Decision Support Systems 77 (2015) 21–30

Contents lists available at ScienceDirect

Decision Support Systems

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

Selecting infrastructure maintenance projects with Robust Portfolio Modeling

Pekka Mild [a], Juuso Liesiö [b,*], Ahti Salo [c]

[a] Pöyry Management Consulting Ltd., P.O. Box 5, Jaakonkatu 3, 01621 Vantaa, Finland
[b] Department of Information and Service Economy, Aalto University School of Business, P.O. Box 21220, 00076 Aalto, Finland
[c] Systems Analysis Laboratory, Department of Mathematics and Systems Analysis, Aalto University School of Science, P.O. Box 11100, 00076 Aalto, Finland

ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form 24 April 2015
Accepted 3 May 2015
Available online 11 May 2015

Keywords:
Portfolio Decision Analysis
Multiple criteria decision making
Project selection
Resource allocation
Incomplete information

ABSTRACT

Project portfolios for the annual maintenance of infrastructure assets may contain dozens of projects which are selected out of hundreds of candidate projects. In the selection of these projects, it is necessary to account for multiple evaluation criteria, project interdependencies, and uncertainties about project performance as well as financial and other relevant constraints. In this paper, we report how Robust Portfolio Modeling (RPM) has been used repeatedly at the Finnish Transport Agency (FTA) for bridge maintenance programming. At FTA, project selection decisions are guided by the RPM's Core Index values which are derived from portfolio-level computations and reflect incomplete information about the relative importance of evaluation criteria. To-date, this application has been rerun with fresh data for six consecutive years. By drawing on experiences from this application, we discuss preconditions for the successful use of RPM or other methods of Portfolio Decision Analysis in comparable settings. We also develop an approximative algorithm for computing non-dominated portfolios in large project selection problems.

1. Introduction

One of the most important classes of decisions at companies and public funding agencies is which projects they should spend their limited resources on [17]. These decisions can be assisted with models of Portfolio Decision Analysis (PDA) which: (i) capture relevant information about project candidates, evaluation criteria, selection constraints and uncertainties, and (ii) synthesize such information into decision recommendations with appropriate techniques of decision analysis and optimization (see, e.g. [34] for an overview). The range of reported PDA applications is extensive and spans areas such as military planning [4,9], healthcare capital budgeting [17] and R&D portfolio management [10,37]. Methodologically, there is a rich variety of models, extending from relatively simple multi-criteria scoring and prioritization models (e.g. [1,6,12]) to complex models of portfolio optimization [7,9,10,17,22,23,27].

In infrastructure maintenance management, PDA helps establish more systematic, transparent and repeatable decision making processes (e.g. [18,19,30]). As an application domain for PDA, infrastructure management is attractive yet challenging. First, problems are often very large in that there may be hundreds of project candidates from which only a few dozens can be selected with available resources. Second, assessing the need for maintenance involves multiple criteria of which some are objective technical measurements or classifications while others are more qualitative and subjective. Third, judgments about the relative importance of these criteria are inherently subjective and may differ considerably depending on from whom these judgments are elicited; nor are the respondents necessarily able to make such judgements. Fourth, the available data about project candidates can be incomplete or partly outdated; in particular, cost estimates can be difficult to establish in the project screening phase. Fifth, even if some portfolio constraints are explicit and 'hard' (resource limitations and performance targets, for example), other constraints may be less so and even subject to some negotiation. Sixth, the implementation of maintenance portfolio planning is typically a year-long iterative process in the course of which information arrives continually; consequently there is no single decision point at which the selection of the 'optimal' portfolio could be finalized, for instance, by organizing a one-shot interactive decision workshop (cf. [17,32], among others).

