Department of Mathematics and Systems Analysis

Portfolio decision analysis for infrastructure and innovation management

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Pekka Mild

Aalto University

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Portfolio decision analysis for infrastructure and innovation management

Pekka Mild

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Abstract

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Abstract

Practically all companies and public agencies make decisions about resource allocation among investment categories and selection of 'lumpy' investments such as projects. While economic calculations tend to be central in these decisions, it is often necessary to account for hard-to-monetize impacts, multiple objectives, stakeholder interests and relevant constraints. For these decisions, Portfolio Decision Analysis (PDA) provides mathematical methods and decision support processes that assist in the construction of portfolios consisting of a set of discrete alternatives.

This Dissertation develops a multi-criteria PDA methodology, Robust Portfolio Modeling (RPM), for problems in which a subset of indivisible projects is to be selected from a large number of candidates, with the aim of contributing to the attainment of multiple objectives while satisfying relevant budgetary and other constraints. The RPM methodology – which is based on the linear-additive value representation – admits incomplete information about criterion weights, project scores and project costs in portfolio selection. A key concept of the RPM, the core index, derives project-level recommendations by computing and analyzing non-dominated project portfolios. These recommendations show (i) which projects are robust choices in the light of the incomplete information and (ii) which projects are promising targets for acquiring additional information that can lead to more conclusive results concerning their inclusion or exclusion to the final portfolio.

The Dissertation also presents real-life applications of PDA in infrastructure and innovation management. The RPM application on bridge maintenance management (Paper [III]) found its way into repeated use at the Finnish Transport Agency. The second infrastructure application (Paper [IV]) is an innovative combination of standard Operations Research methods to support strategic resource allocation between road asset categories and types of operations. The third application (Paper [V]) demonstrates how the RPM can be utilized to ex post evaluation to identify sets of over- and underperforming projects in an innovation program.

The Dissertation shows that the RPM method and its key concepts are readily understood and accepted by practitioners, including senior managers. The method can be tailored to utilize existing project data from sources such as monitoring databases, and it is computationally capable of processing hundreds of project candidates. Moreover, given that repeated real-life applications are relatively rare in decision analysis literature, the methodological development in this Dissertation already can be viewed as a pioneering platform for further avenues of PDA research.

Keywords Portfolio decision analysis, project prioritization, resource allocation, multi-attribute value theory, incomplete information, robustness, applications, infrastructure asset management, innovation management

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Tiivistelmä

Jokseenkin kaikki yritykset ja julkisorganisaatiot tekevät päätöksiä resurssien allokoimisesta investointikategorioille ja edelleen erilaisille projekteille. Taloudellisilla laskelmilla on tyypillisesti keskeinen merkitys tällaisessa päätöksenteossa, mutta usein on huomioitava myös vaikeasti arvotettavia vaikutuksia, useita tavoitteita, sidosryhmien näkemyksiä ja monenlaisia rajoitusehtoja. Portfoliopäätösanalyysi (PDA) on joukko matemaattisia menetelmiä ja niiden soveltamisprosesseja, joilla tuetaan portfolioiden muodostamista joukosta jakautumattomia projektiehdokkaita.

Tässä väitöskirjassa kehitetään monitavoitteinen PDA-menetelmä, Robust Portfolio Modeling (RPM), jossa on valittavana osajoukko projekteja suuresta ehdokasjoukosta tavoitteena tyydyttää useita rinnakkaisia tavoitteita budjetin ja mahdollisten muiden rajoitusehtojen puitteissa pysyen. RPM-menetelmä hyödyntää lineaaris-additiivista arvomallia (painotettu summa) ja mahdollistaa epätäydellisen informaation käytön koskien tavoitteiden painokertoimia, projektien tavoitekohtaisia arvioita ja projektien kustannuksia. Ydinluku (core index) on RPM-menetelmän keskeinen käsite, joka muodostaa projektikohtaisia päätössuosituksia menetelmässä laskettavasta tehokkaiden portfolioiden joukosta. Ydinluvun avulla nähdään (i) mitkä projektit ovat robusteja valintoja lähtötietojen epävarmuus huomioiden ja (ii) minkä projektien osalta informaation tarkentaminen voi tehokkaimmin johtaa projektivalintojen varmistumiseen ja yksikäsitteisen portfolion suosittelemiseen.

Väitöskirja esittelee PDA:n käytännön sovelluksia infrastruktuurien ylläpidon ja innovaatiotoiminnan johtamisessa. Työssä rakennettua RPM-menetelmän sovellusta (Artikkeli [III]) maantiesiltojen vuotuisen korjausohjelmoinnin tukemiseen on hyödynnetty toistuvasti Suomen Liikennevirastossa. Toinen infrastruktuurisovellus (Artikkeli [IV]) yhdistelee erilaisia operaatiotutkimuksen menetelmiä tukemaan strategisen tason päätöksentekoa tienpidon tuotteiden välisessä rahanjaossa. Kolmas sovellus (Artikkeli [V]) havainnollistaa, kuinka RPM-menetelmää voidaan hyödyntää innovaatioprojektien jälkikäteisarvioinnissa niiden onnistumisen luokittelun tukena.

Väitöskirja osoittaa, että RPM-menetelmä ja sen keskeiset käsitteet ovat hyvin ymmärrettäviä ja soveltuvia merkittävien päätösten tukemiseen käytännössä. Menetelmä voidaan räätälöidä hyödyntämään olemassa olevia tietoaineistoja projektiehdokkaista, joita saa laskettavuuden näkökulmasta olla jopa satoja. Toistuvan todellisen käytön saavuttaneet päätösanalyysisovellukset ovat alan kirjallisuudessa varsin harvinaisia, ja väitöskirjassa tehty menetelmäkehitys on jo toiminut uraauurtavana alustana jatkotutkimuksissa PDA-alalla.

Avainsanat Portfoliopäätösanalyysi, projektien priorisointi, resurssien allokointi, moniattribuutinen arvoteoria, epätäydellinen informaatio, robustisuus, sovellukset, infrastruktuuriomaisuuden hallinta, innovaatiojohtaminen

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Finally, I want to thank my wonderful family and parents for always being there for me, and supporting my mood in this rather non-linear doctoral path. One of the final triggers to complete the work was a strong thumbs up from my wife Kia, and my sons Joel and Nooa show such mathematical talent that daddy should be doctor to keep up with them.

