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PORTFOLIO OPTIMIZATION MODELS FOR PROJECT VALUATION

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Abstract: This dissertation presents (i) a framework for selecting and managing a portfolio of risky multi-period projects, called Contingent Portfolio Programming (CPP), and (ii) an inverse optimization procedure that uses this framework to compute the value of a single project. The dissertation specifically examines a setting where the investor can invest both in private projects and securities in financial markets, but where the replication of project cash flows with securities is not necessarily possible. This setting is called a mixed asset portfolio selection (MAPS) setting. The valuation procedure is based on the concepts of breakeven selling and buying prices, which are obtained by first solving an optimization problem and then an inverse optimization problem.

In the theoretical part of the dissertation, it is shown that breakeven prices are consistent valuation measures, exhibiting sequential consistency, consistency with contingent claims analysis (CCA), and sequential additivity. Due to consistency with CCA, the present approach can be regarded as a generalization of CCA to incomplete markets. It is also shown that, in some special cases, it is possible to derive simple calculation formulas for breakeven prices which do not require the use of inverse optimization. Further, it is proven that breakeven prices for a mean-variance investor converge towards the prices given by the Capital Asset Pricing Model (CAPM) as the investor's risk tolerance goes to infinity. The numerical experiments show that CPP is computationally feasible for relatively large portfolios both in terms of projects and states, and illustrate the basic phenomena that can be observed in a MAPS setting.

Keywords: Project valuation, Project portfolio selection, Mixed asset portfolio selection, Multi-period projects, Ambiguity

Academic dissertation

Systems Analysis Laboratory
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Portfolio Optimization Models for Project Valuation

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Official opponent:	Professor James S. Dyer, University of Texas at Austin, USA

Publications

The dissertation consists of the present summary article and the following papers:

[I] Gustafsson, J., A. Salo (2005): Contingent Portfolio Programming for the Management of Risky Projects. *Operations Research* (to appear).

[II] Gustafsson, J., B. De Reyck, Z. Degraeve, A. Salo (2005): Project Valuation in Mixed Asset Portfolio Selection. Systems Analysis Laboratory Research Report E16. Helsinki University of Technology. Helsinki, Finland.

[III] Gustafsson, J., A. Salo (2005): Project Valuation under Ambiguity. Systems Analysis Laboratory Research Report E17. Helsinki University of Technology. Helsinki, Finland.

[IV] Gustafsson J., A. Salo (2005): Valuing Risky Projects with Contingent Portfolio Programming. Systems Analysis Laboratory Research Report E18. Helsinki University of Technology. Helsinki, Finland.

[V] Gustafsson, J., A. Salo, T. Gustafsson (2001): PRIME Decisions - An Interactive Tool for Value Tree Analysis, Proceedings of the Fifteenth International Conference on Multiple Criteria Decision Making (MCDM) Ankara, Turkey, July 10-14, 2000, *Lecture Notes in Economics and Mathematical Systems*, Murat Köksalan and Stanley Zionts (eds.), 507 165–176.

Contributions of the author

Janne Gustafsson has been the primary author of all of the papers. He initiated Papers [I], [II], and [IV], whereas the topics for Papers [III] and [V] were suggested by Prof. Salo.

PREFACE

This dissertation is a compilation of two of my central works on project portfolio selection and project valuation, Papers [I] and [II], together with three more or less related papers. My aim has been to improve my own understanding, as well as that of practitioners and the general academic, about how to value and select projects and other non-tradable investments, especially when it is possible to invest in securities as well. This topic is fundamental to many academic fields, including corporate finance and management science.

First and foremost, my thanks go to my supervisor Professor Ahti Salo for providing invaluable support and for suggesting me to work on this topic as a part of my Master's Thesis. Since that time, the ideas have evolved significantly further and become what you see in this dissertation. I would especially like to thank Professors Bert De Reyck and Zeger Degraeve of London Business School for their support with one of the papers. London Business School was indeed a truly outstanding research environment.

I would also like to thank Professor Jim Dyer of University of Texas at Austin whose review comments on Paper [I] led to a substantial improvement in the quality of the paper. It is unlikely that I will ever receive such quality feedback on any of my present or possible future papers. My sincere thanks also go to Professor Harry M. Markowitz for the time he had for reading and commenting on my manuscripts. The central ideas of his pioneering model and his exemplary writing style have had much influence on my research and the way in which I try to write articles.

Last, I am grateful to Dr. Hannu Kahra and Mr. Lauri Pietarinen for creating an exciting work environment at Monte Paschi Asset Management, where I was employed during the writing of the first version of the summary article. Likewise, I would like to thank my present colleagues Petteri Barman and Mikko Syrjänen for providing an opportunity to work in an outstanding team in London.

London, U.K., June 27, 2005,

Janne Gustafsson

1 INTRODUCTION

1.1 Context and Background

The evaluation and selection of risky projects, such as research and development (R&D) projects, has attracted substantial interest among both academicians and practitioners (see, e.g., Martino 1995, and Henriksen and Treynor 1999). Especially in high-technology firms, the selection of the R&D portfolio can be a major determinant of the future performance of the company.

The task of selecting risky projects has been widely studied within several scientific disciplines, most prominently in corporate finance, operations research, and management science (see, e.g., Brealey and Myers 2000, Ghasemzadeh et al. 1999, Heidenberger 1996, Smith and Nau 1995, Gear and Lockett 1973). Many of the developed approaches aim at placing a value on the project; if this value is positive the project is started; otherwise it is not. For example, in the literature on corporate finance, the value of a risky project, like that of any other risky investment, is calculated as the net present value (NPV) of its cash flows, discounted at a discount rate that reflects the riskiness of the project (Brealey and Myers 2000). It is typically suggested that this rate should be the expected rate of return of a security that is "equal in risk" to the project. Under the Capital Asset Pricing Model (CAPM; Sharpe 1964, Lintner 1965), two assets are regarded equally risky if they have the same beta, and therefore the finance literature suggests that one should use the beta of the project, or equivalently, the covariance between the project and the financial market portfolio, to determine the discount rate for the project (Brealey and Myers 2000). However, the use of the CAPM in project valuation relies on the assumption that the firm is a public company maximizing its share price; yet, many companies make decisions about accepting and rejecting projects before their initial public offering.

