Revised manuscript. 19.9.2016

Portfolio Decision Analysis Methods in Environmental Decision Making

Tuomas J. Lahtinen[a], Raimo P. Hämäläinen[a], Juuso Liesiö[b]

[a]Systems Analysis Laboratory, Department of Mathematics and Systems Analysis, Aalto University School of Science

Postal address:

Systems Analysis Laboratory, Aalto University

P.O. Box 11100, 00076 Aalto, Finland

[b]Department of Information and Service Economy, Aalto University School of Business

Postal Address:

Aalto University School of Business, Department of Information and Service Economy

P.O. Box 21220, 00076 Aalto, Finland

E-mails: tuomas.j.lahtinen@aalto.fi, raimo.hamalainen@aalto.fi, juuso.liesio@aalto.fi

Highlights

- Environmental management decisions are often portfolio problems
- Portfolio decision analysis offers new methods and tools to help solve these problems
- A comparative description of portfolio modelling approaches is provided
- A framework is developed to help the practitioner use portfolio decision analysis
- An illustrative case describes a new method enabling the use of incomplete data

Abstract

Environmental modellers recurrently work with decisions where a portfolio of actions has to be formed to effectively address the overall situation at hand. When creating the portfolio, one needs to consider multiple objectives and constraints, identify promising action candidates and examine interactions among them. The area of portfolio decision analysis deals with such tasks. This paper reviews portfolio modelling approaches and software that are applicable in environmental management. A framework for environmental portfolio decision analysis is provided that consists of steps ranging from problem framing to modelling and optimization, as well as to the analysis of results. The use of this framework is demonstrated with an illustrative case describing planning of urban water services. The problem is analyzed with a recently introduced portfolio decision analysis method called Robust Portfolio Modelling, which enables the use of incomplete preference information and consequence data. This feature can be particularly useful in environmental applications.

Keywords: Portfolio; Multi-criteria decision analysis; Environmental decision making; Resource allocation; Problem structuring; Modern portfolio theory

Software availability. Name of the software: RPM-Decisions; Requirements: Windows 7-10, Java runtime environment; Contact: http://rpm.aalto.fi

1. Introduction

Environmental management decisions are often portfolio problems where the task is to find a portfolio of actions to meet the overall objectives, targets, and constraints. For example, when the goal is to cut greenhouse gas emissions by a certain amount, the decision makers seek to identify a portfolio, i.e. a combination of actions, whose combined effects result in reaching the target reduction level. The actions can be, e.g., energy saving measures, investments in renewables, educational projects, technology development, or regulation policies. Typically, the decision makers also have to consider the overall performance of the portfolio across other relevant dimensions or criteria, such as, costs, social and political impacts, as well as environmental risks. In this paper the following terminology is used. Attributes refer to the measures used to describe the consequences of alternatives. Objectives refer to higher level goals. In the literature attributes are sometimes called criteria. This paper uses the term multi-criteria evaluation when referring to decision analysis approaches where alternatives are evaluated with respect to multiple criteria.

In practice, environmental portfolio problems are often addressed so that experts first generate a number of feasible portfolio alternatives, which are combinations of actions that satisfy the overall requirements. These alternatives are then compared by stakeholders using multi-criteria evaluation to identify the most preferred one. The quality of the resulting decision naturally depends on the experts' ability to initially construct good portfolio alternatives. This task is particularly challenging when the number of action candidates is high and there are many conflicting objectives. There can also be non-linearities or interactions across the set of actions and their consequences. If this is the case, the overall performance of a combination of actions is not necessarily the sum of the action specific performances. Surprisingly, the extensive literature on environmental multi-criteria decision making has so far given very little attention to the possibilities offered by portfolio modelling (see, e.g. Linkov and Moberg 2011, Huang et al. 2011, Gregory et al. 2012).

The current paper contributes to the literature by making the portfolio approach more easily accessible. This paper explains how the emerging area of portfolio decision analysis (PDA; Salo et al. 2011) can benefit the practitioners and researchers in environmental management and decision making. A comparative description of five major portfolio modelling approaches is given. These approaches offer modelling and optimization support to find the best portfolio of actions or the non-dominated portfolios. The final choice of portfolio should be made between the non-dominated portfolios. If a portfolio is dominated, there exists another portfolio of actions, which is better in some attribute and at least equally good in all other attributes. The model based portfolio generation process advocated here can help to consider multiple objectives and resource constraints, interactions related to the actions, as well as uncertainties. The portfolio perspective can also help mitigate the overall risk related to a set of actions (see, e.g. Keisler and Linkov 2010, van der Honert 2016).

This paper develops a general framework for environmental portfolio decision analysis which aims at providing environmental researchers and practitioners an easy entry into implementing decision processes that utilize portfolio models. The use of the framework is demonstrated with an illustrative case related to urban water service planning (Mitchell et al. 2007). The case is analysed using the recently introduced portfolio decision analysis method called Robust Portfolio Modelling (RPM; Liesiö et al., 2007), which enables the use of incomplete preference and consequence information (Salo and Hämäläinen, 1995). This possibility can be useful in environmental management problems. Perfect data about the environmental impacts of the action candidates is rarely available. The stakeholders may not want to give exact numbers to represent their opinions on the relative importance of each decision objective.

The framework described in this paper incorporates elements from both top-down and bottom-up decision support approaches (see, e.g. Montibeller et al. 2009, Linkov et al. 2014). The first phase within the framework is to describe the overall problem and goals. This represents the top-down perspective. The idea is to direct the problem solvers to reflect on the desired overall consequences. Having the big picture in mind can often help in generating new action candidates (Keeney 1992). The bottom-up perspective, in turn, is naturally present almost always in environmental problem solving processes: When a problem solving project is set up, it is often based on the existence of some already available action candidates. In addition, the stakeholders usually bring with them their own ideas of actions, which are related to their interests. One major contribution of the portfolio approach is that all action candidates can be included in the same analysis. The participants and stakeholders can easily bring their ideas and possible actions to the table. This is likely to increase the participants' commitment to the problem solving process and create a sense of shared ownership of its outcomes, which is important in environmental problem solving (Voinov et al. 2016).

So far, the main areas in the environmental management literature where portfolio modeling has been used are conservation network design and investment decisions related to the development of natural capital and ecosystem services. Conservation network design problems typically include a very high number of actions, which relate to areas of land to be included in the network (see, e.g. Ando et al. 1998, Possingham et al. 2000, Moilanen 2007, Kreitler et al. 2014). A similar setting is encountered in conservation auctions where landowners bid pieces of land to be included in conservation networks and the decision makers need to choose which pieces of land to purchase (see, e.g. Hajkowicz et al. 2007). Models related to environmental investments typically deal with the problem of choosing a set of costly improvement or restoration actions with uncertain outcomes (see, e.g. Hajkowicz et al. 2008, Higgins et al. 2008, Marinoni et al. 2009, Marinoni et al. 2011). These studies employ a variety of approaches based on multi-criteria evaluation, optimization, multi-objective optimization, benefit-cost analysis and modern portfolio theory. Yet, the opportunities to utilize portfolio approaches in environmental management problems are much wider. Many environmental multi-criteria decision making processes include an implicit portfolio generation stage in creating the alternatives. The ideas and the framework presented in this paper help to include the portfolio approach explicitly already in the initial stages of these processes.

The paper is structured as follows. Section 2 discusses behavioral issues in unaided portfolio generation. Section 3 provides an outlook on different portfolio modeling approaches. Section 4 introduces a framework for environmental portfolio decision analysis. Section 5 provides the illustrative example demonstrating both the framework and the RPM approach and software. Section 6 discusses software support for portfolio decision analysis. Section 7 summarizes our conclusions.

2. Behavioral issues in portfolio generation

Behavioral issues can easily arise when the problem solving team generates portfolio alternatives. The task is complex and there can be behavioral biases originating from, e.g., motivational, social, and cognitive phenomena (Fasolo et al. 2011). The outcome of an unaided portfolio generation process is likely to be path dependent (Lahtinen and Hämäläinen 2016, Hämäläinen and Lahtinen 2016), i.e. depend on the starting point and the order in which different actions are considered. For general discussions on behavioral issues in operations research and environmental modelling, see Hämäläinen et al. (2013) and Hämäläinen (2015).

The traditional approach (Figure 1) used in environmental portfolio problems is that the problem solving team generates portfolio alternatives to be compared against each other with multi-criteria evaluation (see, e.g., Marttunen and Hämäläinen 1995, Prato and Herath 2007, Linkov and Moberg 2011, p. 144; Gregory et al. 2012, pp. 155-171). These alternatives are typically constructed in a stepwise process where new actions are included into a portfolio following the feedback obtained from the stakeholders. The goal is to generate combinations of actions, which are non-dominated with respect to the criteria. In such processes there is a risk that there are better portfolios, which are not found and are left out of the evaluation.