Espoo, January 2017

Pekka Mild

Contents

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

[I] Liesiö, J., Mild, P., Salo, A. (2007). Preference Programming for Robust Portfolio Modeling and Project Selection, *European Journal of Operational Research*, Vol. 181, pp. 1488-1505. http://dx.doi.org/10.1016/j.ejor.2005.12.041

[II] Liesiö, J., Mild, P., Salo, A. (2008). Robust Portfolio Modeling with Project Interdependencies and Incomplete Cost Information, *European Journal of Operational Research*, Vol. 190, pp. 679-695. http://dx.doi.org/10.1016/j.ejor.2007.06.049

[III] Mild, P., Liesiö, J., Salo, A. (2015). Selecting Infrastructure Maintenance Projects with Robust Portfolio Modeling, *Decision Support Systems*, Vol. 77, pp. 21-30. http://dx.doi.org/10.1016/j.ejor.2007.06.049

[IV] Mild, P., Salo, A. (2009). Combining a Multiattribute Value Function with an Optimization Model: An Application to Dynamic Resource Allocation for Infrastructure Maintenance, *Decision Analysis*, Vol. 6, pp. 139-152. http://dx.doi.org/10.1287/deca.1090.0143

[V] Salo, A., Mild, P., Pentikäinen, T. (2006). Exploring Causal Relationships in an Innovation Program with Robust Portfolio Modeling, *Technological Forecasting & Social Change*, Vol. 73, pp. 1028-1044. http://dx.doi.org/10.1016/j.techfore.2006.03.005

Contributions of the author

Mild is the initiator and main contributor in papers [III] and [IV]. The algorithm in paper [III] was developed by Liesiö. Mild, Liesiö and Salo contributed equally to paper [I], where Mild was the initiator of the *core index* concept. In paper [II], Mild contributed to the conceptual development and reporting, whereas the mathematics and numerical computations were developed by Liesiö. In paper [V], Mild was the secondary author, responsible for the computations and their reporting.

1. Introduction

Basically all companies and public agencies are faced with decisions of allocating limited resources among organizational categories and selecting which projects and/or actions to pursue within those categories. Although economic calculations tend to drive many business decisions, multiple objectives, stakeholders and/or constraints must often be accounted for. Moreover, in many application domains there are no “natural” and unanimously recognized measures to monetarize (all) impacts and considerations relevant in these kinds of complex decisions. By definition, methods and tools of Multiple Criteria Decision Analysis (MCDA) are designed to provide decision support for such problems (e.g., Keeney and Raiffa, 1976; Keeney, 1992; Belton and Stewart, 2002; Edwards *et al.*, 2007). Portfolio Decision Analysis (PDA) is a relatively newly established research field, although it has long roots in early capital budgeting and project selection models dating back to the 1960’s (an overview in, e.g., Salo *et al.*, 2011), and it has been recognized to account for a significant share of commercial decision analysis consulting (Kleinmuntz, 2011).

The distinguishing feature of PDA is in the paradigm of *portfolio* choice: the task is to choose a combination of items, a subset from a large pool of candidates instead of a single alternative, which has traditionally been the standard set-up in most (multi-criteria) decision analysis literature. The range of reported PDA applications is extensive and growing, spanning areas such as military planning and procurement (Ewing *et al.*, 2006; Burk and Parnell, 2011; Kangaspunta *et al.*, 2012), healthcare capital budgeting (Kleinmuntz and Kleinmuntz, 1999; Kleinmuntz, 2007), R&D portfolio management (Golabi *et al.*, 1981; Peerenboom *et al.*, 1989; Heidenberger and Stummer, 1999; Stummer and Heidenberger, 2003), environmental planning (Peerenboom *et al.*, 1989; Bryan, 2010; Lahtinen *et al.*, 2016), public sector resource allocation (e.g., Phillips and Bana e Costa, 2007) and air traffic management (Grushka-Cockayne *et al.*, 2008). Interestingly, the seminal overviews in PDA (Salo *et al.*, 2011; Morton *et al.*, 2013) call for further research, and experiences in the recurrent use of PDA models to foster the practical usability and integration of PDA methods within organizational decision making.

Infrastructure asset management refers to monitoring, strategic planning, project selection and procurement of the construction and maintenance of (mostly public) infrastructures. This Dissertation considers transportation infrastructure, more specifically road network assets, but buildings, underground pipings and transmission networks are just a few examples of infrastructure asset networks with similar characteristics. Imposing new investments or major expansions tend to gain most public attention and news coverage, but maintenance and smaller re-investments of the existing asset base often consume a larger share of the responsible agencies' resources and have a wider reach in terms of geography and the number of individual stakeholders impacted (e.g., OECD, 2008).

Infrastructure asset management decisions are taken at roughly two main levels: (i) the network level, where the focus is on aggregate quality distributions and performance indicators of the assets and the task is to set targets and allocate resources among asset categories and main types of investments/expenditures, and (ii) program level, where the task is to select maintenance projects and actions to annual maintenance programs subject to constraints set on the higher level. The network level decisions are inherently more strategic because they address longer time horizons, consider fairly broad and fundamental objectives and involve different kinds of alternatives that contribute to the same overall objectives and compete for the same resources. The programming level decisions typically deal with tens or hundreds of concrete candidates, there is more detailed data available, and the outcomes of the decisions are clearly visible in the following year when the actual maintenance works take place (Sinha and Labi, 2011).

There is a long tradition of models and formal practices to monetarize travel time, safety and vehicle costs, among others, to enable cost/benefit analysis of transportation infrastructure investments. However, these 'driving cost' models are generally not very well applicable to maintenance (e.g, Kulkarni *et al.*, 2004); consequently systematic and transparent approaches for understanding and analyzing the inevitable trade-offs between multiple objectives have been called for in discussions with the Finnish road authorities as well as internationally (NCHRP, 2005; Krugler *et al.* 2007). Thus, transportation infrastructure asset management seems to offer a fertile domain for PDA applications.

