European Journal of Operational Research 207 (2010) 420–433

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Decision Support

Optimization of R&D project portfolios under endogenous uncertainty

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ARTICLE INFO

Article history:
Received 1 September 2009
Accepted 30 April 2010
Available online 19 May 2010

Keywords:
OR in research and development
Project portfolio
Technology management
R&D
Multistage stochastic programming
Endogenous uncertainty

ABSTRACT

Project portfolio management deals with the dynamic selection of research and development (R&D) projects and determination of resource allocations to these projects over a planning period. Given the uncertainties and resource limitations over the planning period, the objective is to maximize the expected total discounted return or the expectation of some other function for all projects over a long time horizon. We develop a detailed formal description of this problem and the corresponding decision process, and then model it as a multistage stochastic integer program with endogenous uncertainty. Accounting for this endogeneity, we propose an efficient solution approach for the resulting model, which involves the development of a formulation technique that is amenable to scenario decomposition. The proposed solution algorithm also includes an application of the sample average approximation method, where the sample problems are solved through Lagrangian relaxation and a new lower bounding heuristic. The performance of the overall solution procedure is demonstrated using several implementations of the proposed approach.

1. Introduction

Project portfolio management, as defined in this paper, refers to selecting and allocating resources to research and development (R&D) projects to design, test and improve a technology, or the process of building a technology. Project portfolio management is an essential part of the operational planning process for most private and public organizations. Such organizations typically have several potential R&D projects with different performance characteristics that they can choose to invest in using available resources.

The primary characteristics of technology projects, which include parameters such as the required resource levels, i.e. the total expenditure necessary to create returns, as well as the projected returns themselves, are typically unknown at the time of investment. However, some information, in particular on the uncertainty in the estimates of these characteristics, is mostly available. Given these uncertainties and resource limitations over a planning horizon, the project portfolio management problem becomes one of selecting R&D projects and determining optimal resource allocations for the current planning period such that the expected total discounted return or the expectation of some other function over a long time horizon is maximized.

Depending on the organization and the domain, the set of candidate projects may have several attributes. For instance, the realization of returns after the completion of research is typically subject to delay, length of which may vary for each project. In addition, an R&D effort can continue over multiple years, while a fixed operating cost can be incurred and allocated for each project that remains active. Furthermore, multi-way dependencies almost always exist between different projects, which implies that the joint return of two dependent technologies will typically be different from the sum of their individual returns.

Markowitz (1952) laid the background for modern financial portfolio theory, when he suggested that investors should select portfolios based on the overall risk-reward characteristics of the securities, rather than investing on a single security with the best risk-reward characteristic. Since then, many other modeling and optimization techniques have been proposed for financial portfolio optimization.

Although at first glance, it may seem that financial portfolio optimization theory could be directly applied to R&D project portfolio management, there are clear differences between the two problems. One distinction is in the realization of returns. The realization time and the variance in the return of an R&D project is dependent on the investment made on that project. However, for financial securities, both the risk and the time of return realization is independent of the amount of the security that is purchased. Assuming that no one investor will

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doi:10.1016/j.ejor.2010.04.032

seek to make a single purchase of all or the vast majority of a company's stocks that will cause the price of the security to change by virtue of the purchase itself, the value of the security will solely be based on the performance of the company in question. A second difference between the two problems is about the correlation between project returns. In financial portfolio theory, the correlation in returns is assumed to be independent of the way in which resources are allocated. On the other hand, the correlation between the returns of R&D projects is dependent on investment levels, because resources spent on one project are taken away from other projects, thus preventing early return realization in these projects. Finally, a third distinction is the dependencies of technology projects in terms of the returns that are produced. In financial theory, the cumulative return from two purchased securities is assumed to be equal to the sum of the individual returns of the securities. However, as noted above, projects have dependencies which can have a positive or negative effect in the realization of cumulative joint returns.

1.1. Relevant literature on R&D portfolio management

Despite the importance and economic significance of project portfolio selection and the existence of several operations research models, the industrial use of these models has been limited. This is mainly due to the fact that none of the proposed models has been able to capture the full range of complexity that exists in project portfolios. De Reyck et al. (2005) study the impact of project portfolio management techniques on the performance of projects and overall portfolios. The authors identify certain key components required for an effective portfolio management approach, which include the following capabilities: (i) capturing of financial returns and risks of assets, (ii) modeling interdependencies, (iii) determination of prioritization, alignment and selection of projects, (iv) modeling organizational constraints, and (v) ability to dynamically reassess the portfolio. Linton et al. (2002) provide a review of proposed project portfolio management methods in the literature, and categorize the existing methods into several groups. However, neither of the methods reviewed in that study, nor those that were developed after the study are able to model and deliver the complete set of capabilities identified by De Reyck et al. (2005).