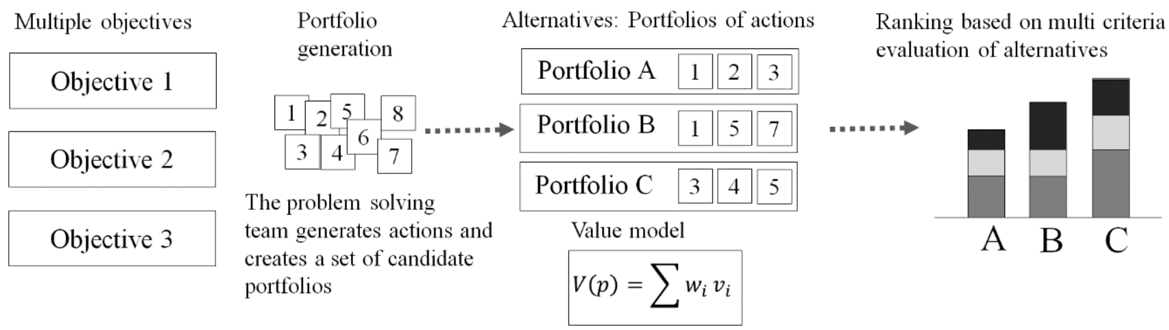

Figure 1: Traditional approach: Multi-criteria evaluation of portfolios.

Paying attention to the overall performance of each portfolio can be an overwhelming challenge in portfolio generation without modelling and optimization support. There can be many action candidates, multiple objectives, and interactions across the actions and their consequences. Interactions can relate to the effects of the actions, to their resource consumption, and give rise to constraints that prevent some of the actions to be jointly included in the same portfolio (see, e.g. Fox et al., 1984). Due to interactions, the consequences of an action can depend on other actions included in the portfolio. For instance, emissions from cars can be reduced by developing improved emission reduction technologies or by reducing the total miles driven. The effect of reducing the miles driven clearly depends on the technology available for the emission reductions in the cars. It can be very difficult to consider such interactions without computational support. For example, the well-known climate wedge game (http://cmi.princeton.edu/wedges/game.php) based on Pacala and Socolow (2004) ignores interactions. Furthermore, if actions are considered and added in the portfolio one at a time, it can happen that only those actions are selected, which score well in every attribute. Yet, it can be a mistake to discard an action which is weak in some attributes but has strong positive impact across the other attributes. The right choice can be to select such actions into the portfolio and compensate their weaknesses with some other actions.

Path dependence (Lahtinen and Hämäläinen 2016, Hämäläinen and Lahtinen 2016) can easily emerge in the stepwise portfolio generation process. How the first step is taken can influence the path followed in the process, and the outcome of the process can be path dependent. For example, after the first action is included in a portfolio, the problem solving team can myopically start looking only for synergies that this first action can benefit from and ignore other elements of the problem. The first action can be selected, e.g. based on a ‘champion’ argument (Fasolo et al. 2011). Champion actions with wide support from the participants of the process can easily be included in a portfolio without trying to create a portfolio without them. There is a risk that a champion action does not perform well together with the other actions. Including it in the portfolio of actions does not necessarily lead to a non-dominated portfolio.

When portfolio modelling is used, all action candidates are included simultaneously in the same optimization model which generates the non-dominated portfolios. This can mitigate the risk of path dependence and biases.

3. Modeling portfolio decisions

This section describes five portfolio modelling approaches, which help identify a portfolio of actions (Figures 2 and 5), or a set of non-dominated portfolios (Figures 4 and 6), to best meet multiple objectives while satisfying the problem constraints. The goal can also be to find the efficient resource allocations (Figure 3). Heuristic model based portfolio generation approaches are also discussed in this section. An illustrative list of environmental applications of these approaches is given in Table 1.

The roots of portfolio decision models go back to the work of Markowitz (1952) on risk diversification in financial investments. The mean-variance model of Markowitz and the capital asset pricing model by Sharpe (1964) support investment decisions related to purchasing financial assets with uncertain future returns. In another strand of research, capital budgeting methods were developed to support comparison of projects based on net present value and other economic attributes (Lorie and Savage, 1955). Later, a variety of approaches also incorporating non-economic objectives, group decision making, and an array of optimization methods have been developed to support project portfolio selection (see, e.g. Heidenberger and Stummer, 1999, Salo et al. 2011).

The value-cost approach (Figure 2), also called value-to-cost, or benefit-cost approach, is a simple portfolio generation method (see, e.g., Kleinmuntz 2007, Phillips and Bana e Costa 2007) where multi-criteria evaluation of the actions is first performed and their costs are estimated. Actions are then selected into the portfolio in a descending order of their value-cost ratios until the budget limit is reached. If there are no synergies or interactions between the actions, the resulting portfolio of actions provides the optimal use of the resources spent.

Otherwise, optimality is not guaranteed. This approach is often not sufficient in environmental problems where interactions can play a major role.

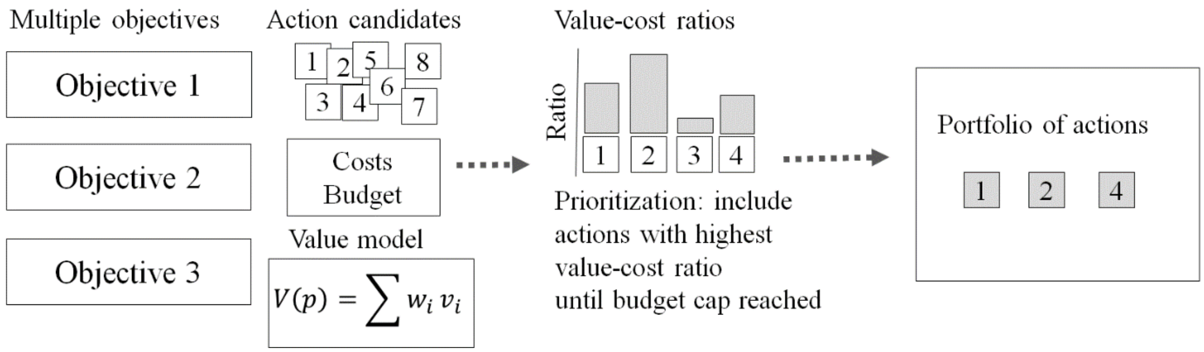

Figure 2: Value-cost approach: Prioritize actions according to value-cost ratio.

The modern portfolio theory approach (Figure 3) helps forming a portfolio when the goal is to find a balance between expected benefits and risks. Benefits can be measured with an aggregate score based on multiple objectives. Risk is typically quantified as the variance of the benefit score. The decision problem is to choose the level of resources spent on each action. The outcome of the analysis is an efficient frontier showing the maximum possible expected benefit with each risk level. Each point on the frontier corresponds to one efficient allocation of resources to the actions. In environmental applications, the computation of expected benefits and risks is typically based on scenarios related to, e.g., future climate (see, e.g. Marinoni et al. 2011, Paydar and Qureshi 2012).

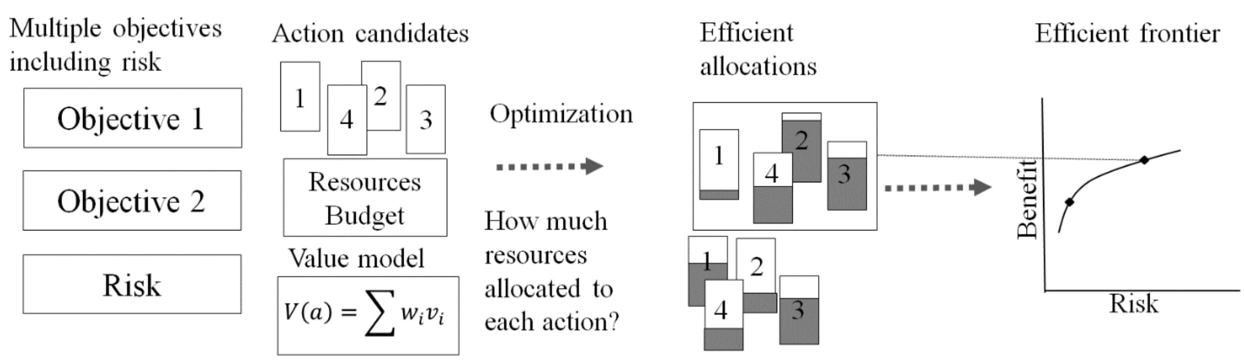

Figure 3: Modern portfolio theory approach: Identify the optimal resource allocation for each risk level.

In the multi-objective optimization (MOO) approach (Figure 4) the goal is to identify non-dominated portfolios. Interactions among the actions and portfolio constraints can be considered. A multi-objective optimization problem is formulated and solved to find the feasible non-dominated portfolios of actions. The performance profiles of these portfolios can be visualized in different ways, e.g. by 2D scatterplots, which help the decision makers choose the most preferred portfolio from the set of non-dominated portfolios (see, e.g. Stummer et al. 2009). In interactive MOO approaches only a subset of all non-dominated solutions is solved and displayed to the decision makers at once. This set of portfolios is iteratively updated in response to preference information given by the decision makers until they are satisfied with the solutions obtained (see, e.g. Korhonen 1988, Stummer and Heidenberger 2003, Alves and Clímaco 2007).

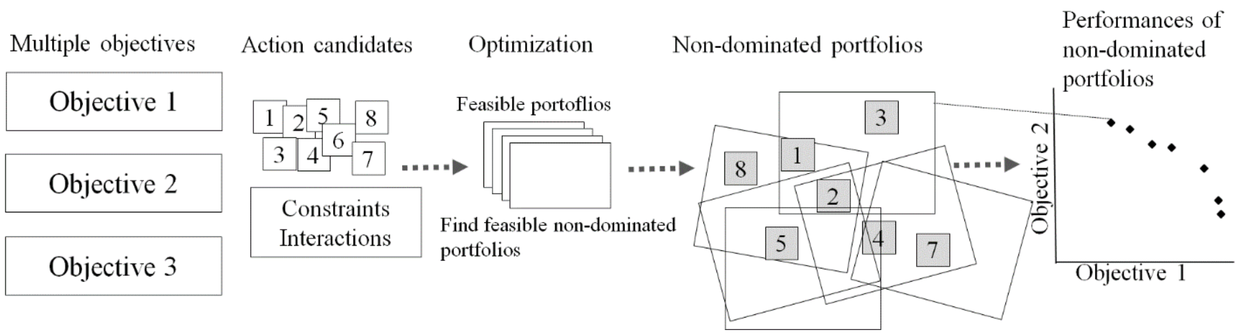

Figure 4: Multi-objective optimization approach: Identify the non-dominated portfolios.

