discrete random variables. Typically, a binomial random variable is the number of successes in a series of trials.
Binomial model	A method of pricing options in which the probability over time of each possible price follows a Binomial distribution. The basic assumption is that prices can move to only two values (one higher and one lower) over any short time period.
Black-Scholes model	The first complete mathematical model for pricing options, developed by Fischer Black and Myron Scholes. It examines market price, strike price, volatility, time to expiration, and interest rates, but is limited to certain kinds of options.
Call option	A call option on an asset gives the right, but no obligation, to acquire the underlying asset by paying a prespecified price—the exercise price—on or before a given maturity.
Call value	Call value of one of the project's dimensions calculated with the Black-Scholes formula for European call options.
Cash flow	The net spendable income from an investment determined by deducting all operating and fixed expenses from the gross income. Net income minus preferred dividends plus depreciation.

[25] Note that underlined terms in the glossary refer to general definitions, whereas terms that are not underlined are defined as used within the portfolio evaluation framework, but the definition may not be generally applicable.

Certainty equivalent	A certainty equivalent of a lottery refers to an amount x such that the decision maker is indifferent between the lottery and the amount x for certain.
Confidence interval	Provides a range of plausible values for an unknown parameter. The width of the confidence interval gives some idea about how uncertain the unknown parameter is.
Copula	A copula is a multivariate distribution function defined on the unit cube $[0, 1]^n$, with uniformly distributed marginals.
Correlation	The simultaneous change in value of two random numeric variables.
Correlation coefficient	A statistic in which the covariance is scaled to a value between minus one (negative correlation) and plus one (positive correlation).
Covariance	Statistic describing the relationship between two variables. A positive value means that when variable takes on a value above its expected value, the other has a propensity to do the same. If the covariance is negative, the deviations tend to be of an opposite sign.
Cumulative distribution function	A function giving the probability that the random variable X is less than or equal to x, for every value x.
Dependency	Dependency of projects for a portfolio means that the contributions of the various projects to the portfolio depend on each other, and are thus not additive when determining the value of the portfolio.
Dimension	An aspect of the project *e.g.* finance, knowledge, social impacts, environmental impacts, ethical value etc., that contributes to the success/failure of the project.
Discounted cash flow	Calculates the value of a future cash flow in terms of an equivalent value today.
Duration	Duration of the project measured in months or years.
Dynamic programming	Dynamic programming is a method of solving a problem by combining the solutions of its subproblems using a Divide and Conquer method. Dynamic programming is typically applied to optimisation problems. In such problems there can be many possible solutions and the objective is to find a solution with the optimal value. There may be more than one optimal solution to the problem.
Estimates	Experts' estimates for possible future values of the project's dimensions.
European option	An option that can be exercised at maturity only.
Exercise price	The price set for buying an asset (call) or selling an asset (put). The strike price.
Expected cash flows	Present value of expected cash flows gained by accomplishing the project.
Expected value	The expected value $E(x)$ population mean, of a random variable indicates its average or central value.
Expiration date	The date of maturity of an option contract.
Hedge	A securities transaction that reduces or offsets the risk on an existing

	investment position.
Internal rate of return	Internal rate of return (IRR) is the average annual rate of return that is obtained from an investment over the period during which it generates cash flows. In other words, it is the discount rate that makes the net present value of the project's cash flow stream zero.
Investment cost	Present value of investment cost needed for the project.
Knapsack problem	Given a Knapsack of capacity c (a positive integer) and n objects with sizes $s_1,...,s_n$ and profits $p_1,...,p_n$ (where s_i and p_i are positive integers), find the largest total profit of any subset of the objects that fits into the Knapsack (and find a subset that achieves the maximum profit). The capacity of the Knapsack corresponds to the available investment and the sizes correspond to the costs of the various projects.
Linearity	The relationship that exists between two quantities, when a change in one of them produces a directly proportional change in the other.
Maturity date	Date on which the principal balance of a loan, debt instrument or other financial security is due and payable to the holder.
Mean	Average value of the experts' estimates per dimension.
Model	Mapping of the dynamic process of a project to a formalised description (*e.g.* a mathematical formula) in order to evaluate and control the project.
Monotonicity	The degree to which the slope of a function does not change sign.
Multi-attribute utility analysis MAUA	A vector of attributes of, for example, a project, is translated into a single utility metrics by separately defining functions that describe the value of individual attributes. Then, an importance weight is assessed and assigned to each attribute and the results are combined (multiplicative and/or additive) to a model that defines total utility.
Multiple linear regression	Sampling points and corresponding utility values have to be entered for a multiple linear regression. The slope of the regression is the weight for the additive utility function.
Net present value NPV	The present value of an investment's future net cash flows minus the initial investment. If positive, the investment should be made, otherwise it should not.
Normal distribution	Normal distributions model continuous random variables. The Normal distribution is a distribution of random variables, which can be regarded as the sum of superimpositions of values, being approximately equally error prone. The sum of n independent random variables, that belong to the same distribution, will always converge against the Normal distribution with increasing n.
Option	A right to buy or sell specific securities or commodities at a stated price (exercise or strike price) within a specified time.
Orthogonality	Two geometric objects have this property if they are perpendicular.
Payments lost	Loss of payments (cash flows) caused by a delay of the investment.
Permanent uncertainty	Permanent with regard to uncertainty means that there is no indication that the uncertainty may change over time or that it can be affected in any way, diminished or resolved.

Portfolio	The totality of the various types of securities and other financial instruments (stock, bonds, treasury bills, etc.) held by an investor. A set of projects that can be transitively interdependent and are selected because they contribute to the overall goal of the portfolio, such as maximising the profit, under certain constraints.
Present value	Today's value of an investment that yields some future value when invested to earn compounded interest at a known interest rate; *i.e.* the future value at a known period in time discounted by the interest rate over that time period.
Probability	A probability provides a quantitative description of the likely occurrence of a particular event. Probability is conventionally expressed on a scale from 0 to 1, where a rare event has a probability close to 0 and a very common event has a probability close to 1.
Probability density function	The probability density function of a continuous random variable is a function, which can be integrated to obtain the probability that the random variable takes a value in a given interval.
Put option	A put option on an asset gives the right, but not the obligation, to sell the underlying asset and receive the exercise price.
Real option	An investment with option-like characteristics not traded at financial markets. The term real option is used to distinguish between options arising in not purely financial contexts from financial options relating to securities or commodities.
Return on Investment	The amount of net profit earned by the principal amount invested, usually expressed as an annual percentage return.
Risk-averse	A decision maker is risk-averse if he prefers the expected consequence of any lottery, where no single consequence has a probability of one of occurring, to that lottery. A decision maker is risk-averse if and only if his utility function is concave.
Risk-free interest rate	If there is no uncertainty involved within the cash flows gained from an investment, they are discounted with the risk-free interest rate, which is the opportunity cost of capital of a risk-free investment. The risk-free rate can for example be regarded as the interest rate obtained from U.S. treasury bonds.
Risk-neutral	A decision maker is risk-neutral if he is indifferent between every lottery, where no single consequence has a probability of one of occurring, and the expected consequence of that lottery.
Risk premium	Expected additional return for making a risky investment rather than a safe one.
Risk-prone	A decision maker is risk-prone if he prefers any lottery, where no single consequence has a probability of one of occurring, to the expected consequence of that lottery. A decision maker is risk-averse if and only if his utility function is convex.
Standard deviation	A measure of the variation in a distribution, equal to the square root of the arithmetic mean of the squares of the deviations from the arithmetic mean; the square root of the variance.