This Dissertation develops a novel multi-criteria portfolio decision analysis methodology and reports two practical applications at the Finnish Transport Agency (FTA). One of the applications is at the strategic network level, the other at the project portfolio selection level. Responding to the call for repeated applications, the project portfolio selection model found its way to FTA's annual bridge maintenance decision making practice, and it was reused in the organization for six consecutive years. Specifically, the developed Robust Portfolio Modeling (RPM) methodology extends the use of incomplete information about criterion weights and project evaluation scores from its earlier single choice setting to portfolio problems and develops ways to convert this information into decision recommendations about individual project choices based on a comprehensive comparison of full portfolios. The RPM is also applied to *ex post* evaluation of projects in a national innovation program as well as extended methodologically to enable project interdependencies and incomplete project cost and budget information – practically motivated extensions awaiting for applications in further research.

The rest of this summary article is structured as follows: Section 2 discusses the methodological foundations of the RPM methodology development. Section 3 summarizes the contributions of the Papers [I]-[V]. Section 4 discusses the implications and generalizations of the lesson learned. Section 5 concludes and suggests avenues for further research.

2. Methodological background to project portfolio selection

Multi-Criteria Portfolio Decision Analysis (MCPDA) for project selection is a substream of the more general PDA (Salo *et al.*, 2011; Morton *et al.*, 2013). This Dissertation focuses on the linear-additive variant of portfolio value modelling without probabilistic uncertainty about the project outcomes. Thus, the basic set-up is to choose a subset of projects in the light of multiple evaluation criteria subject to the available budget and possibly other portfolio constraints. The problem is often referred to as multi-criteria *project prioritization* and approached with relatively straightforward *scoring models* accompanied with the logic to choose projects in descending order of the benefit/cost ratio until the budget is exhausted (e.g., Henriksen and Traynor, 1999; Archer and Ghasemzadeh, 1999; Cooper *et al.*, 1999; 2001; Phillips and Bana e Costa, 2007). However, this approach does not extend to multiple portfolio constraints. Linear Programming (LP), on the other hand, is a powerful standard tool that captures multiple linear constraints and has been used in capital budgeting problems for decades (see, e.g., Salo *et al.*, 2011 for an overview).

Throughout this Dissertation, the overall multi-criteria value of an individual project or other unit of analysis is modelled by an *additive value function* based on the Multi-Attribute Value Theory (MAVT; e.g., Keeney and Raiffa, 1976; French, 1986; Belton and Stewart, 2002). Assuming preferential independence of the evaluation criteria, each project's overall value is represented as a weighted sum of the project's criterion-specific scores, where the scores are possibly non-linear mappings of the measure scale to the criterion-specific value scale and the weights represent the relative importance of the criteria, more specifically, the relative value increase associated with increasing the criterion-specific performance from its worst level to its best. The additive value model provides an easy-to-understand analytical structure of the problem. Often it provides a satisfactory approximation of the preference structure, and has been employed in countless practical applications (see, e.g., overviews by Keefer *et al.*, 2004; Hämäläinen, 2004).

Golabi *et al.* (1981) derive a measurable value function for project portfolios and show that under certain preferential independence assumptions the overall value of a project *portfolio* can be expressed as the sum of the values of the projects it contains. Recently, a more general class of portfolio value functions has been developed (Liesiö, 2014), while methods and applications in this Dissertation build on the linear-additive portfolio value model. Combined with a set of linear constraints, such as the budget, the problem to maximize the multi-criteria overall value of a project portfolio (and thus to select the optimal projects) can be formulated as an Integer Linear Programming (ILP) problem in which each project-specific decision variable assumes a value 1, if the project is included in the portfolio and 0 otherwise (e.g., Stummer and Heidenberger, 2003; Bertsimas and Tsitsiklis, 1997). This formulation implicitly sets the baseline value of each project to zero, i.e., the value associated with not choosing the project – a topic that has attracted attention recently (e.g., Clemen and Smith, 2009; Morton, 2010; Liesiö and Punkka, 2014; Morton, 2015). A fundamentally similar value model is applied also in Paper [IV], although there the decision variables are continuous amounts of asset units in different classes (cf. states in Markov Chains) in each period.

The solution to the aforementioned ILP problem can be obtained with a standard MILP solver and it typically provides a unique 0/1 solution of which projects to choose and which not. However, it does not provide any insight into which projects may be "close" to entering the portfolio if the model parameters change a little or how to construct a new solution if the decision maker were to divert from the suggested solution due to external factors not captured in the formal mathematical model, for example. The model with such complete information can serve its purpose well, particularly if there is a chance to organize an interactive session with decision makers (e.g., Decision Conferencing, Phillips, 2007; Phillips and Bane e Costa, 2007) where on-the-fly computations can be carried out to support post-optimal sensitivity analyses or to test the impacts of forcing particular projects in or out of the portfolio, for example (e.g., Kleinmuntz, 2007). However, several approaches have been developed to study the *robustness* of the decision recommendations and to support the elicitation of preference statements for comparable multi-criteria decision analysis with the single choice paradigm (e.g, Salo and Hämäläinen, 2010). Thus, it seems natural to extend these approaches to portfolio models.

Preference Programming methods build on the MAVT and model *incomplete information* about the criterion weights and scores (Salo and Hämäläinen, 2010 for an overview and summary; selected early developments and recent advances, e.g., Kirkwood and Sarin, 1985; Hazen, 1986; Weber, 1987; Arbel, 1989; Rios Insua and French, 1991; Salo and Hämäläinen, 1992; 1995; 2001; Salo and Punkka, 2005; Mustajoki and Hämäläinen, 2005; Punkka and Salo, 2013; 2014). Incomplete information is modelled by imposing a set of linear constraints on the criterion weights that are consistent with the elicited preference statements. Typical statements are concerned with (possibly incomplete) rank-ordering of the importance of the criteria: for example criterion 1 is the most important one and criteria 5 and 6 are the two least important ones, i.e., among the bottom two without stating which one is ahead of the other. These statements translate into constraints that the weight of criterion 1 must be (pairwise) higher than or equal to all other weights and that the weights of criteria 5 and 6, respectively, cannot exceed any of the weights of criteria 1-4. Project scores are modelled as real-valued intervals wide enough to cover the ‘true’ values.