The portfolio decision analysis approach (Figure 5) combines multi-criteria evaluation and mathematical optimization. The basic goal is to form one portfolio of actions out of a set of action candidates while taking into account multiple objectives, interactions, and resource constraints. The decision makers' preferences regarding the objectives are captured with a multi-attribute value function. Integer optimization is used to find the feasible portfolio with the greatest overall value. Interactive 'what-if' analyses can be performed to see how the optimal portfolio of actions changes in response to changes in model parameters or constraints. For instance, the decision makers can be interested in comparing the optimal portfolios that are obtained when different budget limits are used.

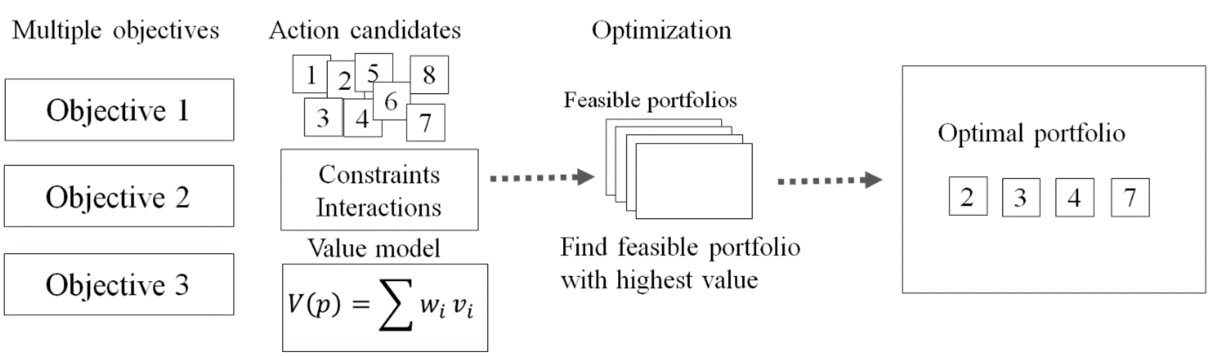

Figure 5: Portfolio decision analysis approach: Find the optimal portfolio.

Portfolio decision analysis with incomplete information (Figure 6) admits the use of intervals to describe the consequences. Ordinal preference statements can also be used regarding the preference weights in the value model (Salo and Hämäläinen 1995, Liesiö et al., 2007). A stakeholder can state, for example, that the reduction of one ton in annual nitrogen emissions is more important than the reduction of two tons in annual phosphorus emissions without specifying the precise trade-off ratio. Optimization is used to identify the non-dominated portfolios of actions with regard to the incomplete information given. A portfolio dominates another if it is better with some combination of possible weights and consequences, and at least equally good with all other combinations (Liesiö et al., 2007). Stricter preference statements typically result in a lower number of non-dominated portfolios. The number of non-dominated portfolios usually remains much smaller than with the multi-objective optimization approach, because the multi-objective optimization models do not utilize any preference information. If the decision makers cannot make a choice between the non-dominated portfolios, one option is to obtain more precise information and solve the model again.

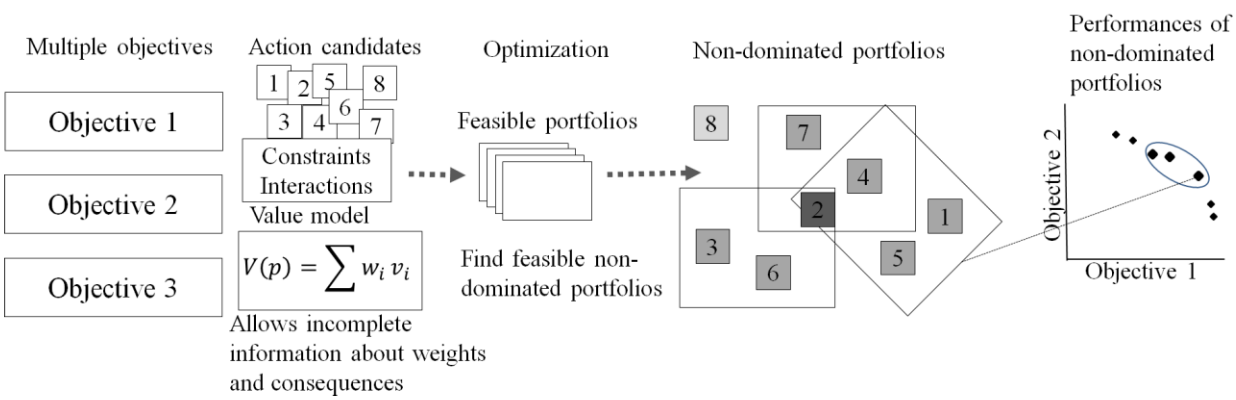

Figure 6: Portfolio decision analysis with incomplete information: Identify the non-dominated portfolios.

In heuristic approaches a heuristic solution procedure is followed instead of using optimization to find the portfolio of actions with the highest overall value. In these approaches the goal is to find a feasible portfolio with an overall performance which is considered satisfactory. The Zonation method by Moilanen (2007) is one such approach developed to support the choice of land areas to be included in a conservation network. The solution procedure in Zonation starts with the situation where all land areas are included in the network. Land areas are then repeatedly removed from the network until a feasible and satisfactory solution is found. Different rules can be used to select the land area to be removed at each iteration. One possibility is to remove the land area whose removal reduces the overall environmental value the least relative to the cost of the area.

Possingham et al. (2000) describe another procedure to form a conservation network. The idea is to find the minimal set of land areas, which satisfies the constraint that all species must be represented within the total area. This task can be formulated as an integer optimization problem.

The method by Kurttila et al. (2009) uses incomplete preference information in the development of forest management plans. The plans specify the action to be taken at each forest stand. The actions differ with respect to the timing and the extent of cutting. In this method, one first solves a set of management plans which are optimal for some plausible preference parameters. The decision makers then analyze these plans and fix the actions for some of the forest stands. After this, they repeatedly re-analyze the situation and fix the actions for more forest stands until the final management plan is formed.

Table 1: Illustrative papers on environmental portfolio problems.

Approach	Problem	Examples of attributes	Solution method
Value-cost			
Marinoni et al. (2011), case 1	Improving sites in a river catchment	Pollutant reduction, rehabilitation, recreational effect, site access	Value-cost based prioritization
Hajkowicz et al. (2008)	Enhancing water quality	Nitrogen reduction, phosphorus reduction, strategic benefits	Value-cost based prioritization with heuristic procedure to find improved solutions
Portfolio Decision Analysis (PDA)			
Kreitler et al. (2014)	Agricultural land conservation	Agricultural viability, conservation priority, flood liability	Integer optimization
Convertino and Valverde Jr (2013)	Restoration planning in coastal areas	Habitat quality and species richness	Integer optimization
Multi-objective optimization (MOO)			
Zheng and Hobbs (2013)	Removals of dams	Effect to fish populations, public safety, cost	Multiple objective integer optimization
Higgins et al. (2008)	Improving landscapes	Biodiversity, water run-off, carbon sequestration	Heuristic multiple objective integer optimization
Modern Portfolio Theory (MPT)			
Paydar and Qureshi (2012)	Irrigation related investments under climate uncertainty	Monetary expected value and variance calculated with climate change scenarios	Monte Carlo simulation
Marinoni et al. (2011), case 2	Investments in river catchment sites	Expected multi-criteria benefit and variance	Monte Carlo simulation

		calculated with climate change scenarios	
Crowe and Parker (2008)	Forest restoration under climate uncertainty	Adaptation score and variation of the score under climate scenarios	Quadratic programming
Heuristic			
Kurttila et al. (2009)	Developing forest management plans	Monetary net present value, saw log volume, cutting removal	Heuristic routine combined with heuristic integer optimization
Moilanen (2007)	Conservation network design	Number of animals within the area, connectivity, costs	Heuristic routine similar to the gradient descent method
Possingham et al. (2000)	Forming a representative conservation network	Number of species within the network, number of sites selected	Heuristic integer optimization

4. A framework for environmental portfolio decision analysis

The framework outlined in Table 2 contains the most important steps and tasks that the portfolio decision analysis process includes. It is not always necessary to implement every step of the framework. Depending on the application, some information may be available from the outset and some model elements may not be needed. Although the steps of the framework are presented in a sequential order, this does not rule out the possibility of iterating between the steps.