Temporary uncertainty	Temporary uncertainty means that the uncertainty can be resolved over time.
Topological sort	If there is a path from node π_i to π_j in an acyclic directed graph, the relation $\pi_i < \pi_j$ holds. This relation corresponds to a half order, because it is not defined between every pair of nodes.
Transitivity	If whenever object *A* is related to *B* and object *B* is related to *C*, then the relation at hand is transitive provided object *A* is also related to *C*.
Utility	Additive and general utility value of the project consolidating the valuations (call values) of the various project dimensions using multi-attribute utility analysis.
Value-at-Risk	Value-at-Risk (VaR) is an amount, where the chance of losing more than this amount is, *e.g.* 1 in 100, over some future time interval.
Variability	The term variability refers to real and identifiable differences between, for example, individuals within a population. Variability describes measurement units of attributes, that vary concerning their parameter-values.
Variance	The dispersion of a variable. The square of the standard deviation.
Volatility	The standard deviation of the annualised continuously compounded rate of return of an asset.

Abbreviations

Abbreviation	Meaning
ϱ_λ	Risk measure
λ	Confidence level
w_λ	Value-at-Risk at confidence level λ
Φ	Standard Normal distribution
α	1-λ percentile of the Standard Normal distribution Φ
p	Probability
E(x)	Expected value
σ^2	Variance
π_i	Project *i*
$v_{i,k}$	Call value of dimension *k* of project π_i
$c_{i,k}$	Costs of dimension *k* of project π_i
$s_{i,k}$	Success of dimension *k* of project π_i
s_i^{in}	Intrinsic contribution to the success of project π_i
s_i^{ex}	Extrinsic contribution to the success of project π_i
d_{ij}	Dependencies between projects *i* and *j*
θ_{ij}	Project π_i´s success threshold for success of project π_j
U_i	Utility of Project *i*
$\mu_{i,k}$	Mean of experts' estimates for dimension *k* of project π_i
$\sigma_{i,k}$	Deviation of experts' estimates for dimension *k* of project π_i
r	Interest rate
y	Dividend payments
S	Current value of the underlying asset
K	Option's exercise price
t	Project's duration
N (.)	Cumulative Standard Normal density function
Ω	Project portfolio

V	Total expected (call) value of a portfolio
$\vec{V}$	Multi-dimensional call value of a portfolio
U(V)	Utility of a portfolio
C_k	Costs of dimension *k* of a portfolio
C_{max}	Capacity of a portfolio
$\Re$	Set of real numbers
τ	Set of projects
$\omega_{i,k}$	Set of projects fulfilling the preconditions for project π_i in each dimension *k*
ψ_j	The *jth* potential candidate of the subsets of interrelated projects whose investments do not exceed C_{max}
$\varphi_{syn\ i}$	Set of indices of projects causing synergy *i*
$\varphi_{red\ i}$	Set of indices of projects causing redundancy *i*
$V_{\tau syn}$	Additional call value equivalent caused by synergistic effects of subset τ
$V_{\tau red}$	Additional call value equivalent caused by redundant projects of subset τ
h	Information content
H	Average information content
a	Scaling constant

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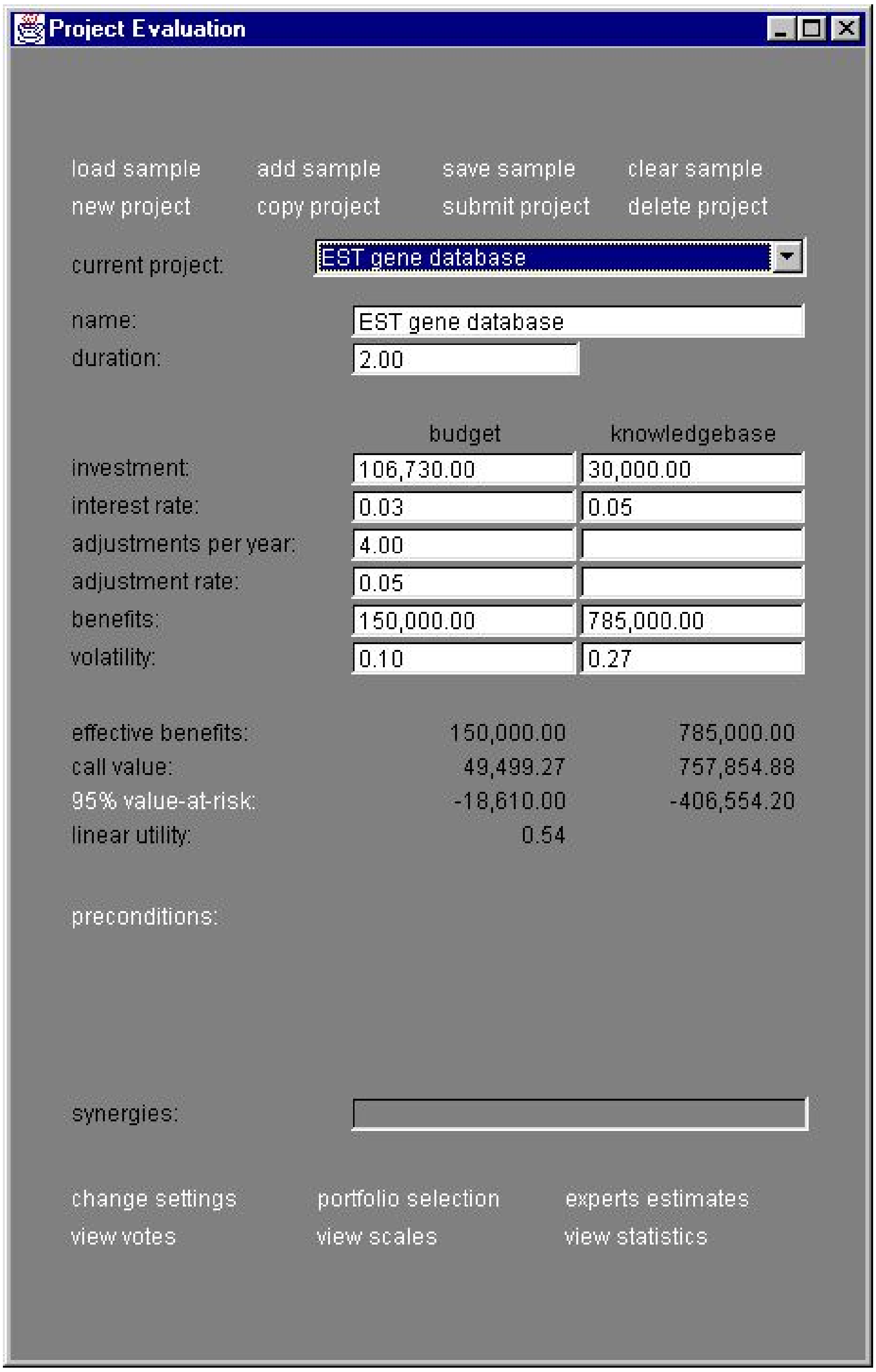
Appendix – Manual

1. Project Evaluation



Menu Items

Load sample

A previously saved sample of projects is loaded from a file. Note that this option is not available when the framework is used as an applet.