Dominance is a central concept in Preference Programming: an alternative is dominated, if there exists another feasible alternative that yields higher or equal overall value with all feasible weights and scores, and strictly higher with some. One can assume that a rational decision maker would not choose a dominated alternative, wherefore focus can be put on the set of *non-dominated* alternatives. *Additional information* refers to reducing the set of feasible weights and scores. Due to the linearity of Preference Programming, this additional information can only reduce the set of remaining non-dominated alternatives, thus enabling a gradual elicitation of information until a single non-dominated alternative has been found. Several decision rules have also been developed to propose *robust* alternatives whose value performs reasonably well across the feasible parameter region (e.g., Punkka and Salo, 2014).

The methodological development in this Dissertation extends Preference Programming methods to portfolio problems. With incomplete information, there is typically no unique solution to the portfolio ILP problem, but the set of non-dominated portfolios needs to be computed as basis of further analyses. The dominance relations are defined on a pairwise basis. The number of possible portfolios grows exponentially with the number of projects, wherefore the explicit enumeration of all combinations and pairwise comparisons between them is computationally intractable (e.g., Stummer and Heidenberger, 2003). Thus, the extension to portfolio problems constitutes a computational challenge that has been addressed by the field of Multi-Objective Zero-One Linear Programming (MOZOLP; Bitran, 1977; Villareal and Karwan, 1981; Kiziltan and Yucaogly, 1983). Furthermore, the possibly vast number of non-dominated portfolios, which overlap in their project composition, challenges the established processes for presenting results and guiding further analysis within the single choice paradigm where the number of alternatives is typically very limited.

3. Contributions and structure of the Dissertation

Table 1 summarizes the contributions of Papers [I] – [V]. Papers [I] and [II] present methodological developments, which establish the fundamental principles, definitions and computations of the Robust Portfolio Modeling (RPM) methodology. Papers [III] and [IV] are applications in the field of infrastructure asset management; Paper [III] focuses on project portfolio selection with the RPM methodology and Paper [IV] focuses on resource allocation at the strategic network level with a novel combination of standard Operational Research (OR) methods. In addition, Paper [III] makes a methodological contribution by presenting an approximative computational algorithm for large RPM problems. Paper [V] is an RPM application focusing on *ex post* project performance evaluation in innovation management, and it shares some structural and processual characteristics with the application in Paper [III].

More specifically, Paper [I] establishes the Robust Portfolio Modeling (RPM) methodology that extends Preference Programming methods to portfolio problems where a subset of projects is selected in view of multiple project evaluation criteria and portfolio constraints such as the available budget. The portfolio value model is linear-additive, i.e., the sum of the weighted sums of the selected projects' criterion weights and scores. The value model follows the multi-criteria project portfolio optimization model of Golabi *et al.* (1981) as well as the additive project value model applied in Preference Programming. The novelty of RPM lies in the combination, i.e., the introduction of incomplete information about the projects' scores and criterion weights into portfolio problems. Adopted from Preference Programming, the incomplete information is captured by set inclusion, which is often elicited as ordinal statements about the relative importance of the criteria and interval-valued evaluations of the project scores.

The use of incomplete information can be generically seen as a proactive or embedded global sensitivity analysis: instead of eliciting fixed input parameters for a starting point (which typically results into a unique optimum solution, followed by post-optimal sensitivity analysis around this solution parameter by parameter), the incomplete information approach begins with a broader set of feasible input parameters, advises what partial conclusions can be drawn based on such information and guides the efforts to elicit additional (more detailed) information to resolve the pending ambiguity/flexibility and make final choices between the remaining candidate projects.

Table 1. Summary of the Papers

	Research objectives	*Methodology*	*Main results*
[I]	Methodology development: Apply and extend Preference Programming principles to project portfolio selection problems.	Multi-Attribute Value Theory, incomplete weight and score information modeled via linear constraints, multi-objective multi-dimensional knapsack problem (with interval valued objective function coefficients).	Establishment of the RPM methodology; computation of non-dominated portfolios, the concept of project-specific *core index* and principles of the decision support process and robust decision recommendations.
[II]	Methodology development: Extend the RPM methodology to account for project interdependencies, incomplete cost information and variable budget levels.	RPM methodology and multi-objective zero-one linear programming (with interval-valued objective function coefficients).	More comprehensive modeling of portfolio features, budget-depended *core index*, cost/benefit analysis on portfolio level; computation of all efficient (non-dominated) portfolios to replace and extend the computation in paper [I].
[III]	Application in infrastructure asset management: Build an RPM model and repeated process to support real-life decision making in selecting projects (bridges) to annual maintenance portfolios out of hundreds of project candidates.	RPM methodology; Monte Carlo simulation and mixed integer linear programming.	Repeated RPM application adopted into operational decision making practice at the Finnish Transport Agency. Methodologically, a new approximative algorithm for computing non-dominated portfolios in large RPM problems.
[IV]	Application in infrastructure asset management: Build a multi-criteria model and facilitate senior workshops to support top level resource allocation between asset classes and maintenance or investment types.	Multi-Attribute Value Theory, linear programming, Markov chains, Monte Carlo simulation.	A model and approach to systematically structure and yield decision support to one of the main aggregate-level challenges at national transportation agencies. A novel combination of standard OR methods.
[V]	Application in innovation management: Build an RPM model to identify subsets of out- and underperforming projects in *ex post* evaluation and explore connections to *ex ante* factors to explain the performance.	RPM methodology; statistical interference.	A demonstration that the RPM can be applied generically in various contexts and decision making or portfolio evaluation settings that feature data on multiple evaluation criteria and a large set of projects or other evaluation items.

Towards this end, Paper [I] establishes several important concepts, mainly elaborated from the single choice setting in Preference Programming to the portfolio setting in RPM. The exact definitions and proofs are developed within the RPM methodology, but the concepts and the analysis logic are applicable beyond the RPM and even beyond formal mathematical models to everyday decision making and normative analysis.