Several methods have been proposed to value projects of a private firm. These include *decision analysis* (French 1986, Clemen 1996) and *options pricing analysis*, which is also referred to as *contingent claims analysis* (CCA; Merton 1973b, Hull 1999, Dixit and Pindyck 1994, Trigeorgis 1996). Still, conventional methods based on decision analysis, such as *decision trees*, may lead to biased estimates of project value, because they do not take into account the opportunity costs imposed by alternative investment opportunities. Options pricing analysis accounts for the effect that financial instruments have on project value, but its applicability is limited, because in practice it may be difficult to replicate project cash flows using financial instruments.

When used to select a project portfolio, most single-project valuation methods are problematic in that they neglect the effect of project interactions, such as synergies and diversification, on the overall performance of the portfolio. Also, these methods do not take into account the firm’s resource constraints, which may strongly limit the projects that can simultaneously be included into the portfolio. Therefore, such methods may lead to a suboptimal project portfolio both in terms of expected cash flows and the risk of the portfolio. For this reason, it is advisable to employ a project portfolio selection method instead. Such a method can potentially determine the most valuable portfolio where project synergies and the effect of diversification on the risk of the portfolio are taken into account, although it may not directly put a value on any single project. Still, as shown in this dissertation, these methods can also be applied to value single assets in the firm’s portfolio through a specific inverse optimization procedure.

Earlier project portfolio methods have, however, suffered from various shortcomings that have hindered the use of the methods in practice. For example, many of the currently available methods, such as the method by Gear and Lockett (1973) and Heidenberger (1996), make restrictive assumptions about the nature of the investor’s risk aversion, failing to imply diversification, for instance. Further, some methods do not consider uncertainty, while others fail to properly account for the multi-period nature of projects.

1.2 Aims and Practical Relevance

This dissertation has two primary aims. First, it aims at developing a framework for selecting a portfolio of risky multi-period projects which is (i) well-founded in the theories of finance, management science, and operations research, and also (ii) practically applicable in the sense that it (a) captures most of the phenomena that are relevant to R&D portfolio selection and (b) is computationally feasible for portfolio selection problems of realistic size. Second, the dissertation aims at developing a procedure for project valuation in a setting where the firm can invest both in private projects and publicly-traded securities, but where replication of project cash flows with securities is not necessarily possible. This setting is called the *mixed asset portfolio selection* (*MAPS*) setting.

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While a framework for selecting a portfolio of risky projects enjoys general interest of practitioners of corporate finance, also MAPS-based project valuation is important in practice. On the one hand, MAPS-based project valuation is, in principle, called for when a corporation or an individual makes investments both in securities and projects, or other lumpy investment opportunities. For example, many investment banks invest in a portfolio of publicly traded securities and undertake uncertain one-time endeavors, such as venture capital investments. On the other hand, a fundamental problem in the literature on corporate finance is the valuation of a single project while taking into account the opportunity costs imposed by securities (see, e.g., Brealey and Myers 2000). This is a MAPS setting that includes one project and several securities.

1.3 Structure of Dissertation

The dissertation includes five papers. Papers [I] and [II] form the core of the dissertation. Paper [I] presents a modeling framework, called *Contingent Portfolio Programming* (CPP), for selecting and managing a portfolio of risky multi-period projects. The framework is taken into use and extended in Paper [II], which examines the valuation of risky projects in a MAPS setting. The valuation procedure is based on the concepts of *breakeven selling and buying prices* (Luenberger 1998, Smith and Nau 1995, Raiffa 1968), which rely on the comparison of MAPS problems with and without the project being valued. Paper [II] shows that breakeven buying and selling prices exhibit several important properties and that they are therefore consistent valuation measures. Paper [I] constitutes the primary modeling contribution of the dissertation, whereas Paper [II] contains the dissertation's main methodological and theoretical contribution.

The three other papers provide additional contributions. Papers [III] examines a single-period MAPS setting where the investor is either unable to give probability estimates or where the estimates are ambiguous. In particular, we concentrate in this paper on the Choquet-Expected Utility (CEU) model, which is able to capture ambiguity, and develop two models to solve MAPS models when the investor is a CEU maximizer. Paper [IV] discusses multi-period project valuation, compares the present approach to other multi-period approaches in the literature, and produces further computational results. Paper [V] describes a decision support system based on an interval value tree method called *Preference Ratios In Multi-attribute Evaluation* (PRIME; Salo and Hämäläinen 2001), and presents a case study where it is used to develop scenarios for the market share of Sonera SmartTrust, a Finnish high-technology company. A similar approach can be used for scenario generation in project portfolio selection.

2 EARLIER APPROACHES

2.1 R&D Project Selection Models

Several methods for the selection of R&D projects have been developed over the past few decades (see, e.g., Martino 1995, and Henriksen and Traynor 1999). Many of these methods are based on mathematical optimization. Such methods are typically focused on capturing some specific characteristics of R&D portfolio selection such as synergies or follow-up projects, as described in Table 1. An ideal project selection framework would implement all of the characteristics in Table 1 in a theoretically rigorous way. However, few methods aim at capturing all of these features, and many of those that do resort to theoretically questionable approaches in modeling some of the features.