Add sample

A previously saved sample of projects is added to the current sample of projects. Note that this option is not available when the framework is used as an applet.

Save sample

The current sample of projects is saved to a file. Note that this option is not available when the framework is used as an applet.

Clear sample

The current sample of projects is deleted.

New project

"New project" has to be clicked before a new project is entered.

Copy project

The data of an existing project is copied and can be modified to submit a similar project.

Submit project

After having entered or altered the data of a project "submit project" has to be clicked in order to add the project to the list of projects. The successful submission of a project is confirmed in green at the bottom of the frame.

Delete project

Deletes the current project from the list of projects.

Current project

A list of projects (*e.g.* a loaded sample), where a specific project can be selected for evaluation or altering data. The selected project is referred to as "current project". The data of the current project are displayed as described in the following.

Project Data

Name

Enter a new project's name or alter an existing project's name.

Duration

Enter the project's duration in *e.g.* years or months. Note that the unit of measurement of the projects' durations must be consistent for all the projects that are candidates for portfolio selection.

Investment

Enter the investment necessary for each dimension of the project. Again the unit of measurement (*e.g.* millions of Euros) must be consistent in each dimension for all projects that are candidates for portfolio selection.

Interest rate

Enter the interest rate for each of the project's dimensions. The interest rate must be in the range from 0 to 1, *e.g.* 0.05 meaning 5%.

Adjustments per year

Enter the number of events per year, *e.g.* reviews, altering the project's value. Entering the adjustments per year is optional. Together with the adjustment rate, it is one way to determine the project's volatility. Alternatively the volatility can be determined through the deviation of the experts' judgements (3).

Adjustment rate

Enter the amount of change in the project's value per review. The adjustment rate must be in the range from 0 to 1, *e.g.* 0.05 meaning 5%. Entering the adjustment rate is optional. The project's volatility can be determined and altered using the adjustments per year and the according adjustment rate. Alternatively the volatility and the adjustments per year can be entered and the according adjustment rate is calculated. If neither adjustments per year nor adjustment rate are entered the volatility is determined with the help of the expert judgements (3).

Benefits

Refers to the mean of the experts' estimates (3) concerning the project's performance in each dimension. The unit of measurement of the project's performance is the same as of the investment. If the project benefits are not estimated with the help of experts' judgements, they can also be entered directly.

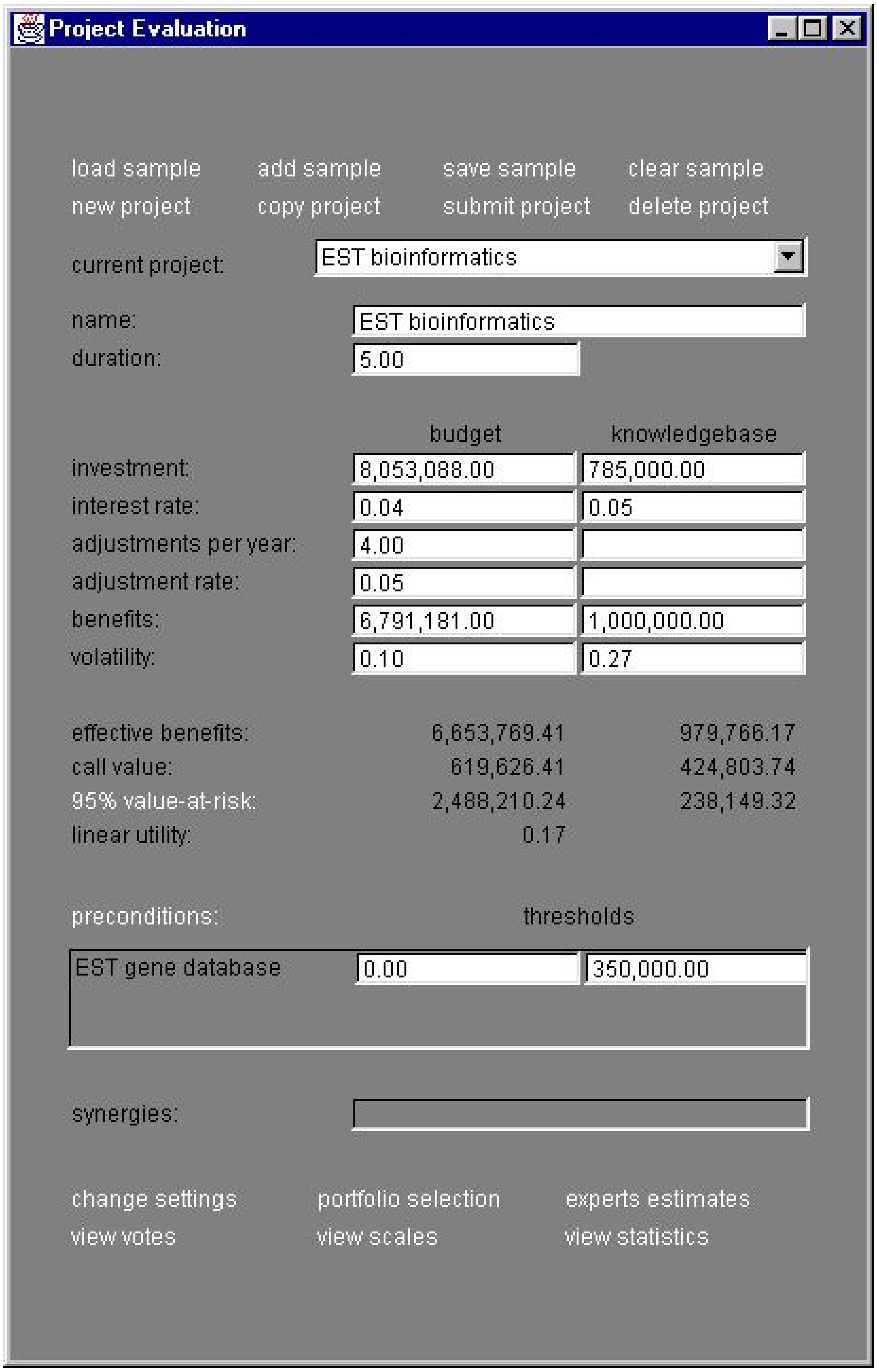
Volatility

The volatility of the project's value can be determined with the help of adjustments per year and adjustment rate. If neither adjustments per year nor adjustment rate are entered the volatility refers to the deviation of the experts' estimates (3) for the performance of the project in each dimension.