In Paper [I], first, under incomplete information it is rational to search for and focus on non-dominated solutions. In RPM, the *non-dominated portfolios* are feasible combinations of projects for which there does not exist another feasible portfolio that would yield an equal or higher overall value with all feasible weights and scores. A non-dominated portfolio does not necessarily yield the highest value with any feasible parameters; for instance a portfolio that ranks second across the whole feasible region would be deemed a robust choice facing the uncertainty. Second, perhaps the most characteristic concept of RPM is the project-specific *core index*. The *core index* translates the portfolio level results to project level so that, by definition, for each project it is the share of non-dominated portfolios that contain the particular project. In particular, the *core index* is utilized to identify subsets of *core projects* that are included in all non-dominated portfolios, *exterior projects* included in none and *borderline projects* included in some, but not all non-dominated portfolios. Thus, as for decision recommendations, the core projects can be deemed as certain choices and the exterior projects can be discarded from further analysis. The third key concept in RPM is the *additional information*, and, more specifically, the insight that the elicitation of additional information can be focused only on narrowing the borderline projects' score intervals and/or giving more conclusive statements on the criterion weights. In RPM, additional information corresponds to further preference statements that reduce the feasible set of weights and scores (referred to as the information set). Paper [I] contains a proof showing that such additional information can only reduce the set of non-dominated portfolios, wherefore the (inclusion) status of the previously identified core and exterior projects cannot change and thus the focus should be eyed on the borderline projects. Paper [I] also outlines a staged decision support process, in which it is encouraged to start with broad preference statements and wide score intervals, and to gradually elicit additional information focusing on the borderline projects to converge towards a unique portfolio.

Paper [II] extends the RPM methodology to account for (i) project interdependencies, (ii) incomplete cost information and (iii) variable budget levels. It retains the key features of RPM from Paper [I], but the extensions permit more comprehensive modelling of project synergies and other mutual interdependencies as well as allow interval-valued project costs and portfolio-level cost/benefit analysis. The interdependencies, such as value synergies or mutual exclusivity, are modelled via linear constraints and in some cases with dummy projects (e.g., Stummer and Heidenberger, 2003). However, in RPM the synergy values, too, can be given as intervals and their role in the non-dominated portfolios can be analysed with the corresponding dummy projects' *core indexes* similarly to the ordinary projects. The possibility to use value intervals is relevant particularly when modeling synergies, which may often be even more uncertain than the concrete project evaluations. With the extensions developed in Paper [II] one can, for example, express that certain synergies may or may not occur by setting an interval with a zero lower bound and an optimistic scenario as an upper bound.

The issues of uncertain (i.e., incomplete) cost information and variable/flexible budget level are relevant in practical project portfolio decisions. Towards this end, Paper [II] admits interval-valued cost estimates as an input parameter and develops the concept of *efficient portfolios*, which can be seen as an extension of the non-dominated concept in the face of incomplete cost and budget information. Given an information set of feasible criterion weights, project scores and project costs, a portfolio is efficient, if no other feasible portfolio gives a higher overall value at a lower cost. The portfolio efficiency analysis yields two key results for the decision makers: First, a benefit-cost band that describes the upper and lower bound of overall value that non-dominated portfolios can assume at different levels of the total budget. A traditional counterpart to this band would be a cumulative benefit-cost curve obtained by maximising the portfolio value with fixed parameter values (complete information) and gradually increasing total budget. Second, the portfolio level results are again taken to the project level by the *core index*. However, in Paper [II], it is defined as the *budget-depended core index*, which allows an analysis of how each project's *core index* evolves as a function of the total budget. These two benefit-cost analyses results can be utilized to support the determination of both the preferred size of the portfolio and its project composition.

From the computational point of view, the extensions in Paper [II] are made possible by relaxing the non-negativity assumptions of the objective function coefficients and constraints that were vital in Paper [I]. Paper [II] develops a novel Multi-Objective Zero-One Linear Programming (MOZOLP) algorithm with interval-valued objective function coefficients for the computation of efficient portfolios in RPM. The new algorithm outperforms and replaces the one developed in Paper [I], making it the prevailing method of computing (exactly) all efficient portfolios in RPM.

Paper [III] reports an extensive application in the field of infrastructure asset management. More specifically, it develops and applies an RPM model to support bridge maintenance portfolio selection where tens of bridges out of hundreds of candidates are selected into annual rehabilitation/re-investment portfolios in view of multiple evaluation criteria and portfolio constraints. The application was developed with the Finnish Transport Agency (FTA) for five of its administrative regions, whose bridge maintenance managers used the RPM results to support their selection decisions that led to actual investments and visible maintenance actions. As an indication of the perceived added value and actual use, the model results were updated upon request annually with fresh measurement data for six consecutive years. The repeated application also gave a unique track record of structurally unchanged (updated) model data and corresponding evolution of the *core index* results. Such data allowed us to make longitudinal analysis of how the *core index* results were “followed” or not. In comparison with the broad spectrum of portfolio modeling possibilities introduced in Paper [II], the model itself in Paper [III] is rather straightforward, applying only the basic concepts of RPM. The key deliverable result was the *core index* value ranking of the bridges, accompanied with the underlying criterion scores and other measurements as raw data. Thus, rather than in the intricacies or complexity of the mathematical model, the relevance of this paper stems from the art of practical application and lessons learned in process, many of which extend to other application fields of RPM or other PDA methods.

From the model structuring point of view the key characteristics of the Paper [III] application were (i) the large problem size, i.e., ranging from nearly 200 to over 600 candidate bridges per region, (ii) the requirement to build the model on existing data and factors available in the national bridge inventory database, because it would not have been feasible to assume any new bridge-by-bridge measurements or expert judgements conducted for such a broad set of alternatives, and (iii) an early recognition of the tacit knowledge that would not be captured by the quantified factors and of the possible timing-related connections to other assets’ maintenance programs. This made it clear at the outset that the RPM model would not be used for a complete quantification of the whole decision problem, but rather to deliver a systematic approach to support multi-criteria prioritization of the large data mass at the heart of portfolio planning. Such characteristics are common in a wide range of practical PDA applications, wherefore the set-up provides a research platform from which to draw generalizable conclusions.