Optimization-based R&D project selection methods, such as the ones in Table 1, can be viewed as extensions of standard capital budgeting models (see, e.g., Luenberger 1998). These models capture rather complex problems with project interdependencies and resources constraints, but they do not usually address uncertainties associated with the projects' outcomes, which makes it impossible to

Table 1. Overview of Approaches to R&D Project Selection.

	Features							
Model	**RN**	**FP**	**VA**	**CO**	**PV**	**RC**	**RD**	**SY**
Ghasemzadeh et al. 1999		X			X	X		
Heidenberger 1996	X	X			X	X		
Santhanam & Kyparisis 1996		X				X		X
Czajkowski & Jones 1986		X				C		
Fox et al. 1984						X		X
Mehrez & Sinuary-Stern 1983						X		
Aaker & Tyebjee 1978				X		X		X
Gear & Lockett 1973	X	X			X	X		
Gear et al. 1971								
Bell et al. 1967					X	X		
Watters 1967			X			C		
Brandenburg & Stedry 1966						X	X	

Key: CO = correlation or other probabilistic interaction between project outcomes, FP = follow-up projects, PV = project versions, RC = resource constraints, RD = resource dynamics, RN = reaction to new information, SY = synergies (cross terms for project outcomes), VA = variability aversion, X= feature present in basic model, C = chance-constrained model

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attach risk measures to project portfolios. Also, these models do not usually offer possibilities for reacting to new information. In Table 1, the scarcity of X's in columns "VA", "CO", and "RN" highlights these shortcomings.

Even though some methods do deal with project uncertainties and the investor's risk aversion, they often do so by resorting to unrealistically restrictive assumptions or theoretically unfounded approaches. For example, the method by Mehrez and Sinuany-Stern (1983) relies on restrictive assumptions about the investor's utility function while Czajkowski and Jones (1986) employ chance-constraints that may lead to preference models that are inconsistent with expected utility theory and other well-founded preference frameworks. Also, the models of Gear and Lockett (1973) and Heidenberger (1996) do not account for the variability of portfolio returns, even though they allow the investor to react to new information.

Another limitation in some optimization models (e.g., Gear and Lockett 1973, Czajkowski and Jones 1986, and Ghasemzadeh et al. 1999) is that project inputs are separated from outputs, wherefore projects cannot produce inputs for other projects, for instance. These models typically also assume that there exists a predefined, static supply of resources in each time period (see, e.g., Ghasemzadeh et al. 1999 and Gear and Lockett 1973) which makes it impossible to invest profits for later or immediate use. There is consequently a need for dynamic modeling of resources; early attempts into this direction have been presented by Brandenburg and Stedry (see Gear et al. 1971).

In summary, there appears to be need for an optimization method that rigorously captures (i) project uncertainties, (ii) the investor's risk preferences, and (iii) dynamic production and consumption of resources.

2.2 Stochastic Programming

Stochastic programming models analogous to R&D portfolio selection models have appeared in investment planning as well as in asset-liability management (e.g., Bradley and Crane 1972, Kusy and Ziemba 1986, Mulvey and Vladimirou 1989, Birge and Louveaux 1997, Mulvey et al. 2000). These two problem contexts share similarities with the selection of R&D projects in that (i) the investor seeks to maximize the value of a portfolio of risky assets in a multi-periodic setting and (ii)

Table 2. Comparison of Some Stochastic Programming Approaches to Portfolio Selection

	Bradley and Crane (1972)	**Kusy and Ziemba (1986)**	**Mulvey and Vladimirou (1989)**	**Birge and Louveaux (1997, §1.2)**	**CPP (Paper [I])**
Model type	Linear	Linear	Quadratic or non-linear, network	Linear	Linear, mixed integer
Multiple time periods	Yes	Yes but only two stages	Yes but only two stages	Yes	Yes
Model of uncertainty	State (event) tree	States for second stage; for external cash flows only	States for second stage	State tree	State tree
Objective	Expected value of terminal wealth	Expected discounted net revenues	Mean-variance model *or* Expected utility of terminal wealth	Expected utility of terminal wealth	Utility of terminal wealth; mean-risk model
Model of risk aversion / risk measure	Loss constraints	Penalty from constraint violations	Variance *or* power utility function	Piecewise linear utility function	LSAD or EDR
Type of decisions	Quantitative (asset trading)	Quantitative (asset trading)	Quantitative (asset trading)	Quantitative (asset trading)	Choices between actions
Decisions influence future decision possibilities	No	No	No	No	Yes

there are several asset categories which parallel the multiple resource types consumed and produced by R&D projects.

A key difference between R&D portfolio selection models and the financial stochastic programming models is that in financial optimization, the (dis)investment decisions are unconstrained quantities that do not restrict the investor's future decision opportunities (e.g., security trading). In contrast, R&D project selection involves "go/no go"-style decisions (Cooper 1993) where the "go"-decision leads to later project management decisions while the "no go"-decision terminates the project without offering further decision opportunities. Table 2 contrasts the key characteristics of selected financial models of stochastic programming to CPP, which is developed in Paper [I]. Among these, CPP has close parallels with the dynamic model of Bradley and Crane (1972), as well as the models of Birge and Louveaux (1997) and Mulvey et al. (2000) which employ state (scenario) trees.