Preconditions

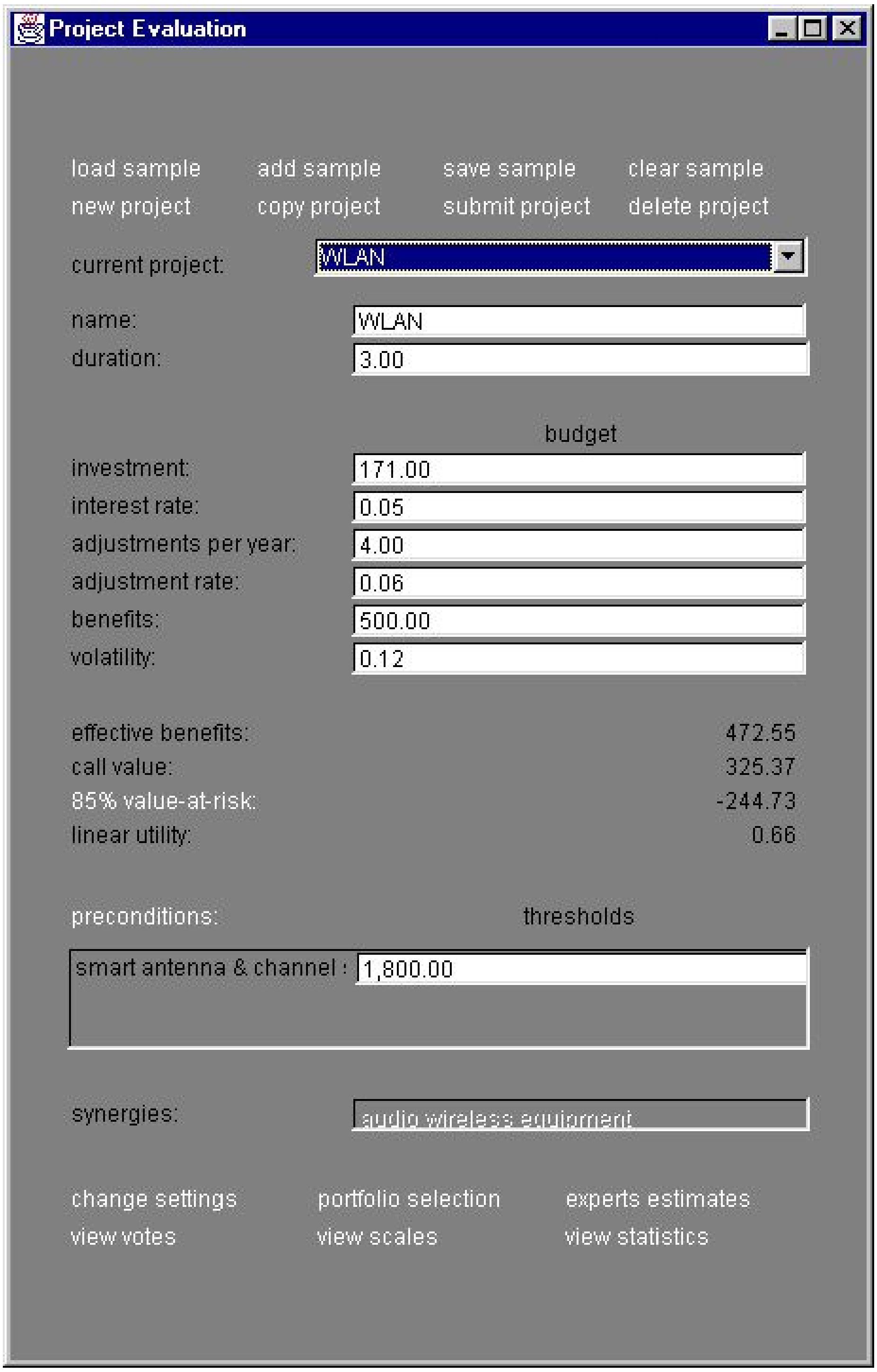
Projects which are necessary preconditions for the success of the currently selected project can be selected here, by clicking on "preconditions" and selecting the projects serving as precondtions by clicking on the projects' names. For the projects selected as preconditions, thresholds, *i.e.* the minimum performance the preconditional project must achieve in selected dimensions, can be entered. Per default the mean benefits of the preconditional project are used as thresholds. To confirm the selection of preconditions for a project "submit project" must be clicked. The selected preconditions are displayed in black. By clicking again they are deselected. Every time preconditions are to be altered "preconditions" has to be clicked to make all projects listed as potential preconditions accessible. Consequently the preconditional projects must be contained in the portfolio to enable the current project to be selected for the portfolio. Note that preconditions must not be cyclic.

For the sample project "EST bioinformatics" in the screenshot below, the knowledge gained within the project "EST gene database" serves as a precondition.



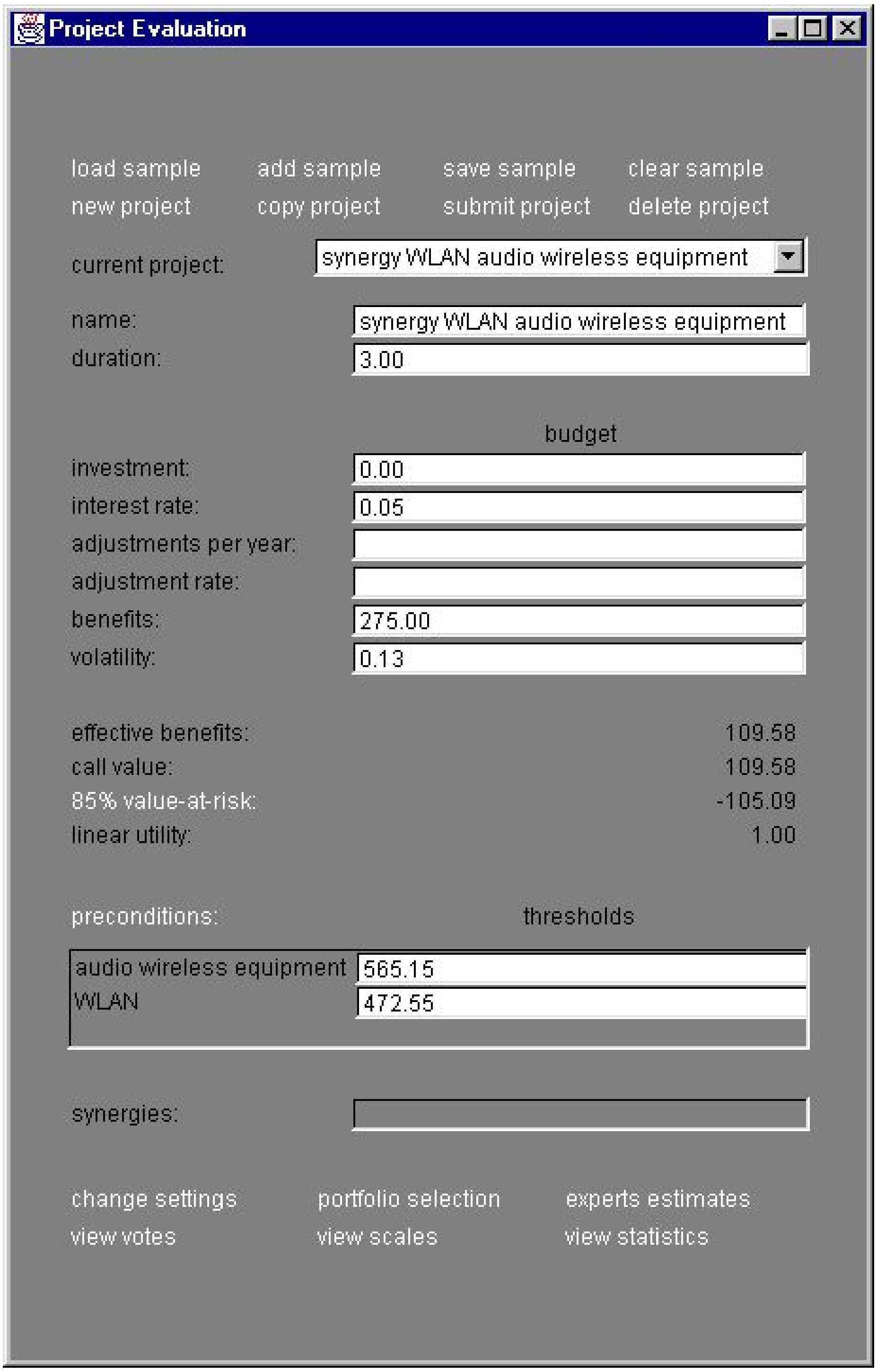
Synergies

Projects causing synergistic effects when being selected together with the current project for the portfolio are listed here.