The findings of Paper [III] suggest that (i) the key concepts of RPM, most notably the incomplete information, non-dominated portfolios and the *core index* can be well understood and adopted by decision makers with limited experience in decision analysis, (ii) even inconclusive results – be it the *core index* listing of RPM, a partial ranking (Salo and Punkka, 2014), clustering/sorting (Zopounidis and Doumpos, 2002) or another form of indicative prioritization – can offer an attractive value-to-effort ratio and lead to a better fit with the needs and realities of organizational decision making than the aim to provide a single ‘optimal’ portfolio subject to the information available at the time of the analysis intervention, and (iii) useful RPM models can be built on limited existing data even if this data does not meet all the requirements of an ideal set of measurable attributes (see, e.g., Keeney, 1992) by involving the decision makers into the model structuring process and running at least one iteration round where the DMs can holistically assess and reflect the key results of the proposed model. Apart from paving the way towards a model that fits the prevailing decision making practices, such involvement and iteration supports buy-in even if the results include a few anomalies or exceptions that motivate decisions that divert from the recommendations of the formal model. In the repeated application, the managers learned to read the updated results in a way that best supported their decision making – the extended set of results (including complementary data on each bridge, not just the model parameters and/or blind *core index* values) played an important in this respect.

As a methodological contribution, Paper [III] develops an approximate algorithm for the computation of non-dominated portfolios in RPM. The dynamic programming algorithm developed in Paper [II] was not computationally capable for solving the problem with hundreds of projects. The new approximative algorithm is based on a weighted max-norm distance to a utopian portfolio (which has a higher overall value than any feasible portfolio for all feasible scores and weights) instead of straightforward maximization of the portfolio value, wherefore it can find also non-dominated portfolios that are not necessarily optimal with any feasible parameter combination (cf., unsupported efficient solutions in multiple objective optimization, see, e.g., Bowman, 1976; Miettinen, 1999). It is proven that all the solutions generated by the algorithm are non-dominated, but it cannot be guaranteed that all non-dominated portfolios are found – hence the notion approximative. The algorithm draws randomly generated weights for the max-norm dimensions and project scores and solves a Mixed Integer Linear Programming (MILP) problem in each round. The typical computations carried out in Paper [III] took about one hour (Dual-core, 1.8 Ghz, 1 GB memory), and consequently the algorithm is practically feasible at least for the tested 200-600 project problems, but it would not support on-the-fly computations in live workshops with the decision makers, for example.

Paper [IV] is a resource allocation application focused on a higher hierarchy/aggregation level in infrastructure asset management, i.e., the budget allocation between asset classes and types of maintenance activities. More specifically, the focus was on the overall maintenance and rehabilitation of the road network. This high level allocation is particularly challenging, because the assets and activities as well as their direct impacts and relevant time horizons are quite different – yet they serve joint fundamental objectives to secure mobility both short and long term and they compete for the same funding pool. Thus, systematic and transparent decision support has been called for (e.g., NCHRP, 2005; Krugler *et al.*, 2007). The application developed in Paper [IV] does not explicitly involve the RPM methodology, but it does combine a multi-attribute value model with incomplete preference information and a (dynamic) optimization model, analyzed in workshops with the Finnish Road Administration's senior managers to facilitate exploratory discussions about the funding levels and possible departures from the status quo. The case study was recognized as a Finalist for the INFORMS Decision Analysis Society Practice Award[1] in 2007.

Key features of the model are (i) an additive value model that spans over a quality class distribution describing the status of the particular subnetwork, i.e., the value model was built on the quality classes and the quantity of, e.g., road kilometers in each class, (ii) a Markov chain model to describe the deterioration of the quality (distribution) over time and the rehabilitating impacts of maintenance actions that were connected to the funding decisions (cf., Golabi *et al.*, 1982; Golabi and Shepard, 1997), and (iii) a Linear Programming model that ties the two together, technically by maximizing the linear-additive overall value subject to constraints that captured the deterioration-improvement dynamics and other portfolio constraints, to yield dynamic resource allocation recommendations for the funding of the different specified activities. As a proactive sensitivity analysis, incomplete information based on a partial rank-ordering of the relative importance was applied to the criterion weights, and the results were also studied in the extreme points of the feasible weight region to explore a broad spectrum of the solution space.

The key findings and contributions of Paper [IV] are (i) the model itself, which combines innovatively several standard Operations Research methods – fitted into a largely pre-set problem structure and data – to tackle a long-standing strategic challenge calling for methodological support, (ii) the case-specific strategic insights and their enthusiastic uptake by senior management, most notably the quantification and analytical backbone to many implicitly recognized issues provided in an aggregate level analysis as well as a clear highlighting of the key trade-offs faced in the allocation decisions, and (iii) similarly to Paper [III], a demonstration that the concepts of incomplete information and relatively straightforward PDA model components are well understood and accepted by decision makers with limited background in decision analysis, and (thus) even non-exhaustive models yielding only partial or indicative conclusions can be valuable in complex practical applications.

Paper [V] shifts the perspective to another context by reporting how RPM was applied to ex post analysis of an innovation program data. An RPM model was built, including a multi-criteria model span over the funded projects' *ex post* performance evaluation data and incomplete information about the criterion weights. The *core index* was utilized to identify sets of out- and underperforming projects (basically the *core* and *exterior* projects). The corresponding recorded *ex ante* characteristics of the two sets were compared and statistical interference accompanied with expert judgement by the program manager were applied to explore significant causal relationships between *ex ante* indicators and *ex post* performance to facilitate understanding and possibly support better project selection in similar programs in the future. The application

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[1] https://www.informs.org/Recognize-Excellence/Community-Prizes-and-Awards/Decision-Analysis-Society/DAS-Practice-Award - Past Awardess

shares characteristics with Papers [III] and [IV] in the sense that value model was set to be built on an existing set of data and only the criterion weights were subjected to judgement (whereby incomplete information was applied). Thus, this application fosters the notion that in practical applications the model often has to fit to the existing structure and data, which may force to compromise some of the assumptions and ideal procedures to build (value) models. As a key contribution to this Dissertation, Paper [V] demonstrates that RPM and its key concepts can be applied to *ex post* evaluation and in other contexts as well, although the determination of the out- and underperforming projects could have been conducted with other methods as well (for example, the ranking interval approach introduced by Punkka and Salo, 2014). In addition, this application fosters the observation that the concepts of incomplete information and the *core index* can be readily understood and adopted in practical applications.