The models that have thus far been proposed for project portfolio management include capital budgeting models, which capture the interdependencies between different projects, but fail to model the uncertainty in returns and required investments (Luenberger, 1998). While more recent project portfolio models capture both the uncertainty in returns and interdependencies, they typically assume that the required cash flows for projects are known, and the investment decisions consist of binary starting or stopping decisions for projects (Ghasemzadeh et al., 1999; Gustafsson and Salo, 2005). One example where the amount of resources allocated to each project is treated as a decision variable in a stochastic integer program is given by Norkin et al. (1998). Beaujon et al. (2001) also note the importance of resource allocation decisions, and develop a linear programming approximation. In a generalization of that approximation, Loch and Kavadias (2002) define some limiting assumptions, and develop some important analytical results under these limitations in the context of new product development. In addition, simulation optimization has also been used as an approximate but mostly effective approach for R&D project portfolio management (Subramanian et al., 2001, 2003; April et al., 2003; Blau et al., 2004).

Somewhat more easy-to-implement approaches to R&D project portfolio management either contain deterministic models or include several restrictive assumptions. Dickinson et al. (2001) present a deterministic nonlinear integer programming model to optimize a portfolio of product development improvement projects, while Lincoln et al. (2006) develop a method for prioritization of technology investments using a deterministic linear programming formulation to maximize an objective function subject to cost based constraints. In addition to these models, most strategic planners and project portfolio managers rely on tools based on expert opinions, such as Analytical Hierarchy Process and Quality Function Deployment, in planning the funding of technology development (Thompson, 2006). Similar systematic evaluation methods are also proposed by Sallie et al. (2002) and Utturwar et al. (2002), where the authors propose bilevel approaches in selecting technologies to invest. The latter study also contains an optimization procedure based on a genetic algorithm implementation. However, these tools are also not complete in their ability to fully quantify the complicated return and investment structure inherent in project portfolios, mainly due to their deterministic nature and other simplifying assumptions.

Other more complex approaches to project portfolio management include real options based methods (Campbell, 2001; Lee et al., 2001; Bardhan et al., 2004; Tralli, 2004; Bardhan, 2006). These methods capture most complexities in R&D portfolios, but the valuation methods used in such approaches may not be able to model project evolutions and combinatorial recourse decisions accurately. This is especially true when the endogenous structure in R&D portfolios is considered. More specifically, uncertainty in project returns or resource requirements is typically revealed gradually over time, depending on the dynamic resource allocation decisions in the projects. This endogenous decision process, which we describe in detail in Section 3.1, is noted as an important characteristic of R&D portfolio management in several papers in the literature. This characteristic however requires more complex models and solution approaches for such problems.

1.2. Relevant literature on endogenous uncertainty

In a study similar to this paper, Colvin and Maravelias (2008) emphasize the need for modeling endogenous uncertainty in R&D project portfolios and include it in a multistage stochastic programming model for pharmaceutical R&D. The problem that the authors study involve planning of clinical trials, where the decisions correspond to the selection of the trials for a portfolio of potential drugs. Significant reductions in problem size are achieved by exploiting several logical relationships in the problem structure, and the resulting manageable size problem is then solved through classical methods. In two follow-on papers, the same authors present extensions of their original model and develop new solution procedures to handle larger instances, which include effective relaxation-based heuristic approaches (Colvin and Maravelias, 2009) and a branch-and-cut algorithm (Colvin and Maravelias, 2010). While several similarities exist between these studies and the approach proposed in this paper, one major distinction is that our model involves continuous investment decisions over a planning horizon, in addition to the binary starting and completion decisions for the projects. Moreover, the investment requirement for each project is assumed to be stochastic and also revealed gradually as a function of the progress on the project. Hence, the model presented in this paper involves relaxations of several assumptions in Colvin and Maravelias (2008). These generalizations add further complexity to the R&D portfolio model, and require new tractable solution methods.

In another related paper Boland et al. (2008) consider an application involving the open pit mine production scheduling problem which contains endogenous uncertainty, and describe a general nonanticipativity constraint reduction procedure. In addition, Choi et al. (2004) describe a dynamic programming approach for a simplified version of the online resource-constrained stochastic project scheduling problem,