In the example above the project "WLAN" causes synergistic effects when being selected together with the proect "audio wireless equipment". Vice versa the project "audio wireless equipment" causes synergistic effects when being selected together with the project "WLAN".

The synergistic effects are described by an additional pseudo project. This pseudo project is entered and altered like any project. Note that synergies do not have any investments as they are an additional benefit when all of the projects causing the synergies are selected for the portfolio. The synergistic projects serve as preconditions for the pseudo project. The name of the pseudo project has to start with "synergy". There is no restriction on the number of synergistic pseudo projects. One project can cause synergies for an arbitrary number of sets of other projects.



Just like normal projects, the additional synergistic performance of the synergy has to be valued by the experts.

Results

Effective Benefits

Refers to the effective benefits for projects with preconditions, taking the probability that the preconditional projects' performances exceed the necessary thresholds into account.

Call value

The call value for each of the projects dimensions is calculated assuming that the projects are priced like European call options.

λ% Value-at-Risk

The Value-at-Risk VaR, *i.e.* the maximum loss of a project at confidence level λ is calculated. The absolute value of a negative VaR refers to the minimum profit to be expected with confidence level λ. The unit of measurement of the project's risk is the same as the unit of measurement of the investment. The range of values for *λ* can be chosen within "Settings" (2). The values for *λ* can be altered by clicking on the currently displayed percentage.

Utility

Accumulates the valuations of the various project dimensions to an overall utility value using multi-attribute utility analysis. In "Settings" (2) the user can choose between an additive and thus linear and a multiplicative or general utility function.

Activating Further Frames

Change settings

Choose settings and preferences for the framework, refer to (2).

Portfolio selection

Selects projects for a portfolio with resource constraints, taking preconditions as well as synergies into account, refer to (7).

Experts estimates

Experts enter their estimates for the performances of the projects' dimensions here, refer to (3).

View votes

The experts' estimates per dimension of a project are displayed, refer to (4).

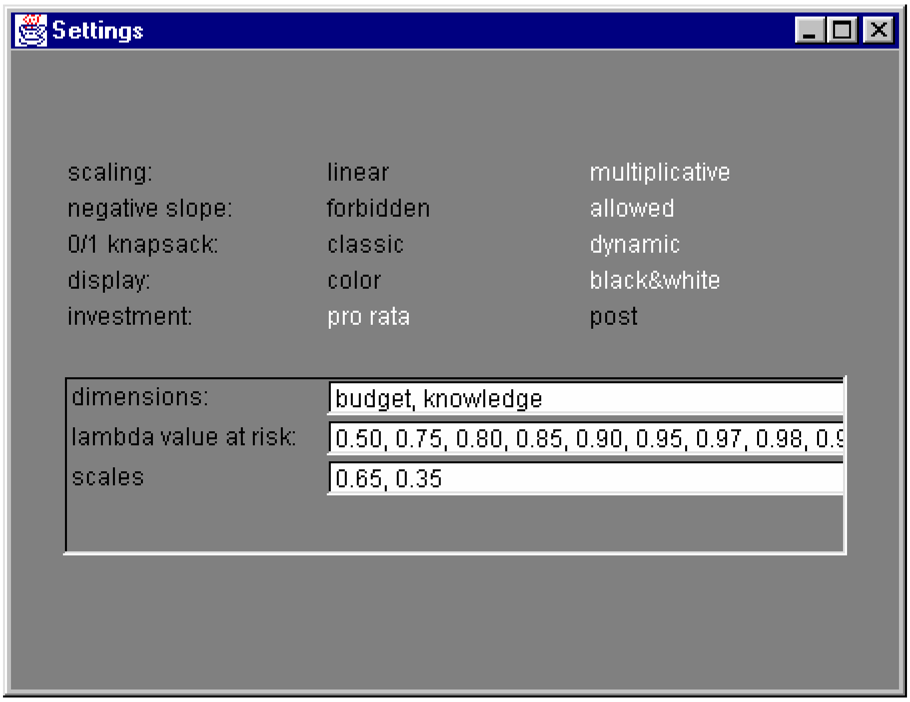
View scales

Choose coefficients, best and worst cases respectively for the multi-attribute utility analysis, refer to (6).

View statistics

Displays the graphs of risk for the various dimensions depending on the confidence level λ, refer to (5).

2. Settings



Scaling

Choose between a linear or multiplicative utility function.

Negative slope

Defines whether the utility of a dimension may decrease when the call value increases. This can *e.g.* be the case when the unit of measurement of the dimension refers to pollution.

0/1 Knapsack

Choose between a classic or dynamic programming solution of the Knapsack problem used for portfolio selection, see (7).

Display

Choose between color or black and white display.

Investment

"Pro rata" splits the total investments necessary for each dimension equally to the project's periods, whereas "post" assumes that the investment is needed for the development phase at the end of the research project. This distinction is necessary for the discounting.

Dimensions

The number and names of dimensions are specified.

Lambda Value-at-Risk

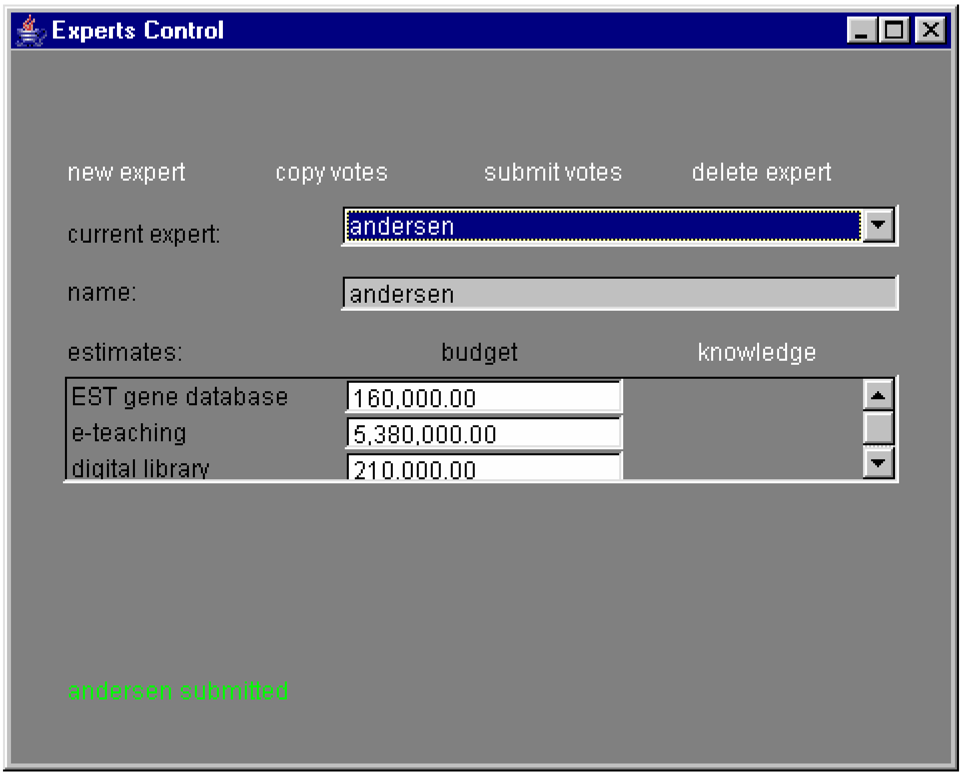
The set of values for the confidence level λ required for the calculation of the project's Value-at-Risk is entered here.