Table 2: A portfolio decision analysis framework for environmental decision making

Steps	Tasks
1. Problem framing	Determine context and scope Specify initial resource constraints and performance targets Identify stakeholders Design the participation and analysis process
2. Objectives and actions	Generate the initial set of objectives and actions Use objectives to generate additional actions Use actions to identify missing objectives Screen and specify the objectives, constraints, and actions Specify attributes and measurement scales
3. Interactions and overall consequences	Identify interactions between the actions Specify constraints related to the interactions

	Specify models for calculating the overall consequences Collect data and estimate the consequences of actions
4. Value model	Determine the forms of the value functions on the attributes Elicit weights for the attributes
5. Computation and analysis of results	Find optimal or non-dominated portfolios of actions Perform what-if analyses Communicate and visualize results Compare results between stakeholder groups

4.1. Step 1: Problem framing

Framing the problem is an essential phase in environmental problem solving in general (see, e.g. Bardwell 1991, Gregory et al. 2012). The frame guides all the subsequent problem solving steps and helps the problem solving team focus their thinking.

Context refers to the system or systems where improvements or solutions are sought. Scope directs the attention of the problem solving team to specific issues and concerns within the context. One possibility is to specify what types of solutions are looked for. Consider, for example, the context of managing water resources in a river basin. The problem solving team could focus only on the operation of the hydro power plants to control the water level, or consider also other factors, such as nutrients produced by the agriculture, or the possibility to invest in water treatment facilities. Broader context and scope generally leave more possibilities for creativity and overall optimization (see, e.g. Evans 1989). For instance, it is less expensive to tackle global problems related to energy, air-pollution and global warming simultaneously rather than addressing each problem separately (McCollum et al., 2013). Yet, taking a broader frame cannot always be advocated since it can make the problem too difficult to analyze. The breadth of topics that can be considered in the analysis depends on the time and modelling resources available for the project.

In environmental decision problems, the performance targets and resource constraints can stem from regulatory standards, aspirations of policy makers, or budgetary reasons, for instance. Resource constraints limit the amount of money, energy or other resources that can be consumed by the chosen portfolio of actions. A performance target specifies a level of performance that has to be achieved by the portfolio. Such targets typically relate to specific attributes such as emission reductions. The constraints or targets can be negotiable, for example, if relaxing a constraint enables to form a portfolio with significantly improved overall performance.

Before proceeding to the generation of objectives and actions, the stakeholder participation process should be planned. Facilitation and stakeholder engagement are important for the overall success of decision analysis and model based problem solving processes in general (Franco and Montibeller 2010, Voinov and Bousquet 2010, Voinov et al. 2016). Phillips and Bana e Costa (2007) describe ways in which stakeholders can be engaged in a portfolio decision analysis process. They find strongly engaged stakeholders to be more committed to implementing the results of the analysis. Many of the tools and principles followed in standard decision analysis are applicable also in portfolio decision analysis. Examples are the decision structuring dialogue (Slotte and Hämäläinen 2015), decision analysis interviews (Marttunen and Hämäläinen, 2008), decision conferences (Phillips and Bana e Costa, 2007), tools for public engagement (Hämäläinen et al. 2010), and the structured decision making framework by Gregory et al. (2012).

4.2. Step 2: Objectives and actions

In the iterative process of defining the objectives and generating the actions, the objectives guide the search for promising action candidates, and the actions can help identify missing objectives (Keeney 1992). The objectives can refer to any tangible and intangible concerns, goals, and aims related to the problem. In the portfolio optimization model, these can be included in the value function, as performance targets, or as constraints. The goal is to generate concrete and well specified objectives, constraints, and actions. At first, all stakeholders and participants in the process should be allowed to bring their ideas on the table. Unnecessary constraints should be discarded because this can enable forming a better portfolio. Initially suggested objectives can be discarded if they are of negligible importance. If basically the same action or objective is suggested multiple times in slightly different forms, these can be merged into one. An action can be discarded if it individually violates the constraints or does not sufficiently contribute to reaching the objectives.

The idea that people generate better actions when given a list of objectives as a stimulus has been suggested by Keeney (1992). Recently this claim has gained experimental support (Selart and Johansen 2011, Siebert and Keeney 2015). Gregory et al. (2012) and Gregory and Keeney (1994) describe how to use objectives to generate alternatives in participatory environmental problem solving.

Attributes are the measures to describe the consequences of alternatives. Ideally, the set of attributes is comprehensive and non-redundant. When possible, the attributes should use quantitative natural measurement units, which are directly linked to the fundamental objectives of the decision (Keeney and Gregory, 2005). Such a measurement unit could be, for example, the number of organisms belonging to a particular rare species within a conservation area. It is also possible to use a proxy attribute or develop a constructed scale (Keeney and Gregory, 2005). When developing the list of attributes one should pay attention to the behavioral splitting bias phenomenon. It refers to the situation where people give more weight to an attribute if it is split into multiple more detailed attributes (Pöyhönen et al., 2001, Hämäläinen and Alaja 2008). Therefore, one should avoid going into too much detail in the development of attributes.

4.3. Step 3: Interactions and overall consequences

An essential contribution of creating and solving a portfolio model is that the interactions and synergies related to the actions will be taken into account. These interactions and synergies can relate to the effects of the actions, and to the way they use the available resources. Interactions can also impose constraints on the actions that can be in the same portfolio (Fox et al., 1984).

Mutual exclusivity constraints can arise from technical or physical restrictions, for instance. Actions are mutually exclusive if only one of them can be selected into the portfolio. There can also be ‘follow-up’ actions which can be selected only together with its prerequisite action. Technically, it is straightforward to incorporate exclusivity or follow-up constraints in the portfolio optimization model (see, e.g. Kleinmuntz, 2007).

The analysts should tell apart attributes in which the overall consequence of a portfolio of actions can be obtained by summing up the consequences of individual actions, and attributes in which the overall consequence of a portfolio results non-linearly from the consequences of the actions that are selected. For example, there can be a ‘one-shot’ effect related to a group of actions. The effect takes place if at least one of the actions is implemented. Such effect could be due to a common initialization effort or a physical equipment that has a fixed cost irrespective of how many actions share it (Keisler 2005). Technically, a one-shot effect can be modeled as a dummy action that is forced into the portfolio if the condition for the effect to take place is met (see, e.g. Stummer and Heidenberger 2003).

In some applications there are attributes in which a known non-linear formula captures how the overall consequence of a portfolio of actions results from the consequences of the individual actions. For example, a multiplicative formula can be appropriate when there are several actions causing percentage improvements in the performance of a system (see, e.g. Grushka-Cockayne et al., 2008). Other techniques to model interactions and synergies are discussed, for example, in Dickinson et al. (2001) and Toppila et al. (2011).

Furthermore, there is always the option to estimate the possible overall consequences related to a small group of actions by separately considering all combinations of these actions. If the number of combinations is too large, the analysts can first try run a lighter process with experts to identify the most promising combinations and subsequently only consider these. Technically, the different combinations of actions can be inserted in the portfolio optimization model as distinct mutually exclusive actions.

4.4. Step 4: Value model

A standard value function can be used to obtain the overall scores of portfolios of actions once their overall consequences can be calculated in all attributes. The additive multi-attribute value function is practical and the most widely used value model. It gives the overall score of a portfolio as the weighted sum of the attribute-specific scores of the portfolio. Elicitation of the additive value function consist of two parts. The first part is to specify the attribute-specific value functions that map the portfolio level measurement scales of attributes (e.g. CO_2 reduction in tons) to attribute-specific scores. The shape of such function can capture, for instance, decreasing marginal value on an attribute. The second part is to assess the attribute importance weights, which determine the relative increases in the overall score resulting from unit improvements in the attribute-specific scores.

A rich literature exists on the methods to construct the attribute specific value functions and to assess the weights (see, e.g., von Winterfeldt and Edwards, 1986). Montibeller and Winterfeldt (2015) discuss a number of cognitive and motivational phenomena that can distort the construction of the additive value function. One example, is the range insensitivity phenomenon (von Nitzsch and Weber, 1993). It refers to the tendency to give too low weights for attributes with wide range. In response, one of the recommendations by Montibeller and Winterfeldt (2015) is to use a weighting protocol such as SWING (von Winterfeldt and Edwards, 1986) which explicitly considers the whole range of each attribute. Use of multiple methods to assess the weights can also be a good idea. If the results are sensitive to the methods used, then one should try to understand why. Obtaining similar weights with different methods can increase confidence in the results.

Incomplete information about the weights can also be used (Salo and Hämäläinen, 1995). For instance, rather than using precise weights $w_1 = 0.7$ and $w_2 = 0.3$ for attributes 'CO_2 reduction' and 'Societal impact', robust value models can capture the statement 'change from the worst level to the best level in attribute CO_2 reduction is at least as important as a similar change in attribute Societal impact' by considering all weights satisfying the constraint $w_1 \geq w_2$. With incomplete information one can try to find decision recommendations that stay the same with all weights within the boundaries given. For example, if portfolio A is worse than portfolio B with all possible weights, then it can be recommended that A should not be selected (Liesiö et al., 2007).

There are several examples in the literature which follow a value modelling approach that differs from the approach described above. In these examples, the additive value function is first developed for individual actions. Portfolio overall scores are then obtained by aggregating the action specific scores (see, e.g. Golabi et al., 1981, Liesiö, 2014, Morton et al., 2016).

4.5. Step 5: Computation and analysis of results

The computations and analyses of results are often intertwined. Analysing some results produced by the model can raise questions that call for more analyses, which are based on different parameter values or an updated model. The basic computational task is to use integer optimization algorithms to find the portfolio of actions, which maximizes the portfolio value function subject to constraints on the portfolio composition. With modern computers this task often takes only a few seconds in problems with up to hundreds of action candidates and an additive portfolio value function.