2.3 Project Valuation Methods

The literature on corporate finance contains a large number of apparently rivaling methods for the valuation of risky projects. The most popular approaches include (i) *decision trees* (Hespos and Strassman 1965, Raiffa 1968), (ii) *expected utility theory* (von Neumann and Morgenstern 1947, Raiffa 1968), (iii) t*he risk-adjusted NPV* *method* (see, e.g., Brealey and Myers 2000), (iv) *real options* (Dixit and Pindyck 1994, Trigeorgis 1996), (v) *Robichek and Myers'* (1966) *certainty equivalent method* (see also Brealey and Myers 2000, Chapter 9), (vi) *Hillier's* (1963) *method*, and (vii) *Smith and Nau's* (1995) *method*. These methods are summarized in Table 3. The three columns under the heading "Purpose" indicate the purpose to which the method is intended. As Table 3 describes, decision trees and expected utility theory are complementary techniques to the other methods, which aim at calculating the present value of an investment. In a complete project valuation framework, there is a specific method addressing each of the three purposes.

Table 3. Methods for the valuation of risky multi-period investments.

	Purpose			
Method	**CE**	**PV**	**ST**	**Formula / explanation**
Risk-adjusted NPV		X		$NPV = -I + \sum_{t=1}^{T} \frac{E[c_t]}{(1+r_{adj})^t}$
Decision tree			X	A chart with decision and chance nodes
Expected utility theory	X			$CE[X] = u^{-1}\left(E[u(X)]\right)$
Contingent claims analysis		X		$NPV = -I + \sum_{i=0}^{n} S_i x_i^*$
Robichek and Myers (1966)		X		$NPV = -I + \sum_{t=1}^{T} \frac{CE[c_t]}{(1+r_f)^t}$
Hillier (1963)		X		$NPV = -I + CE\left[\sum_{t=1}^{T} \frac{c_t}{(1+r_f)^t}\right]$
Smith and Nau (1995)		X		*NPV* = breakeven selling or buying price Preference model for cash flow streams: $U[(c_1, c_2, \ldots, c_T)] = E\left[u^*(c_1, c_2, \ldots, c_T)\right]$
MAPS (Paper [II])		X		*NPV* = breakeven selling or buying price Preference model for terminal wealth levels

Key: **CE** = Certainty equivalent for a risky alternative, **PV** = Present value of a risky cash flow stream, **ST** = Structuring of decision opportunities and uncertainties, I = investment cost, c_t = risky cash flow at time t, r_{adj} = risk-adjusted discount rate, u = utility function, S_i = price of security i, x_i^* = amount of security i in the replicating portfolio, r_f = risk-free interest rate, u^* = intertemporal (multi-attribute) utility function.

The MAPS valuation approach developed in Paper [II] is most closely related to the method by Smith and Nau (1995), the main difference being in the employed preference model. It is also consistent with contingent claims analysis, and in some special cases, with Hillier's (1963) method, as discussed in Papers [II] and [IV]. On the other hand, the CPP framework, which is developed in Paper [I] and

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consequently used in Papers [II] and [IV], implements a decision-uncertainty structure similar to decision trees, and also allows the use of a wide range of preference models, including the expected utility model. Paper [III] employs a Choquet-expected utility model, which is an alternative to expected utility theory.

In the following, the methods in Table 3 and their limitations and possible uses are discussed in more detail.

2.3.1 Decision Trees and Related Approaches

A decision tree describes the points at which decisions can be made and the way in which these points are related to unfolding uncertainties. Conventionally, decision trees have been utilized together with expected utility theory (EUT; von Neumann and Morgenstern 1947) so that each end node of the decision tree is associated with the utility implied by the earlier actions and the uncertainties that have resolved earlier. This decision tree formulation does not explicitly include the time axis or provide guidelines for accounting for the time value of money.

In corporate finance, decision trees are used to describe how project management decisions influence the cash flows of the project (see, e.g., Brealey and Myers 2000, Chapter 10). Here, decision trees are typically applied together with the risk-adjusted NPV method, whereby an explicitly defined time axis is also constructed. However, the selection of an appropriate discount rate for NPV is often problematic, mainly because the rate is influenced by three confounding factors, (i) the risk of the project, which depends on the project's correlation with other investments, (ii) the opportunity costs imposed by alternative investment opportunities, and (iii) the investor's risk preferences.

Several methods for determining the discount rate have been proposed in the literature. However, most of them have problematic limitations. For example, the weighted average cost of capital (WACC) is appropriate only for average-risk investments in a firm, whereas discount rates based on expected utility theory do not account for the opportunity costs imposed by securities in financial markets. The real options literature suggests the use of contingent claims analysis (CCA) to derive the appropriate discount rate by constructing replicating portfolios using market-traded securities. Still, it may be difficult to construct replicating portfolios for private projects in practice. Last, the use of a CAPM discount rate is appropriate only for public companies whose all shares are traded in markets that satisfy the CAPM assumptions. Even when these assumptions are satisfied, a CAPM discount rate is applicable for single projects only when there are no synergies between projects.

2.3.2 Robichek and Myers' and Hillier's Methods

Robichek and Myers' (1966) and Hillier's (1963) methods are two alternative ways of determining a risk-adjustment to a discount rate in a multi-period setting. These methods have been widely discussed in the literature on corporate finance (see, e.g., Keeley and Westerfield 1972, Chen and Moore 1982, Ariel 1998, and Brealey and Myers 2000). They both employ expected utility theory or a similar preference model to derive a certainty equivalent (CE) for a risky prospect.

In Robichek and Myers' method, the investor first determines a CE for the cash flow of each period, and then discounts it back to its present value at the risk-free interest rate. Yet, because CEs are taken separately for each cash flow, the method does not account for the effect of cash flows' temporal correlation on the cash flow stream's aggregate risk; hence, it may lead to an unnecessarily large risk-adjustment. In contrast, in Hillier's (1963) method, we first determine the cash flow streams that can be acquired with the project in different scenarios and then calculate the NPVs of these streams using the risk-free interest rate. The result is a probability distribution for risk-free-discounted NPV, for which a CE is then determined. However, the use of the risk-free interest rate essentially means that any money received before the end of the planning horizon is invested in the risk-free asset. Yet, it might be more advantageous to invest the funds in risky securities instead. Therefore, Hillier's method is, strictly speaking, applicable only in settings, where the investor cannot invest in risky securities.