In this paper, we report how PDA has been used repeatedly to support the process of selecting bridge maintenance projects at the Finnish Transportation Agency (FTA). At the heart of this process is the Robust Portfolio Modeling (RPM; [22,23]) methodology which: (i) captures incomplete information about the multiple criteria with which the maintenance needs of bridges are measured, and (ii) identifies non-dominated maintenance project portfolios based on a new approximative algorithm. Projects' Core Indexes – which show the share of non-dominated portfolios in which a project is included – have been used by bridge managers in their annual portfolio planning

* Corresponding author.
E-mail addresses: pekka.mild@poyry.com (P. Mild), juuso.liesio@aalto.fi (J. Liesiö), ahti.salo@aalto.fi (A. Salo).

http://dx.doi.org/10.1016/j.dss.2015.05.001
0167-9236/

in which they must account for other considerations alongside with the factors that are formally incorporated into the RPM model. Over the past eight years, the model has become an integral and recurrent part of FTA's maintenance programming activity. Since 2008, the model structure (i.e., evaluation criteria and constraints) has been kept intact while the inspection data on the bridges' maintenance needs and available maintenance resources has been updated annually from FTA's data records. This provides a unique track record of activities and results for analysis.

This paper contributes to theory and practice of PDA in several ways. First, we report a high-impact successful application of the RPM methodology for maintenance decision making. This application differs from the majority of reported PDA applications in that it provided recurrent computer-aided decision support rather than a one-shot decision workshop intervention. Second, this application demonstrates that the use of incomplete preference information and the communication of decision recommendation through Core Indexes helps deliver decision support that is readily accepted by the decision makers (DMs). Indeed, our experiences suggest that these concepts can be easily understood by DMs who have very limited experience in using decision analysis. Third, this application provides evidence that RPM and other portfolio optimization models can be useful even when they do not provide a final portfolio recommendation. In fact, the delivery of ‘partial’ results may lead to a better fit with the needs of organizational decision making than that of providing a single ‘optimal’ portfolio. Finally, necessitated by the large number of bridges, we developed an approximate algorithm for obtaining a representative set of non-dominated portfolios with standard mixed integer linear programming (MILP) solvers. Through this methodological contribution, this paper extends the applicability of RPM to other problem contexts in which there are hundreds of project candidates.

The remainder of this paper is organized as follows. Section 2 first summarizes earlier PDA methods and applications, and then outlines the key characteristics of the RPM methodology. Section 3 describes the application to bridge maintenance programming at FTA and presents the approximative algorithm. Section 4 presents the results from the recurrent application. Section 5 discusses the insights from the application that are relevant when applying PDA models in other contexts. Section 6 concludes.

2. Multi-criteria Portfolio Decision Analysis

2.1. Linear-additive portfolio value model

In most PDA approaches, multiple scalar evaluations are aggregated into an overall project value by using a multi-criteria value/utility function (e.g. [1,9,10,12,17,22,23,27]). This aggregation can be performed by using different functional forms which each corresponds to specific assumptions about preferential independence of the criteria (see, e.g. [8,14]). By far the most common form is the additive value function in which the m projects $x^1, \ldots, x^j, \ldots, x^m$ are evaluated with regard to the n criteria to determine scores $v_i^j \in [0, 1]$, $i = 1, \ldots, n$, and the overall value of the project is expressed as the weighted sum of these scores, i.e.,

$$V\left(x^j\right) = \sum_{i=1}^{n} w_i v_i^j.$$

The criterion weight w_i captures the increase in overall value when the ith criterion changes from its least preferred level to the most preferred one. Usually the criteria weights $w = (w_1, \ldots, w_n)^T$ are scaled so that they sum up to one, i.e., $w \in S_w^0 = \{w \in \mathbb{R}_+^n | \sum_{i=1}^n w_i = 1\}$.