Scales

Enter the coefficients for each dimension used for linear multi-attribute utility analysis. To guarantee comparability of the results the sum of the coefficients ought to be 1. If the coefficients are altered during the evaluation of a project the project has to be reselected in "Current project" (0) in order to display the new utility values.

3. Experts Estimates

Using the frame "Experts Control" the experts can enter their estimates for the projects' performances in the dimension of their expertise. The dimensions "budget" and "knowledge" are chosen for demonstration purposes here. Specific dimensions can be defined in "Settings" (2).



New expert

A new expert can be added to the list of current experts. Click on "submit votes" to add the expert and their votes to the list of experts. The submission of the expert's votes is confirmed in green at the bottom of the frame.

Copy votes

A new expert is added using the copied votes as default values.

Submit votes

After an expert has entered or altered their estimates "submit votes" has to be clicked. The submission of the votes is confirmed in green at the bottom of the frame.

Delete expert

Deletes the current expert and their votes.

Current expert

A list of experts available for providing their estimates, where a specific expert can be selected for providing new estimates or altering existing ones. The selected expert is referred to as "current expert".

Name

Enter the name of a new expert.

Estimates

List of the projects for which the experts provide estimates.

Budget

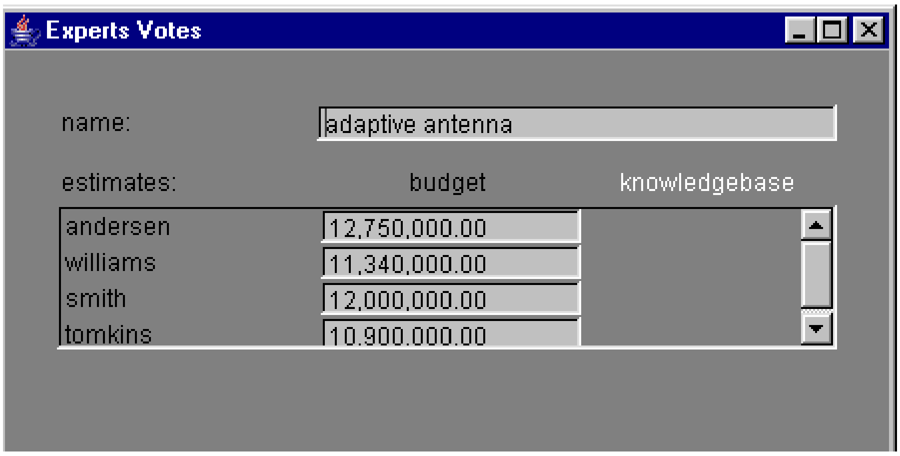
The estimates of an expert for the cash flows of the projects can be entered in the textfields. The unit of measurement for the cash flows (*e.g.* millions of Euros) must be the same for all projects.

Knowledge

The estimates of an expert for the knowledge generated by the projects can be entered in the textfields. Again the unit of measurement for the knowledge (*e.g.* data in a database or scores) must be the same for all projects.

4. View Votes

The experts' estimates per dimension of one project can be viewed and compared.



Name

A project can be chosen out of the list of projects from the current sample in the "Project Evaluation".

Estimates

The estimates from each expert for the selected dimension of the current project are displayed.

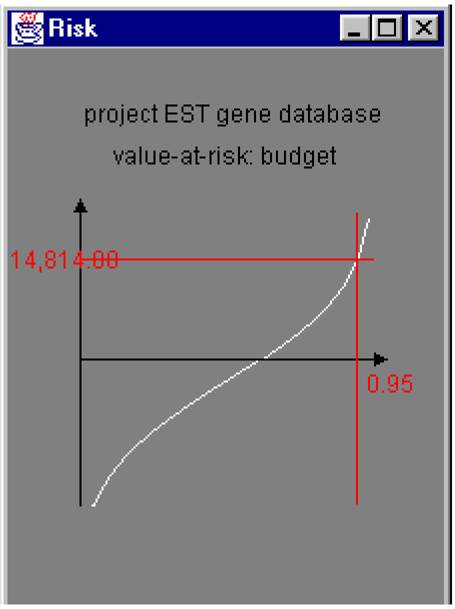
Budget/Knowledgebase

Change the selected dimension by clicking on the dimension's name.

5. View Statistics

This frame shows the graphs of the Value-at-Risk for the various dimensions depending on the confidence level λ for the selected project or underlying portfolio, depending on the most recent activity. Alter λ in "Project Evaluation" or the according portfolio selection in order to display the results in "Statistics."

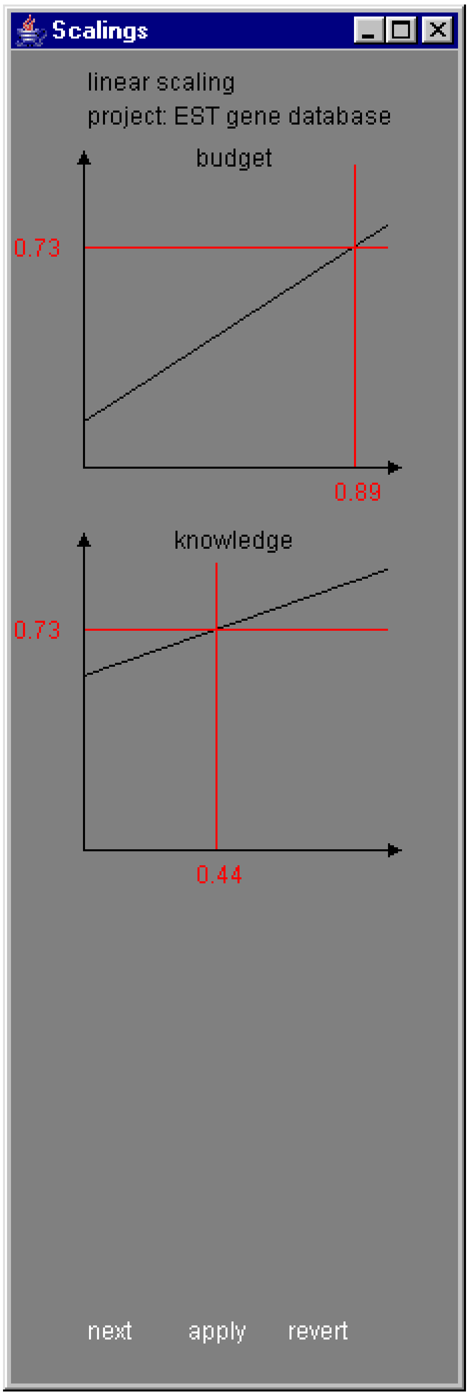
The graphs show the according Value-at-Risk as a function of the confidence level λ. Drag the red lines in order to pinpoint the confidence level displayed. The graph shows that the maximum expected loss increases for an increasing confidence level λ. A VaR of zero shows the confidence level λ for which the project benefits compensate for the investments. A negative VaR refers to the minimum profit to be achieved with confidence level λ.