2.3.3 Smith and Nau's Method

The idea behind Smith and Nau's (1995) method, which Smith and Nau call "*full decision tree analysis*," is to explicitly account for security trading in each decision node of a decision tree. The main advantage of the approach is that it appropriately accounts for the effect that the possibility to invest in securities has on the discount rate of a risky project. Incorporating decision trees, a preference model, and security trading, Smith and Nau's method is one of the most complete project valuation methods to date. However, it does not consider alternative projects, which impose an opportunity cost on the project being valued, wherefore it is applicable only in a setting where the investor can invest in a single project and several securities. In a multi-project setting, the method is subject to the usual shortcomings of single-project valuation methods; in particular, it fails to account for the effect of diversification and project synergies.

Also, the practically appealing form of the method, the *integrated rollback procedure*, relies on several restrictive assumptions: (i) *additive independence* (Keeney and Raiffa 1976), (ii) *constant absolute risk aversion* (CARA), and (iii) *partial completeness of markets*. Yet, as pointed out by Keeney and Raiffa (1976), additive independence entails possibly unrealistic preferential restrictions. The CARA assumption may also be questionable, because it leads to an exponential utility function with utility bounded from above. This is known to result in an unrealistic degree of risk aversion at high levels of outcomes (see, e.g., Rabin 2000). In practice, it may also be difficult to create a replicating portfolio for market-related cash flows of a project, as it is assumed in partially complete markets.

In view of the limitations of Smith and Nau's (1995) method, it appears that there is a need for project selection framework that (i) considers all projects in the portfolio, implements (ii) decision trees and (iii) security trading, and allows for (iv) a realistic array of risk preferences without resorting to overly restrictive assumptions.

3 PROJECT PORTFOLIO SELECTION MODEL

The Contingent Portfolio Programming (CPP) framework presented in Paper [I] is the underlying modeling framework that is used throughout this dissertation, except in Paper [V]. CPP allows risks to be managed both through diversification (Markowitz 1952, 1959) and staged decision making (Cooper 1993), and accounts for the firm's resource constraints. The framework has also the advantage that, when the firm's risk measure satisfies a linearity property, it leads to linear programming models, which can readily solved for portfolio selection models of realistic size.

3.1 Framework

In CPP, projects are regarded as risky investment opportunities that consume and produce several resources over multiple time periods. Analogously to Gear and Lockett (1973) and the Stage-Gate process of Cooper (1993), the staged nature of R&D projects is captured through project-specific decision trees, which support managerial flexibility by allowing the investor to take stepwise decisions on each project in view of most recent information (Dixit and Pindyck 1994, Trigeorgis 1996, Brandao and Dyer 2004, Brandao, Dyer, and Hahn 2004). Uncertainties are modeled using a state tree, representing the structure of future states of nature, as shown in

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the leftmost chart in Figure 1. In general, the state tree is a multinomial tree that can have different probability distributions in its branches.

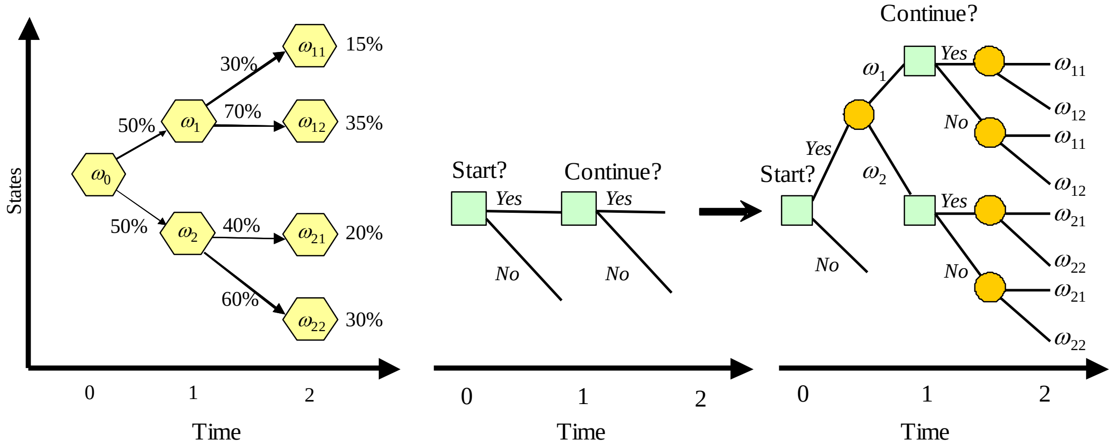

Figure 1. A state tree, a decision sequence, and a decision tree for a project.

Projects are modeled using decision trees that span over the state tree. The two rightmost charts in Figure 1 describe how project decisions, when combined with the state tree, lead to project-specific decision trees. The specific feature of these decision trees is that the chance nodes are shared by all projects, since they are generated using the common state tree. This allows for taking into account the correlations between projects.

Also securities can be straightforwardly incorporated into the CPP framework in order to develop a MAPS setting. While Paper [I] briefly mentions this possibility, a proper development of the resulting CPP MAPS model is given in Papers [II] and [IV]. In such a model, security trading is implemented through state-specific trading variables, which are similar to the ones used in financial models of stochastic programming (e.g. Mulvey et al. 2000) and in Smith and Nau's (1995) method. In addition to introducing security trading, Paper [II] presents a risk-constrained mean-risk version of the CPP model, which is not discussed in Paper [I]. Paper [III] employs a one-period version of this model, formerly called "general deviation-based mean-risk model" in a previous version of Paper [II], which appears in my Licentiate Thesis (Gustafsson 2004).