If the portfolio selection problem is constrained by the budget only, the ratio between overall project values $V(x^j)$ and project costs c^j can be used to prioritize projects. Specifically, the process of building the portfolio by adding projects one-by-one in descending order of value-to-cost ratios $(V(x^j)/c^j)$ until the budget is depleted will yield a portfolio that maximizes the portfolio value per the budget that is spent (assuming that the value of a portfolio is the sum of the selected projects' values; see, e.g. [28]; Theorem 2.1). Yet in general, this approach does not necessarily identify which portfolio has the highest value for a pre-defined budget. It also assumes that there are no other constraints on the portfolio selection problem. For example, selecting a portfolio of small and inexpensive projects of some specific type could offer the highest value-cost ratio, yet such a selection could fail to meet the requirement of building a sufficiently balanced portfolio consisting of projects of different sizes and types.

Golabi et al. [10] derive a measurable value function for project portfolios and show that under certain preferential independence assumptions the overall value of a portfolio can be obtained by summing the values of the projects in this portfolio (for implications of relaxing these assumptions see [21]). In this linear-additive model, the overall value of portfolio $p \subseteq \{x^1, \ldots, x^m\}$ is

$$V(p, w, v) = \sum_{x^j \in p} V\left(x^j\right) = \sum_{j=1}^{m} z_j(p) \sum_{i=1}^{n} w_i v_i^j, \quad (1)$$

where $z_j(p) = 1$ if project x^j is included in portfolio p and $z_j(p) = 0$ otherwise. This formulation assumes that not selecting a project yields zero value (i.e., the baseline value is set equal to zero, see [5]). Resource and other linear portfolio constraints define the set of feasible portfolios

$$P_F = \{p \subseteq \{x^1, \ldots, x^m\} | Az(p) \leq B\}, \quad (2)$$

where the coefficient matrix A and the right-hand-side vector B define the feasibility constraints (see, e.g. [37]). The feasible portfolio with most value can be obtained by solving the integer linear program (ILP) problems

$$\max_{p \in P_F} V(p, w, v) = \max_{z(p)} \left\{ z(p)^T v w \;\middle|\; Az(p) \leq B,\ z(p) \in \{0, 1\}^m \right\}, \quad (3)$$

where the matrix $v \in \mathbb{R}^{m \times n}$ contains the project scores ($[v]_{ji} = v_i^j$).

Still, the unique zero-one solution to Eq. (3) provides no insights into which projects are close to entering or exiting the optimal portfolio if assumptions about the model parameters change, or if there are projects that should perhaps be selected or rejected for reasons that were not explicitly modeled in the first round of analysis. In many situations, such concerns can be addressed by organizing an interactive facilitated workshop in which software tools are used to carry out sensitivity and what-if analyses (e.g., Decision Conferencing [32]). Indeed, the capabilities of optimization models, particularly as vehicles for interactive analyses, have helped overcome the limitations of straightforward ratio-based project prioritization in areas such as healthcare capital budgeting [17], energy-sector R&D portfolio selection [10,31] and military resource allocation [4,9], among many others.

2.2. Robust Portfolio Modeling

Robust Portfolio Modeling (RPM; [22,23]) admits incomplete information about the criteria weights and projects' scores in the linear-additive project portfolio optimization approach (Eq. 3). More specifically, preference statements about the relative importance of criteria are modeled as linear constraints on the criteria weights w, and these constraints define the set of feasible weights $S_w \subseteq S_w^0$. For instance, with $n = 2$ criteria, the statement that the first criterion is more important than the second one corresponds to the feasible weight set $S_w = \{w \in S_w^0 | w_1 \geq w_2\}$. The scores are modeled by real-valued intervals that are wide enough to contain the ‘true’ values. Specifically, the set of feasible scores is $S_v = \left\{ v \in \mathbb{R}_+^{m \times n} | \underline{v} \leq v \leq \overline{v} \right\}$, where matrices $\underline{v}, v \in \mathbb{R}^{m \times n}$ contain the lower and upper bounds for the intervals and the inequalities hold element-wise.

Under incomplete information $S = S_w \times S_v$, the ILP problem (Eq. 3) has a different optimal solution depending on which feasible weights