6. View Scales

This frame allows to set and alter the scales needed for multi-attribute utlity analysis. Whether the analysis is based on a linear or multiplicative utility function can be chosen in "Settings" (2).

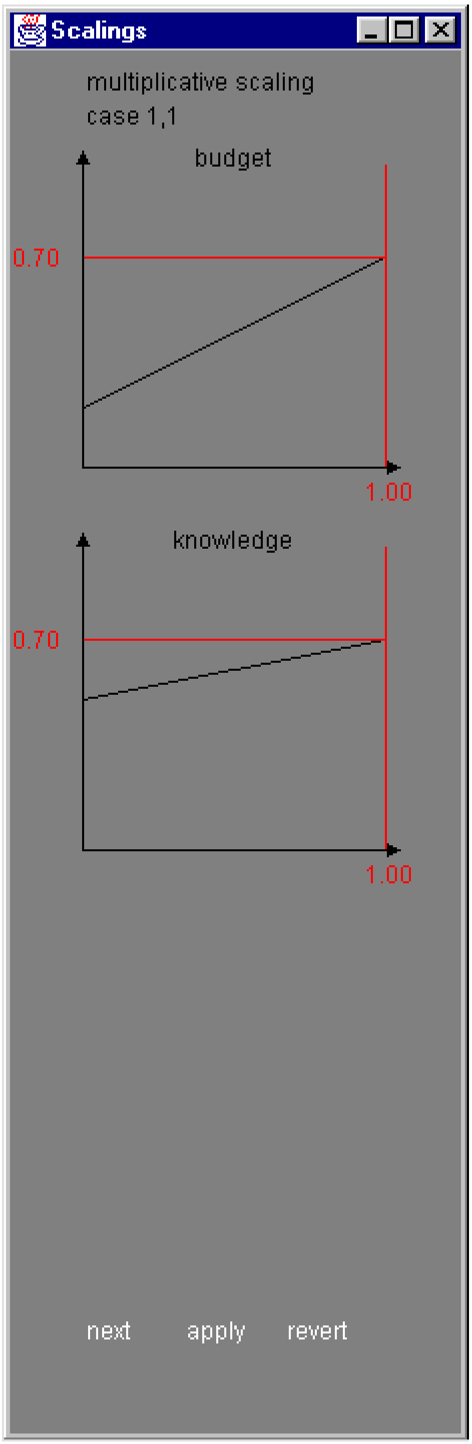
Linear Scaling



The slopes of the additive or linear utility function for the current project with respect to the various dimensions can be defined. The ordinate corresponds to the utility and the abscissa to the transformed call value of the according dimension. The red figures reflect the transformed call values and the utility of the underlying project. Dragging the abscissa value horizontally allows to alter the displayed values. Dragging the ordinate value vertically shifts the utility of the selected call values. Under certain conditions this can lead to conflicting specifications. Thus some combinations of selected values are not allowed. Click on “revert” to undo the setting. Click on “apply” to submit the setting.

Multiplicative Scaling

The following screenshot shows the slopes of the general or multiplicative utility function for the currently selected project with respect to the various dimensions. The ordinate corresponds to the utility and the abscissa to the transformed call value of the according dimension. Again the red figures reflect the transformed call values and the utility of the underlying project. Following the concept of the specification of the general utility function the best and worst cases for the scales are displayed by clicking “next”. Dragging the ordinate value vertically allows setting the utility function for this specific case. Click on “revert” to undo the setting. Click on “apply” to submit the setting.

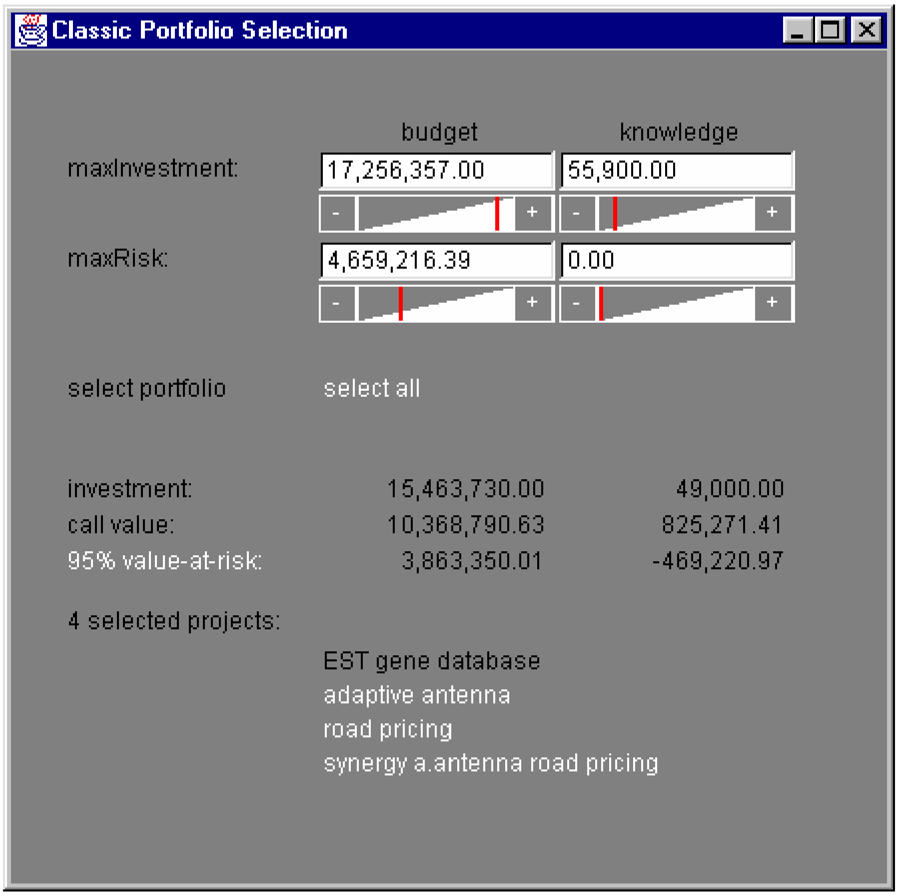


7. Portfolio Selection

Projects can be selected for a portfolio using either the classic 0/1 Knapsack algorithm or a dynamic programming solution to the Knapsack Problem. The preferred algorithm can be selected in “Settings” (2). Both algorithms allow for optimisation considering limited investments and preconditions as well as synergistic effects between projects. Using the classic 0/1 Knapsack algorithm investment limits for any dimension can be set and a risk limit can be specified, which is not possible using the dynamic programming solution. The dynamic programming solution is recommended for a large number of projects, as the drawback of the classic 0/1 Knapsack algorithm is that it is NP-complete.