Four types of constraints are imposed on a CPP model: (i) *resource* (*budget*) *constraints*, (ii) *decision consistency constraints*, (iii) *risk constraints*, which apply to risk-constrained models only, and (iv) *deviation constraints*. Resource constraints ensure that there is a nonnegative amount of cash in each state. Decision consistency constraints implement the projects' decision trees. These constraints require that (i) at each decision point reached, only one action is selected, and that (ii) at each decision point that is not reached, no action is taken. Deviation constraints are needed in the formulation of many deviation-based risk measures.

3.2 Objective Function

The preference models in CPP can be further classified into two classes: (1) *preference functional models*, such as the expected utility model, and (2) *bi-criteria optimization models*. In general, we can refer by a "mean-risk model" either to a preference functional model (like in Paper [I]) or to a bi-criteria optimization model that uses optimization constraints (like in Papers [II] – [IV]). I adopt here the latter terminology.

In a preference functional model, the investor seeks to maximize the utility of the terminal resource position

$$\max U[X],$$

where U is the investor's preference functional and X is the random value of the resource position in period T. Under expected utility theory, the preference functional is given by $U\left[X\right]=E\left[u(X)\right]$, where u is the investor's von Neumann-Morgenstern utility function. A risk-constrained mean-risk model can be formulated as follows:

$$\max E[X],$$

subject to

$$\rho\left[X\right]\leq R,$$

where ρ denotes the risk constraint and R the investor's risk tolerance.

One of the main differences between Papers [I]–[IV] is the objective function used within the CPP framework. Paper [I] concentrates on linear preference functionals, *mean-lower semi-absolute deviation* (mean-LSAD) model and *mean-expected downside risk* (mean-EDR) model, which lead to linear CPP models. Such models can typically be solved when there is a reasonably large number of states and projects (e.g., 100 projects and 200 states), as shown by the numerical experiments in Paper [I]. Lower semi-absolute deviation (LSAD; Ogryczak and Ruszczynski 1999, Konno and Yamazaki 1991) and expected downside risk (EDR; Eppen et al. 1989) are defined as

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LSAD: $\bar{\delta}_X = \int_{-\infty}^{\mu_X} |x - \mu_X| dF_X(x) = \int_{-\infty}^{\mu_X} (\mu_X - x) dF_X(x)$ and

EDR: $EDR_X = \int_{-\infty}^{\tau} |x - \tau| dF_X(x) = \int_{-\infty}^{\tau} (\tau - x) dF_X(x)$,

where μ_X is the mean of random variable *X*, τ is some constant target value, and F_X is the cumulative density function of *X*. The mean-LSAD model exhibits linear pricing and consistency with stochastic dominance (Levy 1992, Ogryczak and Ruszczynski 1999), whereas the mean-EDR model is consistent with expected utility theory (von Neumann and Morgenstern 1947, Fishburn 1977) and hence also dynamically consistent (Machina 1989). Also, as long as the preference model and the underlying random variables satisfy the assumptions of Dyer and Jia's (1997) relative risk-value models, in particular the *relative risk independence* condition and non-negativity of outcomes, the preference model exhibits also the properties observed with relative risk-value models, such as the decomposition to the relative risk-value form.

In contrast, Paper [II] focuses on the risk-constrained mean-variance model, because hereby it is possible to contrast the results with the CAPM, which is based on the Markowitz (1952) mean-variance model. Similarly, Paper [IV] employs the risk-constrained mean-variance model in its numerical experiments, although it is not otherwise limited to this model. The numerical experiments in Paper [IV] involve also expected utility maximizers exhibiting constant absolute risk aversion (CARA; Keeney and Raiffa 1976).

Paper [III] uses the Choquet-Expected Utility (CEU) model (Choquet 1953, Gilboa 1987, Schmeidler 1989, Wakker 1990, Camerer and Weber 1992), which under stochastic dominance reduces to the Rank Dependent Expected Utility (RDEU; Quiggin 1982, 1993) model. This model is given by

$$U[X] = CEU[X] = E_c[u(X)] = \int_{-\infty}^{\infty} u(x)\varphi'(1 - F_X(x)) dF_X(x),$$

where φ is the transformation function describing the investor's ambiguity aversion. Paper [III] focuses on two special cases of the transformation function, quadratic and exponential functions, and presents two alternative formulations of a CEU MAPS model, the binary variable model and the rank-constrained model. Also, Paper [III] presents a MAPS model using Wald's maximin criterion (Wald 1950), which is a limiting special case of the CEU model.

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4 PROJECT VALUATION

While Paper [I] provides a framework for determining the value of a project portfolio, the methodology for calculating the value of a single project within a portfolio is developed in Paper [II]. With a single exception in Section 5.2 of Paper [II], examined project valuation settings in Papers [II] – [IV] are MAPS settings with at least the risk-free asset available. That is, the investor is able to invest in both (i) *securities*, which can be bought and sold in any quantities, and (ii) *projects*, which are lumpy all-or-nothing type investments.

4.1 Breakeven Buying and Selling Prices

Since a project is a non-tradable investment opportunity, the value of a project is defined as the amount of money at present that is equally desirable to the project, which corresponds to the conceptual definition of NPV in the literature on corporate finance. Still, the procedure obtained in Paper [II] is quite different from the conventional NPV formula found in course books on corporate finance (e.g., Brealey and Myers 2000). Nevertheless, as shown in Paper [IV], the approach coincides with many of the conventional project valuation approaches when the investor can invest only in a single project and the risk-free asset.