4. Discussion and lessons learned

The Dissertation presents strong concepts that are widely applicable in portfolio decision analysis – and even more broadly in generic quantitative (business) analysis. In this Dissertation, incomplete information, non-dominated solutions, the *core index* and additional information have been extended/developed and successfully applied in the context of multi-criteria project portfolio selection, but their key ideas extend in different variants to other contexts as well. In general one could even ask that, if (and when) easy-to-use methods and computational tools for proactive sensitivity/robustness analysis do exist, why should any quantitative analysis be conducted with fixed parameter values and post-optimal sensitivity analysis? Experiences from the applications suggest that the approach to enter the analysis with incomplete information, guided exploration of initial results derived from the non-dominated solutions and focused elicitation of additional information, if even needed, is well understood and supported by decision makers with limited prior exposure to mathematical (decision) analysis. Taken to other business contexts, a simple Monte Carlo simulation of a cash flow model with uncertain input parameters and subsequent analysis of the NPV and IRR distributions and the most important risk factors, for example, is a generic example of applying somewhat similar concepts in a perhaps more familiar setting to many business users. The RPM methodology provides a structure to apply these universal concepts and implement the decision support process in multi-criteria project portfolio problems.

As a highlight of the RPM methodology, the concept of the *core index* is particularly suitable to project portfolio problems, because it translates portfolio-level results (set of non-dominated portfolios) to project level and steers the focus on perhaps the most boiling question in such assignments: which projects to choose and which not. More generally, the *core index* and its related decision recommendations demonstrate the philosophy to enter analysis with incomplete information and see what partial conclusions can be drawn based on it already; for example, what parts of the solution can be “locked” and what parts are affected by or dependent on the remaining uncertainty. Even if the uncertainty is not “resolved” and the analysis would not converge to a unique solution, the ability to cluster the problem to certain and uncertain parts can be highly valuable particularly in large problems – identification of the certainly “no” may be as valuable as the certainly “yes”. Furthermore, methodologically guided support to focus the efforts of acquiring additional information only on the parameters where these really matter should save time and add efficiency to the decision making process.

As for suitable application contexts for RPM and multi-criteria PDA in general, the Dissertation suggests that infrastructure asset management is quite attractive. Particularly in maintenance, project portfolio selection problems are common and recurrent. The decision makers need to consider multiple evaluation criteria and portfolio balance constraints, because the underlying transport agencies are typically not-for-profit public organizations and unambiguously accepted monetarized or otherwise unidimensional decision criteria do not exist (e.g., Kulkarni *et al.*, 2004; Krugler *et al.* 2007; Sinha and Labi, 2011; own empirical evidence from the Finnish Transportation Agency). Multi-criteria decision problems tend to be challenging and there seems to be a widespread call for systematic quantitative support in infrastructure maintenance decision making.

Large project data sets are often available in infrastructure asset management, which is one of the prerequisites for practical PDA applications. In most developed countries, the transportation agencies or asset owners perform periodic measurements and inspections of the assets, and typically there are also different kinds of significance classifications and traffic volume indicators available. Wide transportation networks can contain hundreds or even thousands of pieces of a particular asset, which form the candidates in the portfolio selection problems. In general, preferably at least tens of projects with multi-criteria data are needed to make use of the key properties of RPM and create added value to the decision making process. Such data is typically either adopted from an existing database (as in the applications in this Dissertation) or generated in a distributed manner via an internet survey, for example (Brummer *et al.*, 2008). In some cases, the project appraisal and evaluations can be carried out as a part of the participatory PDA process (e.g., Kleinmuntz, 2007; Lindstedt *et al.*, 2008), but this is a more laborious path and requires an extensive commitment and effort from the decision making organization. Arguably, problem contexts that offer existing project data have a lower hurdle to commit required resources and decision maker(s) to these kinds of novel applications. In these cases the modelling needs to adjust to the data, not the other way around. This Dissertation demonstrates that workable and practically valuable RPM applications can be built on existing data – the main prerequisite is that the data exists. A similar phenomenon is prevalent with the widespread trend of big data analysis, for example, when statistical models or other "advanced analytics" techniques seek to explore and make findings from large existing databases that were not necessarily designed and collected for such analysis purposes in the first place.

All three applications in this Dissertation motivate the conclusion that partial and indicative decision recommendations and guidelines can be valuable results of quantitative decision support models. This conclusion has been supported by feedback from the participants within client organizations. At least in infrastructure asset management, where the models have been built on existing data and exhaustive modelling of "everything" has seemed overwhelming, it has been a significant step forward to capture the reasonably straightforward data-backed parts of the problem into the formal model and to leave on purpose some relevant issues that influence the final decision making outside the model scope. This has yielded flexible results that are designed to leave room for subjective judgements in project selections, which has been much appreciated by the decision makers (instead of a rigid optimal result without guidance of how to proceed, if that one results turns out infeasible or unsatisfactory due to factors that were not incorporated into the model). One could argue that such a modelling is left half-way and fails to produce definitive conclusions, but in these applications it has been the mutually desired depth of analysis. Indeed, the RPM methodology would offer readily available tools to continue the process, but the partial/flexible results – most notably the *core index* ranking – were deemed to serve their purpose sufficiently.

It is worth noting that in addition to the applications in this Dissertation, the RPM has been applied in various other contexts as well: To support priority setting in a Scandinavian research program (Lindstedt *et al.*, 2008), screening of innovation ideas and development of research agendas in forest-based industries (Könnölä *et al.*, 2007; 2011; Brummer *et al.*, 2008; 2011), and foresight of emerging policy issues for the Bureau of European Policy Advisors (Vilkkumaa *et al.*, 2014). Reality-based illustrative case studies to demonstrate variants of the RPM have been developed at least in military applications (Kangaspunta *et al.*, 2012; Kangaspunta and Salo, 2014). It has also been argumented in the light of a literature review and typical problem characteristics that the RPM would be suitable to support environmental decision making (Lahtinen *et al.*, 2016). Moreover, independent variants of the *core index* have been developed and applied, with an explicit reference to the RPM, in influential works on European air traffic management (Grushka-Cockayne *et al.*, 2008) and Australian environmental investments (Bryan, 2010). As another example of an international "spin-off" of the RPM, the PROBE method (Lourenço *et al.*, 2012) shares the problem set-up in Paper [II] but focuses the analysis on the robustness/efficiency of specified full project portfolios and the stability of the corresponding project selection recommendations.