In the interactive use of the model, the decision makers and stakeholders can be interested in various 'what-if' analyses. These include finding how the optimal portfolio of actions changes; if resource constraints or performance targets are changed, if an action is forced in the portfolio, and if weights or other model parameters are changed.

Sensitivity to a resource constraint can be studied by solving the optimal portfolio of actions with different limits on the resource expenditure. Such analysis can reveal, for example, whether an additional expenditure could result in a significant increase in the overall value. Results of the analysis can be visualized by displaying the overall scores of the optimal portfolios as a function of the budget limit. In the same way the analysts can study what happens if a performance target is relaxed in some attribute. This may enable to form a portfolio with a higher overall score or less cost.

The stakeholders may want to find out how the composition and the performance of the optimal portfolio change if a certain action is forced into the portfolio (see, e.g. Phillips and Bana e Costa 2007). For example, stakeholders could bring up a new perspective that justifies selecting an action, which was not part of the original optimized portfolio. It can be interesting to calculate the difference in overall value between the new modified portfolio and the original one. This value difference can be informally weighed against the new perspective given. Based on such comparison, the problem solving team may choose to keep or not keep the forced-in action in the portfolio, or revise the model to incorporate the new perspective given. Revising the model may require the development of a new attribute, for instance.

When visualizing optimization results, the analysts typically wish to communicate both the composition of the optimal portfolio of actions, as well as its performance in each attribute. The visualization task is more challenging when the compositions or performance profiles of multiple portfolios need to be depicted in a single graph. The parallel coordinates plot and the heat map are two options for displaying the performance profiles. The experimental research by Kiesling et al. (2011) suggests the parallel coordinates graph to be the better alternative out of these two.

When incomplete information is used, there are typically many non-dominated portfolios. Core index (CI) is a metric to communicate information about the compositions of the non-dominated portfolios (Liesiö et al., 2007). For each action, the core index is the share of non-dominated portfolios that include this action. Core index can serve as a basis for recommendations about which actions to select in the final portfolio. The core indexes of actions with CI of 0% or 100% cannot change in response to obtaining more precise preference information, if the overall consequences of each portfolio are obtained by summing up the consequences of individual actions, and the portfolio value function is linear. Then one can be recommended to choose core actions (core index 100%) and reject exterior actions (core index of 0%). Further attention should be focused to choosing between borderline actions with CI strictly between 0% and 100%. Based on applications, visualizing core indices using bar charts seems to be an intuitive way to communicate the effects of incomplete information to decision makers. Heat maps can be used to visualize the core indices of actions as a function of the budget limit.

In group decision making settings it can be interesting to compare the optimal portfolios of actions that are obtained with weights given by different stakeholder groups. This can serve as the basis for negotiation. One possibility is to look for actions that are in the optimal portfolio of every stakeholder group, and for actions that are not included in the optimal portfolio for any group (Vilkkumaa et al. 2014).

5. An illustrative example with Robust Portfolio Modeling

This illustration concretizes the tasks and concepts related to each step of the framework outlined in the previous section. Since the example is fictitious, it focuses on the modeling and analysis steps. The example case is adopted from Mitchell et al. (2007). It is analyzed using the RPM-Decisions software, which supports the use of incomplete information in portfolio decision analysis. Although incomplete information is used, the example should be instructive also for those practitioners who wish to use a standard portfolio decision analysis approach with crisp data.

5.1. Problem framing

The city of Bass has decided to have a new development constructed in the Bridgewater region near the metropolitan area of Bass. This will increase the demand of water services in the area. The core services include supplying water to households and for irrigation. Due to scarcity of existing sources of water, the city searches for means to cut the water demand of the new development. The city has allocated a budget of 45 million Australian dollars to implement a portfolio of actions with the target of cutting the water demand of the new development to half when compared to similar developments constructed earlier.

5.2. Objectives and actions

The problem solving team identifies three other objectives in addition to the goals stated in the problem definition. These are the long-term financial effects, climate change related impacts, and effects to the local water system. Nine action candidates are developed (Table 3).

Together with environmental and financial experts the problem solving team defines six attributes and corresponding measurement units which are given in Table 4. Effects to the local water system are captured by reductions in phosphorus and nitrogen releases ($i = 1, 2$). Natural scales can be used for these attributes, as well as for implementation costs ($i = 5$) and reductions in water demand ($i = 6$). For climate change impacts ($i = 3$) the problem solving team develops a constructed scale where the score of 0 refers to no impact and 1 refers to the positive impacts of a certain reference action. The other actions are evaluated in comparison with these scores. For example, an action which has twice larger positive impacts than the reference action is given the score of 2. An action with negative impacts of equal magnitude as the reference action's impacts is given the score of -1. For long-run savings (i = 4) the experts develop a scale based on the concept of net present value.

Table 3: Action candidates

j	Description
1	Toilets with reduced water consumption
2	Showers and faucets with reduced water consumption
3	Washing machines with reduced water consumption
4	Raintanks for toilet and garden water use (3 kiloliters)
5	Improving action 4 with extra capacity of 1.5 kiloliters
6	Raintanks for residential hot water (3 kiloliters)
7	Small scale recycling for irrigation
8	Aquifer usage for irrigation of public open space
9	Dual reticulation system for recycling water

Table 4: Attributes

i	Attribute	Abbreviation	Measurement unit
1	Reduction in phosphorus release	Phosphorus	Tonnes per year
2	Reduction in nitrogen release	Nitrogen	Tonnes per year
3	Climate change impacts	Climate	Score based on expert assessment
4	Long-run savings	Savings	Millions of dollars (net present value)
5	Implementation costs	Cost	Millions of dollars
6	Reduction in water demand	Water	Percentage reduction

5.3. Interactions and overall consequences

Table 5: Constraints

Constraint	Description
Follow-up action	Action #5 can be included only if action #4 is included
Mutual exclusivity A	Actions #4 and #6 cannot be included in the same portfolio
Mutual exclusivity B	Actions #7 and #8 cannot be included in the same portfolio
Mutual exclusivity C	Actions #7 and #9 cannot be included in the same portfolio
Budget constraint	Overall implementation cost must be less than 45M$
Water demand target	Overall water demand reduction must be greater than 50%

The problem solving team identifies four interactions that impose constraints on the choice of actions (Table 5). The follow-up action constraint is specified to account for the fact that action #4 consists of installing tanks for collection of rainwater whereas action #5 consists of installing extra capacity to these tanks. Three mutual exclusivity constraints are defined. Mutual exclusivity A is defined because in most buildings it is technically too difficult to construct two separate rain tanks (actions #4, 6) on the roof and connect them to the piping of the building. Mutual exclusivity constraint B is created because actions #7 and #8 are both related to irrigation and implementing both of them would be redundant. Mutual exclusivity constraint C is specified because both actions #7 and #9 are based on the recycling of waste water. Implementing both of these actions would make the piping system of the development too complicated and therefore significantly increase the risk of failure. The list of constraints (Table 5) also includes the budget constraint and the target for water demand reduction.

The overall water demand reduction ($i = 6$) of a portfolio is obtained with a multiplicative function over the action specific reductions. For example, implementing either action 8 or 9 alone would reduce the water demand by 34% or 46%, respectively. Implementing both of them would reduce the water demand by $(1 - 0.66 \cdot 0.54) \cdot 100\% = 64\%$. In the rest of the attributes ($i = 1, 2, 3, 4, 5$), the overall consequence of a portfolio is obtained by summing up the consequences of the actions included in the portfolio.

The problem solving team obtains estimates of the attribute specific consequences of the actions (Table 6). Point estimates are used in the attributes related to implementation costs and water demand reductions ($i = 5, 6$). The estimates are conservative to reduce the risk of exceeding the budget or failing to reach the target for reductions in water demand. To capture uncertainty about the actions' effects in the rest of the attributes ($i = 1, 2, 3, 4$), lower and upper bound estimates are obtained for each attribute specific consequence that is expected to differ from zero. In the attributes related to phosphorus, nitrogen and long-run savings ($i = 1, 2, 4$) experts believe the consequences to fall within the bounds with a probability of 80%. The climate change impact ($i = 3$) related bounds are obtained simply by taking experts' best estimates and adding ±0.5 units to them.

Table 6: Estimated consequences of actions. The numbers inside brackets correspond to lower and upper bound estimates respectively.

j	Phosphorus	Nitrogen	Climate	Savings	Cost	Water
1	[0.9, 1.1]	[0.09, 0.11]	[0, 0]	[1.8, 2.2]	1	3%
2	[1.1, 1.3]	[0.09, 0.11]	[0, 0]	[1.8, 2.2]	1	7%
3	[1.3, 1.7]	[0.14, 0.17]	[0.5, 1.5]	[1.8, 2.2]	2	4%
4	[0, 0]	[0, 0]	[-1.5, -0.5]	[1.8, 2.2]	10	15%
5	[0, 0]	[0, 0]	[0, 0]	[0.9, 1.1]	8	10%
6	[0, 0]	[0, 0]	[0.5, 1.5]	[9, 11]	11	38%
7	[0.50, 0.60]	[0, 0]	[0, 0]	[32, 40]	43	15%

8	[0, 0]	[0, 0]	[0, 0]	[14, 18]	23	34%
9	[4.0, 4.8]	[0.40, 0.48]	[-2.5, -1.5]	[3.5, 4.5]	20	46%

5.4. Value model

The problem solving team together with the city representatives decide to include attributes 1 – 4 in the value model. They use the additive value function to model portfolio overall value. This is justified because they consider the attributes to be independent in such a way that the increase in the portfolio value due to an improvement in one attribute does not depend on the performance of the portfolio in the other attributes. Moreover, they find linear single attribute value functions to be appropriate. The reason is that the ranges of possible attribute 1 – 4 related effects of this decision are not large relative to the aggregate effect of all other attribute 1 – 4 related environmental and economic impacts that take place in the area.