Projects for a portfolio are selected from the current sample. These projects have to be evaluated with respect to the same dimensions.

Portfolio Selection Using the Classic 0/1 Knapsack Algorithm



maxInvestment

The maximum investment for each of the projects’ dimensions is entered here. The units of measurement of the maximum investments of the portfolio must correspond to the units of measurement for the investments of the various projects. The maximum investments can be entered manually and altered with the scroll bar. The default value is 50% of the sum of the investments of all projects of the sample.

maxRisk

Using the classic 0/1 Knapsack algorithm for portfolio selection a risk limit can be specified for each dimension. The maximum Value-at-Risk in each dimension - referring to the maximum loss - can be entered manually and altered with the scroll bar. The confidence level λ for the risk limit is the same as the one chosen for the calculation of the portfolio's VaR.

Select portfolio

The portfolio is selected according to the algorithm specified in "Settings" (2). The selected projects are listed next to "selected projects".

Select all

Selects all project candidates for the portfolio.

Investment

Shows the actual investment for each of the dimensions of the portfolio, which does not necessarily have to be the maximum investment available as no fractions of projects can be selected for the portfolio.

Call value

Shows the call value of the various dimensions of the portfolio.

λ% Value-at-Risk

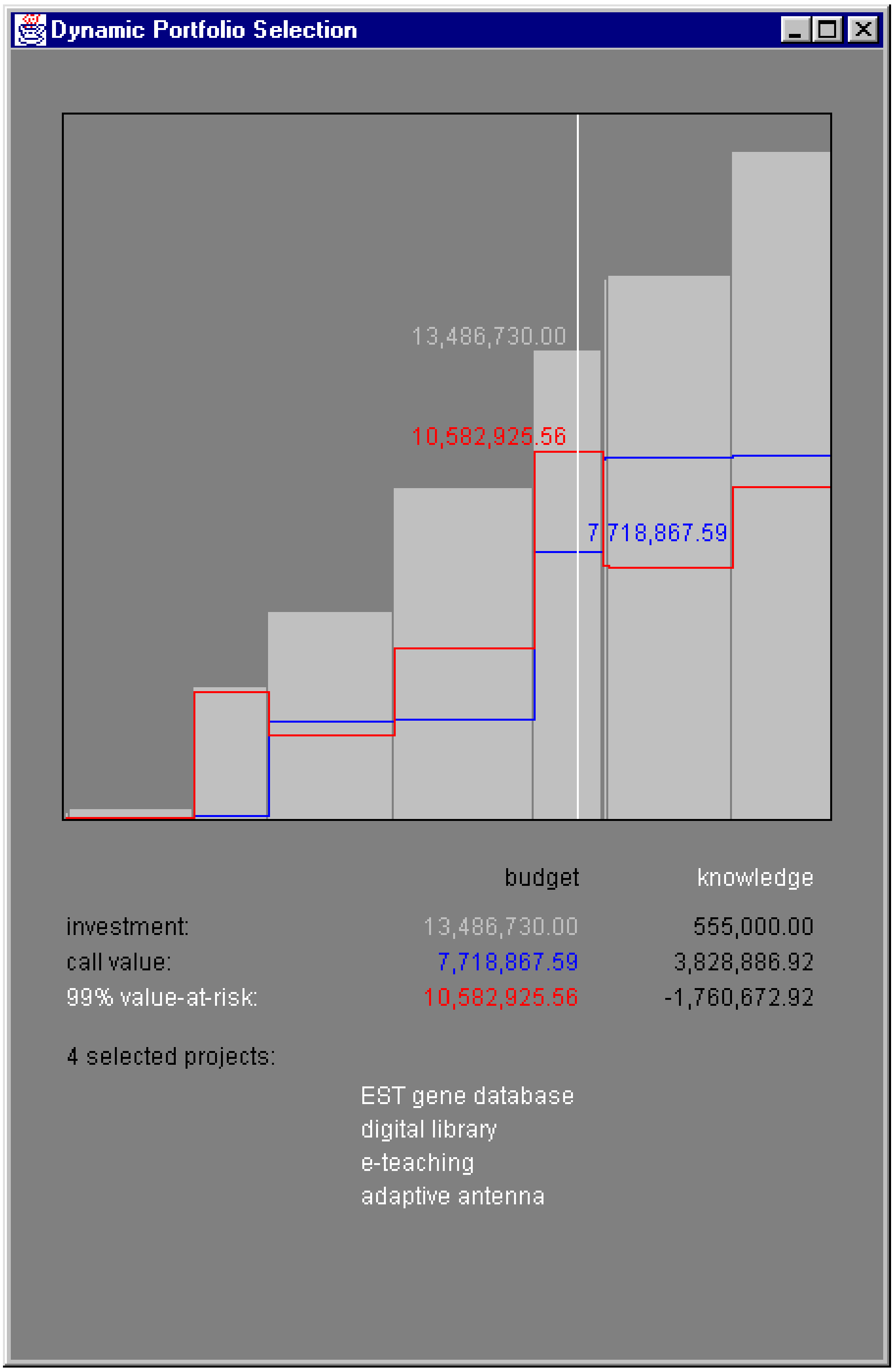
Shows the 100λ% risk of a portfolio corresponding to the portfolio's Value-at-Risk. The range of values for λ can be chosen within "Settings" (2) and altered by clicking on the currently displayed percentage.

Selected projects

The projects selected for the portfolio are listed here. Click on one of the selected projects (*e.g.* "EST gene database") displays this project's data in the project evaluation frame (1).

Portfolio Selection Using Dynamic Programming

In contrast to the classic 0/1 Knapsack algorithm the dynamic programming solution can only handle constraints in the selected dimension, - the dimension "budget" in the screenshot below. The dimension can be altered by clicking on the dimension's name.



The diagram shows the portfolio's total call value (blue line), the total financial investment (grey bars) and the total risk (red line) for various percentages of the total financial investment. The percentage of the maximum investment displayed can be selected by dragging the vertical line.

Curriculum Vitae

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1977	Born in Vienna
1984 – 1988	Elementary School Karl-Toldt Weg 1140 Wien
1988 – 1996	Secondary School „Schule der Dominikanerinnen Neusprachliches Gymnasium“
1996	Graduation with exceptional success
1996 – 2000	Undergraduate studies of information systems at the Technical University of Vienna and the University of Vienna – graduation with distinction
1999 – 2000	Participation in the ESPRIT Project „VegaNT Financial Risk Management Using Rapid Object Oriented Prototyping“, employed at AAA+ Software F&E GmbH
1999 – 2000	Teaching assistant at the Institute for Software Engineering, Technical University of Vienna
2001 – 2004	Research assistant at the department of Systems Research und Information Technologies at the Austrian Research Centers ARC, Seibersdorf
since 2005	Research assistant at the University of Applied Sciences, Department of Information Management/Eisenstadt
2006	Lecturer "Projectmanagement for knowledge management initiatives", University of Applied Sciences, Department of Information Management/Eisenstadt
2007/2008	Lecturer "Computer based project simulation using Simultrain" University of Applied Sciences, Department of Information Management/Eisenstadt