5. Conclusions and future research directions

The Dissertation has presented and applied in practice a novel multi-criteria portfolio decision analysis methodology, the Robust Portfolio Modeling (RPM). The fundamental concepts of the methodology are widely applicable in various practical contexts, and as a general philosophy the incomplete information based modeling and analysis approach extends even beyond the field of decision analysis. The RPM methodology offers rather sophisticated modeling, processual and computational features to capture incomplete information about criterion weights and project scores, project interdependencies, incomplete cost information and cost/benefit analysis subject to variable budget levels. The applications, however, rely on the basic concepts, which have been widely adopted and appreciated by decision makers in the infrastructure asset management sector. The application in Paper [III] found its way into repeated use as a part of the annual maintenance decision making practice at the Finnish Transport Agency, which in part highlights its practical relevance. Furthermore, a repeated application is still a relatively rare contribution in academic (decision analysis) research, and it offers a track record of longitudinal use-case data for, e.g., context-specific analysis of the actual decision making practices or to be utilized as a rich set of anonymous project test data in future methodological research (e.g., Tervonen *et al.*, 2016). The Dissertation has also fostered the view that infrastructure asset management, particularly the annual maintenance resource allocation and project selection decisions, are a fertile ground for practical applications of the RPM or similar variants of PDA.

There are several avenues for further research in both methodological development and applications. Generalization of the portfolio value modeling, allowing non-linear criterion-specific value functions on the portfolio level, for example, is an important and central topic in PDA overall. The RPM relies on a linear-additive value model, where portfolio constraints can be applied to shape the balance of the portfolio value and/or its project composition. However, such applications are not always theoretically elegant and the linear-additive structure may limit the modeling of practically relevant preferences. Seminal work has already been conducted to enable a broader spectrum of measurable multiattribute value functions in portfolio problems (Liesiö, 2014; Morton, 2015; see also Montiel and Bickel, 2014), perhaps partly inspired by the application in Paper [IV]. As a next step, the relaxed value modeling should be tested in practical application(s) to gain experiences and learn ways to adapt the sophisticated methodology to actual decision making practices and existing data. Infrastructure asset management could very well be a suitable context for such application(s).

Another avenue of methodological research would be to develop decision rules and formal process guidelines to utilize the *core index* values of the borderline projects. In this Dissertation the key project-level results are presented in the rank-ordering set by the *core index* values and these values are shown also for the borderline projects. The ordering was adopted as a basis for prioritization also among the borderline projects, although the RPM theory supports conclusive decision recommendations only for the core and exterior projects and implicitly expects additional information to narrow the set of borderline projects or to turn to the portfolio level decision rules to converge towards a unique full portfolio. The prioritization of borderline projects based on their *core index* values was viable in practice – it is a useful heuristic as discussed in Paper [III], but there is room for development and formalization. In addition, behavioral research on the use of the *core index* values in actual decision making situations would be interesting: an experimental tracking of how and why project choices are made in RPM based on the *core index* values and/or other decision support options related to additional information, with a simulated task to converge to a unique portfolio at the end of the process. The data sets generated in Paper [III] are available for such experiments.

In a somewhat similar vein, it would be interesting to see a “full scale” practical application, i.e., actual context and data with executive decision makers involved, which would deploy the advanced features of the RPM methodology and possibly even its latest extensions (e.g., Liesiö, 2014; Tervonen *et al.*, 2016). This Dissertation focuses on – and defends the practical merits of – the basic concepts and rather straightforward versions of portfolio modeling and formalized decision support process. However, to test and unleash the full potential of the advanced methodologies, the RPM/PDA community should aim at applications where (i) the multiattribute value model(s) are carefully constructed with the decision makers by applying for example the principles of the Value Focused Thinking methodology (Keeney, 1992) and the latest advances in portfolio value modeling (e.g., Liesiö, 2014; Morton, 2015) and/or (ii) elements of group decision making are involved so that the whole spectrum of the groups’ preferences is captured in the feasible weights and other parameters, and the RPM is used to facilitate negotiations to form a collectively approved project portfolio (see, e.g., Vilkkumaa *et al.*, 2014), and/or (iii) the concept of additional information is fully deployed and interactively elicited from the decision makers to conclude the process only when a unique portfolio recommendation is set (cf., e.g., decision conferencing; Phillips, 2007; Kleinmuntz, 2007).

Observed from the “market demand” perspective, there are two challenging development avenues: (i) PDA support for hierarchical resource allocation problems, and (ii) support for updating an existing portfolio or a continuous project prioritization plan to incorporate new appraisals and/or updated information. These needs are faced continuously in infrastructure asset management and in other application contexts as well. Hierarchical allocation problem refers to a setting that considers primarily the top level allocation of budgets between various asset classes and/or activities (such as Paper [IV]), but simultaneously needs to consider what is gained in return at different budget levels and which projects could be funded (application in Paper [III], methodology in Paper [II]). This Dissertation, like many other reported PDA methodologies and applications, considers both levels but not simultaneously. The combination easily leads to a large, processually, cognitively and/or computationally heavy model. However, the topic is of such high practical relevance that a workable balance between methodological rigor and pragmatic application is worth searching for.

The need to augment, cut or reshuffle an existing project portfolio stems from the fact that project portfolios are seldom built from scratch. The RPM and other PDA methods can be used to support such considerations, but technically the analysis needs to be conducted by re-computing the full portfolio problem with the updated set of project candidates, data and/or constraints. However, it would be interesting to develop and apply decision support methods with the explicit initial notion that there is a tentative portfolio as a base case and the objective is to shape its profile to some direction (e.g., value-wise, balance-wise) or to decide whether new candidate(s) would fit into the portfolio and which of the existing ones may be forced out (possibly associated with a termination cost, for example). This can also be viewed as a need to maintain a constantly up-to-date ranking of the project candidates, possibly from various perspectives separately (see, e.g., Mavrotas *et al.*, 2008), to be able to react swiftly to sudden impulses to modify the portfolio. Possible development towards using RPM or similar PDA methods more clearly for rank-ordering or clustering of projects (e.g., the sorting problematique; Roy, 1996; Zopounidis and Doumpos, 2002) could be made by building on recent research in ranking intervals (Punkka and Salo, 2014) because of the evident similarities of the inputs and purpose of the analysis.

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