To model the portfolio optimization problem, a decision variable $z = (z^1, \dots, z^9)$ is used, where z^j is 1 if the action j is included in the portfolio and 0 if it is not included. The overall consequence of the portfolio in attributes i = 1, 2, 3, 4 is given by $\sum_{j=1}^{9} x_i^j z^j$, where x_i^j refers to the consequence of action j in attribute i. The value of portfolio *z* is given by

$$V(z) = \sum_{i=1}^{4} w_i \sum_{j=1}^{9} x_i^j z^j, \quad (1)$$

where w_i is the weight of the attribute *i*. The weights are scaled such that they sum to one. Initially, no preference information is used regarding the weights besides requiring each of them to exceed 0.01. Additional information can be obtained during the analysis phase.

5.5. Computation and analysis of results

The portfolios of actions are compared with each other based on the concept of dominance because incomplete information about weights and consequences is used. The portfolio z dominates the portfolio z', if z has greater overall value with some weights and action specific consequences, and has at least as high overall value as z' with all possible combinations of weights and action specific consequences. Non-dominated portfolios are solved with the RPM-Decisions software. Figure 7 shows a screenshot of the input data in this software.

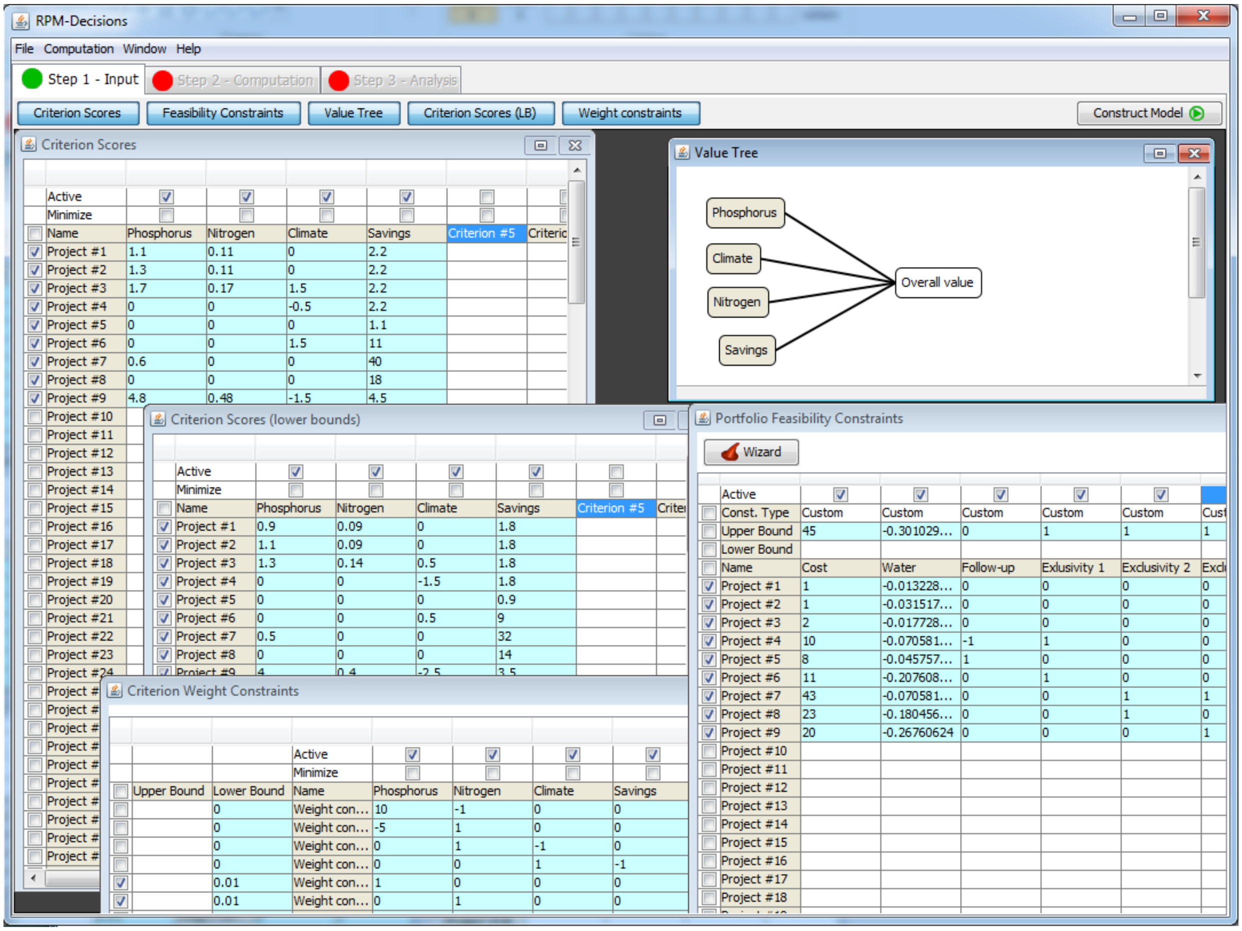

Figure 7: Screenshot of input data in the RPM-Decisions software.

Four non-dominated portfolios of actions are found when no preference information regarding weights is used and action specific consequences are within the bounds given in Table 6. Table 7 shows these portfolios and the core indices of the actions. Actions #1, 2, 3, 8 and #9 are in three out of the four non-dominated portfolios and action #6 is in two. Actions #4, 5 and #7 are not in any of the non-dominated portfolios. Figure 8 shows the ranges of overall consequences of the non-dominated portfolios in the attributes 1 – 4. One can see, for example, that portfolio B has the highest long-run savings and climate change score but rates the worst in nitrogen and phosphorus reductions.

Table 7: The non-dominated portfolios.

Action	Portfolio A	Portfolio B	Portfolio C	Portfolio D	Core index
#1	included	included	included	not	3/4
#2	included	included	included	not	3/4
#3	included	included	not	included	3/4
#4	not	not	not	not	0/4
#5	not	not	not	not	0/4

#6	included	included	not	not	2/4
#7	not	not	not	not	0/4
#8	not	included	included	included	3/4
#9	included	not	included	included	3/4

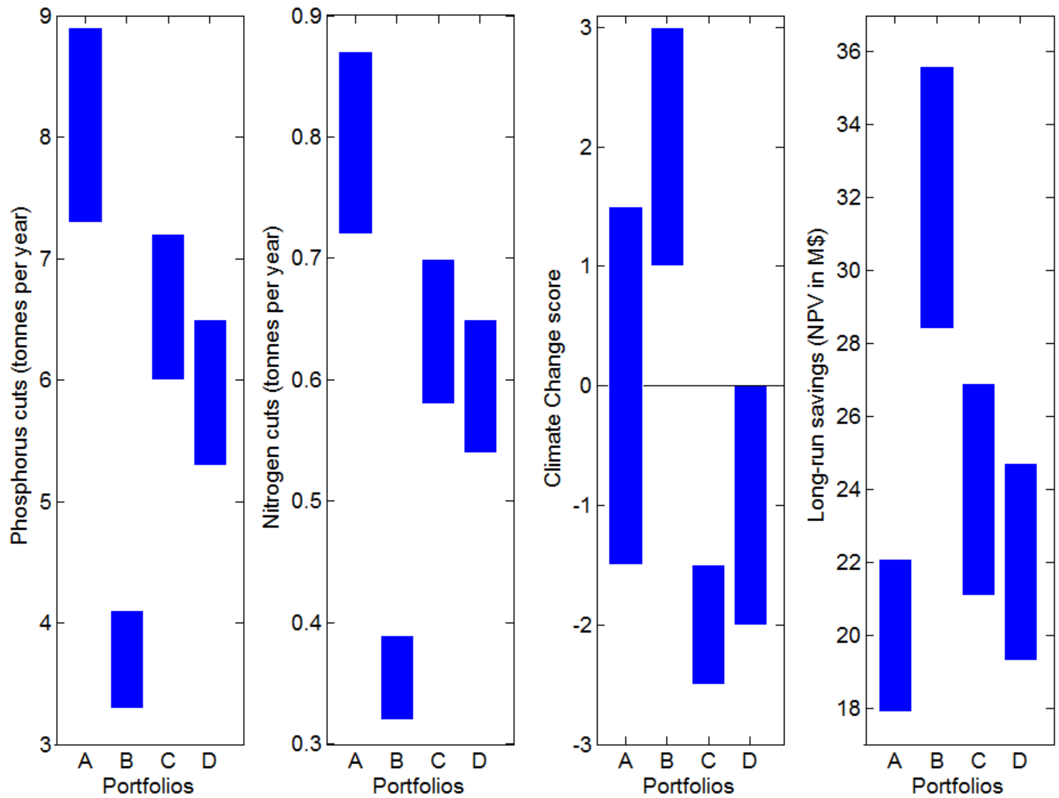

Figure 8: Ranges of overall consequences of the non-dominated portfolios.