In a portfolio context, the above definition for project value can be interpreted so that the investor is indifferent between the following two portfolios: (A1) a portfolio with the project and (B1) a portfolio without the project and cash equal to the value of the project. We may alternatively define the value of a project as the indifference between the following two portfolios: (A2) a portfolio without the project and (B2) a portfolio with the project and a debt equal to the value of the project. The project values obtained in these two ways will not, in general, be the same. The first type of value is called the "*breakeven selling price*" (BSP), as the portfolio comparison can be understood as a selling process, and the second type of value the "*breakeven buying price*" (BBP).

As discussed in Paper [II], finding a BSP and BBP is an *inverse optimization problem* (see, e.g., Ahuja and Orlin 2001): one has to find a change in the budget so that the optimal value of the second portfolio optimization problem matches the optimal value of the first problem. Such problems can be classified into two groups: (i) finding an optimal value for the objective function, and (ii) finding a solution vector. The problem of finding a BSP or BBP falls within the first class; inverse optimization problems of this class can be solved by finding a root to a strictly increasing function. To solve

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such root-finding problems, we can use usual root-finding algorithms, such as the bisection method and the secant method.

4.2 Theoretical Results

4.2.1 Consistency of Breakeven Prices

As shown in Paper [II], breakeven prices exhibit *sequential consistency*, *consistency with CCA*, and *sequential additivity*. Due to sequential consistency, the investor will behave rationally in sequential decision problems. Technically, this means that when an investor first buys a project and then sells it, or vice versa, his/her (sequential) buying and selling prices will be equal to each other.

Consistency with CCA refers to the property of the breakeven prices that, whenever CCA is applicable, i.e. whenever there exists a replicating portfolio for the project, the breakeven buying and selling prices are equal to each other and yield the same result as CCA (see also Smith and Nau 1995). Due to this property, the breakeven prices can be regarded as a *generalization* of CCA.

Finally, sequential additivity states that the (sequential) BSPs / BBPs of two or more projects will always add up to the BSP / BBP of the portfolio composed of the same projects. This is a result of the fact that BSPs and BBPs are *added values*; if valued non-sequentially, projects' breakeven prices are non-additive in general.

4.2.2 Equality of Prices and Valuation Formulas

Paper [II] also shows that breakeven prices exhibit two important properties for a broad class of risk-constrained mean-risk investors: (i) the breakeven prices are equal to each other, and (ii) they can be solved through a pair of optimization problems without resorting to possibly laborious inverse optimization.

Papers [III] and [IV] produce analogous valuation formulas for other settings. Each of these formulas implies that, under the specified circumstances, the breakeven prices will be equal to each other and that they can be solved through a pair of optimization problems without using inverse optimization. Paper [III] develops the formula for expected utility maximizers exhibiting CARA and investors using Wald's maximin criterion. Both of these preference models have been widely used in the literature. On the other hand, Paper [IV] develops a formula for BSP when the investor can invest only in a single project and in the risk-free asset. A similar formula holds for both BSP and BBP when the investor exhibits CARA; further, it is now possible to

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use the certainty equivalent operator directly on the project's future value distribution. The paper also shows that when the investor exhibits linear pricing the breakeven prices coincide with the Hillier's (1963) method. In contrast, the prices will almost never give the same result as Robichek and Myers' (1966) method, because this method typically overestimates the risk of the project.

4.2.3 Relationship to Capital Asset Pricing Model

Paper [II] also derives analytical formulas for BSP and BBP in the case where (a) the investor is a mean-variance optimizer, (b) the optimal mixed asset portfolio at present is known, and (c) projects are uncorrelated with securities. Using first these formulas and then generalizing the result, the paper proves that the breakeven prices of a mean-variance investor will converge, as risk tolerance goes to infinity, towards the price that the CAPM would place on the project. This result is valid regardless of the correlation of the project with market securities or other projects, as long as the optimal project portfolio in the limit is the same with and without the project. If the portfolios differ, the value of the project will converge towards the CAPM price of the difference of portfolios with and without the project.

4.3 Valuation of Real Options

An interesting extension to the breakeven price methodology is the valuation of opportunities, especially that of real options. The term "real option" originates from the fact that management's flexibility to adapt later decisions to unexpected future developments shares similarities with financial options (Dixit and Pindyck 1994, Trigeorgis 1996, Copeland and Antikarov 2001, Black and Scholes 1973, Merton 1973, Hull 1999). For example, possibilities to expand production when the markets are up, to abandon a project under bad market conditions, and to switch operations to alternative production facilities can be seen as options embedded in a project.

Typically, the real options literature employs CCA to value real options, which requires that project cash flows can be replicated using financial securities. When replication is possible for all assets, markets are said to be *complete*. However, it can be difficult to construct replicating portfolios for private projects in practice, especially when the projects are developing innovative new products that do not resemble existing market-traded assets. Therefore, it is relevant to examine how real options could be priced in *incomplete markets*. Since real options of a project have conventionally been valued in the presence of securities, which is a MAPS setting, it is natural to consider the application of the breakeven price methodology to real option valuation.

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Because a real option gives the investor an opportunity but not the obligation to take an action, we need for the valuation of real options concepts that rely on comparing the situations where the investor *can* and *cannot* take an action instead of *does* and *does not*, as breakeven prices do. Such prices are called *opportunity selling and buying prices*. Opportunity prices are always non-negative, because an opportunity cannot lower the value of the investor's portfolio. It is also straightforward to show that the opportunity prices can be obtained by taking a maximum of zero and the respective breakeven price. Since breakeven prices are consistent with CCA, also opportunity prices have this property, and hence they can be regarded as a generalization of the standard CCA real option valuation procedure to incomplete markets.