Next, the city representatives give the following preference statements. One unit of climate change score is more valuable than one ton of annual nitrogen reduction, i.e. $w_3 \geq w_2$. One ton of annual nitrogen reduction is more valuable than two tons of annual phosphorus reduction, i.e. $w_2 \geq 2w_1$. One ton of annual phosphorus reduction is more valuable than two million dollars in net present value, i.e. $w_1 \geq 2w_4$.Ten million dollars in net present value is more valuable than one unit of climate change score, i.e. $10w_4 \geq w_3$. With this preference information, the portfolios A and B are the only non-dominated ones. Considering this, the recommendation can be made to choose actions #1, 2, 3 and #6 as they are included in both of the non-dominated portfolios. If this recommendation is followed, the remaining task of the city representatives would be to choose between actions #8 and #9.

The problem solving team is interested to find whether the results are sensitive to the budget limit used. The initial results were calculated with the budget limit of 45 million Australian dollars. Figure 9 depicts the core indices of the actions with different budget limits. When the budget cap is between 38 and 47 million dollars, the core indices of the actions stay the same, i.e. the portfolios A and B are the only non-dominated ones. If the budget limit is reduced by 7 million dollars or more, then portfolio B can no longer be afforded. If the limit is increased by two million dollars, then a third non-dominated portfolio of actions becomes feasible. This portfolio does not include action #6 but instead it includes both actions #8 and #9.

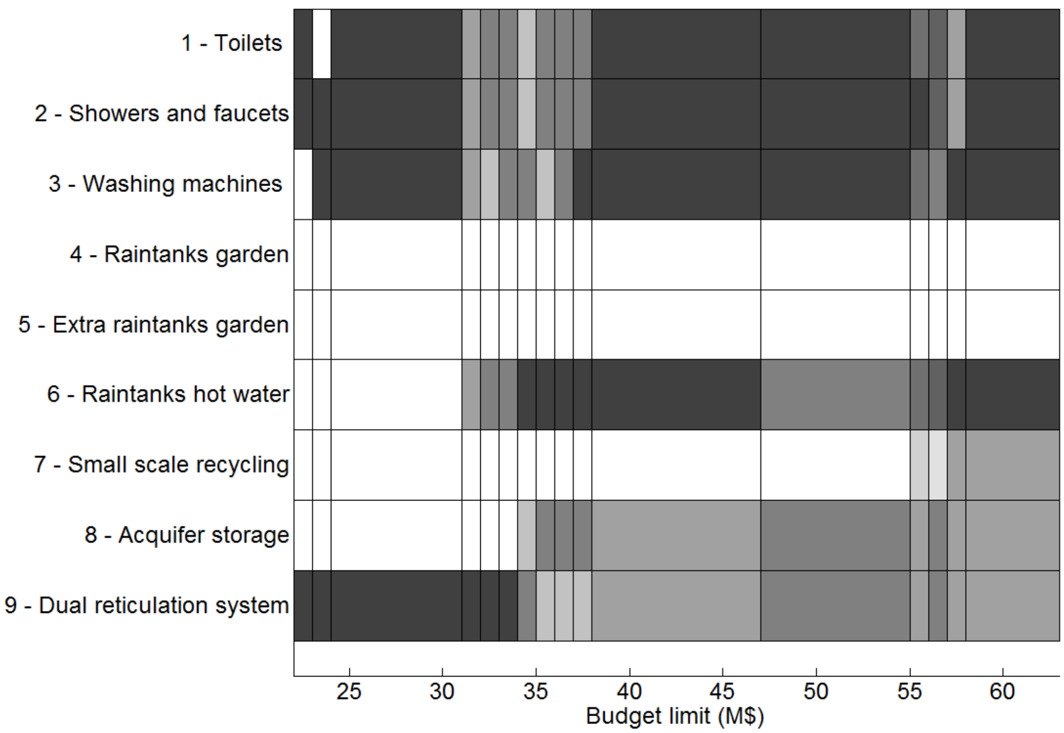

Figure 9: Core indices of the actions with different budget limits. Dark gray corresponds to core index of 1 and white corresponds to core index of 0.

The final decision is made to choose the actions #1, 2, 3, 6 and #8 that constitute the portfolio B. The estimated cost of this portfolio is 38 million Australian dollars. The city representatives find the higher long-run savings and better climate change score of portfolio B to outweigh the importance of cuts in nitrogen and phosphorus emissions that portfolio A would enable.

This example demonstrated the new possibilities offered by the use of incomplete information in portfolio decision analysis and the RPM-Decisions software. Stakeholders can perceive the analysis as more credible when preference parameters and consequences data do not need to be specified precisely. The workflow, where more precise information is gradually incorporated in the analysis can increase transparency of the solution process. At first, the model typically identifies multiple non-dominated portfolios of actions. The number of non-dominated portfolios is reduced as more precise information is incorporated in the model. Such process can help stakeholders better understand how their preference statements influence the outputs of the model.

This example is intended only as an illustration of portfolio decision analysis to help the reader in using the portfolio approach in her future work.

6. Software support for portfolio decision analysis

Software support for portfolio decision analysis is readily available. This section briefly introduces possibilities offered by dedicated portfolio decision analysis software packages, spreadsheets software, and general purpose mathematical software.

The strengths of dedicated portfolio decision analysis software packages include ready-made user interfaces, simple data inputs, as well as tools for visualization and sensitivity analysis. These software have built-in optimization algorithms that can handle large problems with up to hundreds of actions. However, they impose some restrictions on the portfolio model. Non-linear value functions defined over portfolio overall consequences are not explicitly supported by any of the dedicated software packages considered in this section. The freely available software by Marinoni et al. (2009) supports only a single resource constraint and a linear portfolio value function with no interactions. The four commercial software packages reviewed by Lourenço et al. (2008) enable specifying multiple resource constraints, and offer support for modelling certain types of interactions, such as, ‘choosing the actions A and B creates a certain synergy benefit’ or ‘the action C can be chosen only if D is chosen’. The PROBE software (Lourenco et al, 2012) adds support for general linear constraints on the actions. This makes it possible to model multiple resource constraints, performance targets, as well as various types of interactions related to the actions. PROBE can also analyze the robustness of the optimal portfolio found using crisp data. The user can give incomplete information on some model parameters (e.g. actions’ costs and scores) and the software uses it to check whether there exists a less expensive portfolio whose value could exceed that of the optimal portfolio.

RPM-Decisions is a portfolio decision analysis software whose distinguishing feature is the way it enables the use of incomplete information. It can identify *all* non-dominated portfolios in view of incomplete information on the weights and the consequences of the actions. Moreover, it also accepts any number of general linear constraints on the actions. The website http://rpm.aalto.fi can be a useful resource for the reader interested in the RPM-Decisions software. The website gives general information on the software, on its use, and on the Robust Portfolio Modelling method. References to several papers that have made use of the RPM-Decisions software are also provided.

Spreadsheet software are an easily accessible tool for building portfolio models. In many applications all possible portfolios, i.e. combinations of actions, can be enumerated. The main factor limiting applicability of this approach is the number of action candidates. To provide some insight on these limits, our experiences suggest that it is relatively straightforward to structure and solve a model with 15 actions, i.e. $2^{15} = 32768$ portfolios, with Microsoft Excel running on a standard laptop (Intel Core i5 2.4 GHz, 4GB memory). The enumeration approach does not restrict the types of constraints, interactions, or value functions that can be used in the model.

Finally, working with portfolio models including a large number of actions and complicated constraint structure can require the use of a general purpose mathematical software, e.g. Matlab or Python. A high performance optimization solver, such as CPLEX or Gurobi, can be needed to identify the optimal portfolios. Examples of real-life portfolio decision analysis applications harnessing such an approach are reported by Mild and Salo (2009) and Toppila et al. (2011), for instance.

7. Conclusions

Multi-criteria evaluation methods have proven to be very useful in environmental decision making. Today, it is natural to take the next step in environmental decision support and start using portfolio decision analysis methods and tools. Many environmental decisions are, in fact, portfolio problems where the decision makers need to consider a set of actions and create a management policy incorporating relevant concerns and interests in a balanced way. The portfolio decision analysis approach enables stakeholders to constructively engage in the decision making process at an early stage. Both experts and stakeholders can suggest actions to be included in the analysis without restrictions. This is a major advantage compared to the standard multi-criteria approaches. It helps to create shared ownership of the process, which is likely to increase the participants' commitment to the implementation of the management decision.

Portfolio decision analysis can also be useful in integrated environmental assessment tasks. In these assessments, the aim is to measure interdependent environmental impacts with multiple indicators, which relate to different perspectives and scales (see, e.g. Jakeman and Letcher 2003, Laniak et al. 2013). Such problems can be addressed as portfolio assessment problems.

The model based portfolio generation process can mitigate some of the risks arising from behavioral phenomena in unaided portfolio generation. One risk in the unaided process is that the problem solving team myopically builds the portfolio around certain champion actions and fails to see better combinations of actions. This risk can be reduced by considering all actions simultaneously in the same analysis. Such an analysis can be carried out with one of the readily available software approaches. Spreadsheet software is an easily accessible tool, which can be used when the number of action candidates is moderate, e.g. less than fifteen.

Once the opportunities offered by portfolio approaches are more widely recognized, a great number of environmental applications is likely to be seen. An interesting direction of research in the future will be to develop and test practical portfolio decision analysis procedures when working interactively with stakeholders. This paper hopefully encourages and helps the practitioners to engage in portfolio decision analysis in environmental management problems.

Acknowledgements

Tuomas Lahtinen acknowledges the financial support by Emil Aaltonen foundation.

References

Alves, M. J. and Clímaco, J. (2007). A review of interactive methods for multiobjective integer and mixed-integer programming. European Journal of Operational Research, 180(1):99–115.