5 RESULTS FROM NUMERICAL EXPERIMENTS

Numerical experiments are conducted in all of the papers. Paper [I] carries out an extensive numerical study on the computational performance of CPP models. These experiments indicate that CPP models of realistic size can be solved in a reasonable time. When solved as linear programming models, where integer variables are left continuous, CPP models of about a hundred five-staged projects and several hundreds of states can be solved in a reasonable time. Mixed integer programming models with a couple of tens of three-staged projects and less than a hundred states have usually an acceptable solution time. A similar computational experiment is conducted in Paper [V], indicating that PRIME models can be solved in a relatively short time using the PRIME Decisions software.

Also Papers [II] – [IV] conduct numerical experiments. These aim at demonstrating the properties of breakeven prices in different contexts. Because it is not immediately obvious how generalizable the results are, the conclusions are necessarily limited to a rather general level. Overall, two main points can be highlighted.

5.1 Effect of Alternative Investment Opportunities

The results from the numerical experiments indicate that alternative investment opportunities, both projects and securities, do have a major impact on the value of a project. Beginning from the setting where it is possible to invest only in the project being valued, the experiments in Paper [II] show that introduction of new projects to the set of available investment opportunities typically lowers project values. This is understandable in view of the definition of breakeven prices: the value of the optimal portfolio without the project will increase, which lowers the value of the project. Only in the case where the value of the optimal portfolio with the project increases more than the portfolio without the project will the value of the project grow. This might be the case when the project is negatively correlated with other projects.

Similarly, securities can also lower project values by increasing opportunity costs (i.e. by increasing the value of the portfolio *without* the project), and they can also raise them by providing better diversification of risk (i.e. by raising the value of the portfolio *with* the project). The total effect depends on the relative magnitude of these two phenomena. We also see in the numerical experiments that, as predicted by the related proposition in Paper [II], when a project has a replicating portfolio, its value is consistent with the project's CCA value at all risk levels.

5.2 Pricing Behavior as a Function of Risk Tolerance

Another set of insights from numerical experiments is related to the behavior of breakeven prices when the investor's risk tolerance increases. First, the experiments show that, when securities are not available, project values can rise non-monotonically as the risk tolerance is increased. This is because, without securities, opportunity costs are imposed in a lumpy manner, and the price of a project is determined by the projects that fit into the portfolio (limited by the risk constraint) with and without the project. This may result in a lumpy up and down movement in breakeven prices.

In contrast, when securities are available, project values change monotonically by risk tolerance, because securities can be bought in a continuous manner. However, the project values can either rise or decrease by risk tolerance, depending on the correlation of the project with the rest of the mixed asset portfolio. Indeed, it is the correlation with the rest of the *mixed asset portfolio* that determines the limit behavior, not that with the security portfolio only. Therefore, one cannot use the project's beta to make estimates about the sign of change in the project value when the investor's risk tolerance increases.

The limit behavior of the breakeven prices is also examined in the numerical experiments. As predicted by the related propositions in Paper [II], it is observed that the breakeven prices for a mean-variance investor converge towards the CAPM price of the project as the investor's risk tolerance goes to infinity. Similarly, we see in Paper [III] that when an expected utility maximizer becomes less risk averse, project

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values approach values that are close to the projects' CAPM prices. Indeed, in neither case do the prices converge towards the values given by a risk-neutral investor. Finally, it is also observed, as expected, that when the investor becomes increasingly averse to risk or ambiguity, project values approach the values given by a maximin investor, the investor using Wald's (1950) maximin criterion.

6 IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS

The methodology developed in this dissertation provides a way to calculate theoretically justifiable values for risky projects and portfolios of risky projects so that the investor's risk preferences, the opportunity costs of alternative investment opportunities, and project interactions are properly accounted for. In particular, it is now possible to determine the theoretically appropriate discount rate for a risky project, even when the project is owned by a private company or when there are synergies between projects. In addition, the methodology makes it possible to solve project portfolio selection problems where risks are managed using both diversification and staged decision making. Uncertainties can also be modeled with relative accuracy, because the models can be formulated using linear programming, which permits the use of a large number of states.

This dissertation opens up avenues for further work both in practical and theoretical areas. On the practical side, applications of the methodology are called for. For example, the analysis of oil field investments appears to be a promising area for the present methodology, because many oil companies possess portfolios of oil fields and the associated uncertainties are mostly related to external sources. Another interesting application area is the valuation of collateralized debt obligations (CDOs), which are portfolios of assets with a possibly complex tranche structure. In addition, in order to ease the use of the methodology in practice, the development of a dedicated software application to solve CPP models is called for.

On the theoretical side, several extensions of the methodology can be made. It is, for example, possible to include transactions costs and capital gains tax into a CPP MAPS model by using several resource types, each indicating the number of specific assets held, and state-specific decision trees that implement the trading decisions for each asset bought in the associated state. Further work is also needed in the modeling of synergies and follow-up project structure of R&D projects. For example, some synergies can be modeled by describing each project as a sequence of tasks,

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each modeled as an individual project in CPP's sense, that are interconnected so that a task cannot be started before the task preceding it is finished. The synergy then arises from that a single task is used in the task sequence of several projects.

In general terms, the dissertation provides several new research topics for the related academic disciples. In corporate finance, where the limitations of CAPM discount rates have hopefully become more apparent than what they were previously, we need more research to develop procedures to value projects of public companies when all shareholders are not CAPM investors. This is relevant, for instance, with partly state-owned companies, because in order to maintain the necessary voting power the state has to possess a large amount of shares in the company, and therefore it cannot efficiently diversify its investment portfolio, as the CAPM requires. A similar situation may arise also in other cases where the investor is interested both in the financial return and the voting right provided by the share. For researchers of operations research and management science, the present work shows that decision trees, real options, and project portfolio selection models can be profitably combined together into a unified framework, where project values can be determined using inverse optimization. I am confident that these three project selection methodologies and inverse optimization have much to offer to each other and in terms of future research possibilities.

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