Ando, A., Camm, J., Polasky, S., and Solow, A. (1998). Species distributions, land values, and efficient conservation. Science, 279(5359):2126–2128.

Bardwell, L. V. (1991). Problem-framing: A perspective on environmental problem-solving. Environmental Management 15(5):603-612.

Convertino, M. and Valverde Jr, L. J. (2013). Portfolio decision analysis framework for value-focused ecosystem management. PloS one, 8(6):e65056.

Crowe, K. A. and Parker, W. H. (2008). Using portfolio theory to guide reforestation and restoration under climate change scenarios. Climatic Change, 89(3-4):355–370.

Dickinson, M. W., Thornton, A. C., and Graves, S. (2001). Technology portfolio management: optimizing interdependent projects over multiple time periods. IEEE Transactions on engineering Management, 48(4):518–527.

Evans, J. R. (1989). A review and synthesis of OR/MS and creative problem solving (Parts 1 and 2). Omega, 17(6):499–524.

Fasolo, B., Morton, A., and von Winterfeldt, D. (2011). Behavioural issues in portfolio decision analysis. In Salo, A., Keisler, J. M., Morton, A. (Eds.), Portfolio Decision Analysis, 149–165. Springer.

Fox, G. E., Baker, N. R., and Bryant, J. L. (1984). Economic models for R and D project selection in the presence of project interactions. Management science, 30(7):890–902.

Franco, L. A. and Montibeller, G. (2010). Facilitated modelling in operational research. European Journal of Operational Research, 205(3):489–500.

Golabi, K., Kirkwood, C., and Sicherman, A. (1981). Selecting a portfolio of solar energy projects using multiattribute preference theory. Management Science, 27(2):174–189.

Gregory, R. and Keeney, R. L. (1994). Creating policy alternatives using stakeholder values. Management Science, 40(8):1035–1048.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., and Ohlson, D. (2012). Structured Decision Making: A Practical Guide to Environmental Management Choices. Wiley-Blackwell.

Grushka-Cockayne, Y., Reyck, B. D., and Degraeve, Z. (2008). An integrated decision-making approach for improving European air traffic management. Management Science, 54(8):1395–1409.

Hajkowicz, S., Higgins, A., Williams, K., Faith, D. P., and Burton, M. (2007). Optimisation and the selection of conservation contracts. Australian Journal of Agricultural and Resource Economics, 51(1):39–56.

Hajkowicz, S., Spencer, R., Higgins, A., and Marinoni, O. (2008). Evaluating water quality investments using cost utility analysis. Journal of Environmental Management, 88(4):1601–1610.

Hämäläinen, R. P., and Alaja, S. (2008). The threat of weighting biases in environmental decision analysis. Ecological Economics, 68(1):556-569.

Hämäläinen, R. P., Mustajoki, J., and Marttunen, M. (2010). Web-based decision support: Creating a culture of applying multi-criteria decision analysis and web-supported participation in environmental decision making. In Rios-Insua D., French S. (Eds.), e-Democracy, 201–221. Springer.

Hämäläinen, R. P., Luoma, J., and Saarinen, E. (2013). On the importance of behavioral operational research: The case of understanding and communicating about dynamic systems. European Journal of Operational Research, 228(3):623-634.

Hämäläinen, R. P. (2015). Behavioural issues in environmental modelling – the missing perspective. Environmental Modelling & Software, 73:244–253.

Hämäläinen, R. P., and Lahtinen, T. J. (2016). Path dependence in Operational Research – How the modeling process can influence the results. Operations Research Perspectives, 3:14-20.

Heidenberger, K. and Stummer, C. (1999). Research and development project selection and resource allocation: A review of quantitative modelling approaches. International Journal of Management Reviews, 1(2):197–224.

Higgins, A. J., Hajkowicz, S., and Bui, E. (2008). A multi-objective model for environmental investment decision making. Computers & Operations Research, 35(1):253–266.

Huang, I. B., Keisler, J. M., and Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Science of the Total Environment, 409(19):3578–3594.

Jakeman, A. J. and Letcher, R. A. (2003). Integrated assessment and modelling: features, principles and examples for catchment management. Environmental Modelling & Software, 18(6):491–501.

Keeney, R. L. (1992). Value-focused thinking: A path to creative decision making. Harvard University Press.

Keeney, R. L. and Gregory, R. S. (2005). Selecting attributes to measure the achievement of objectives. Operations Research, 53(1):1–11.

Keisler, J. M. (2005). When to Consider Synergies in Project Portfolio Decisions. College of Management Working Papers and Reports. Paper 11. http://scholarworks.umb.edu/management_wp/11

Keisler, J. M. and Linkov, I. (2010). Managing a Portfolio of Risks. Wiley Encyclopedia of Operations Research and Management Science.

Kiesling, E., Gettinger, J., Stummer, C., and Vetschera, R. (2011). An experimental comparison of two interactive visualization methods for multicriteria portfolio selection. In Salo, A., Keisler, J. M., Morton, A. (Eds.), Portfolio Decision Analysis, 187–209. Springer.

Kleinmuntz, D. N. (2007). Resource allocation decisions. In Edwards, W., Miles Jr, R.F., von Winterfeldt, D. (Eds.), Advances in Decision Analysis: From Foundations to Applications, 400–418. Cambridge University Press.

Korhonen, P. (1988). A visual reference direction approach to solving discrete multiple criteria problems. European Journal of Operational Research, 34(2):152–159.

Kreitler, J., Stoms, D. M., and Davis, F. W. (2014). Optimization in the utility maximization framework for conservation planning: A comparison of solution procedures in a study of multifunctional agriculture. PeerJ, 2:e690.

Kurttila, M., Muinonen, E., Leskinen, P., Kilpeläinen, H., and Pykäläinen, J. (2009). An approach for examining the effects of preferential uncertainty on the contents of forest management plan at stand and holding level. European Journal of Forest Research, 128(1):37–50.

Lahtinen, T. J. and Hämäläinen, R. P. (2016). Path dependence and biases in the even swaps decision analysis method. European Journal of Operational Research, 249(3):890–898.

Laniak, G. F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G., Quinn, N., Blind, M., Peckham, S., Reaney, S., Gaber, N., Kennedy, R., and Hughes, A. (2013). Integrated environmental modeling: A vision and roadmap for the future. Environmental Modelling & Software, 39:3–23.

Liesiö, J., Mild, P., and Salo, A. (2007). Preference programming for robust portfolio modeling and project selection. European Journal of Operational Research, 181(3):1488–1505.

Liesiö, J. (2014). Measurable multiattribute value functions for portfolio decision analysis. Decision Analysis, 11(1):1–20.

Linkov, I. and Moberg, E. (2011). Multi-criteria decision analysis: Environmental applications and case studies. CRC Press.

Linkov, I., Anklam, E., Collier, Z., DiMase, D. and Renn, O. (2014). Risk-based standards: integrating top–down and bottom–up approaches. Environment Systems and Decisions 34(1): 134-137.

Lorie, J. H. and Savage, L. J. (1955). Three problems in rationing capital. The Journal of Business, 28(4):229–239.

Lourenço, J. C., Bana e Costa, C. A., and Morton, A. (2008). Software packages for multi-criteria resource allocation. IEEE Engineering Management Conference, IEMC Europe 2008. http://dx.doi.org/10.1109/IEMCE.2008.4617948

Lourenço, J. C., Morton, A., and Bana e Costa, C.A. (2012). PROBE – A multicriteria decision support system for portfolio robustness evaluation. Decision Support Systems, 54(1):534-550.

Marinoni, O., Higgins, A., Hajkowicz, S., and Collins, K. (2009). The multiple criteria analysis tool (MCAT): A new software tool to support environmental investment decision making. Environmental Modelling & Software, 24(2):153–164.

Marinoni, O., Adkins, P., and Hajkowicz, S. (2011). Water planning in a changing climate: Joint application of cost utility analysis and modern portfolio theory. Environmental Modelling & Software, 26(1):18–29.

Markowitz, H. (1952). Portfolio selection. The Journal of Finance, 7(1):77–91.

Marttunen, M. and Hämäläinen, R. P. (1995). Decision analysis interviews in environmental impact assessment. European Journal of Operational Research, 87(3):551–563.

Marttunen, M. and Hämäläinen, R. P. (2008). The decision analysis interview approach in the collaborative management of a large regulated water course. Environmental Management, 42(6):1026–1042.

McCollum, D. L., Krey, V., Riahi, K., Kolp, P., Grubler, A., Makowski, M., and Nakicenovic, N. (2013). Climate policies can help resolve energy security and air pollution challenges. Climatic Change, 119(2):479– 494.

Mild, P., and Salo, A. (2009). Combining a Multiattribute Value Function with an Optimization Model: An Application to Dynamic Resource Allocation for Infrastructure Maintenance. Decision Analysis, 6(3):139-152.

Mitchell, C., Fane, S., Willetts, J., Plant, R., and Kazaglis, A. (2007). Costing for Sustainable Outcomes in Urban Water Systems: A guidebook. CRC for Water Quality and Treatment.

Moilanen, A. (2007). Landscape zonation, benefit functions and target-based planning: Unifying reserve selection strategies. Biological Conservation, 134(4):571–579.

Montibeller, G., Franco, L. A., Lord, E., and Iglesias, A. (2009). Structuring resource allocation decisions: A framework for building multi-criteria portfolio models with area-grouped options. European Journal of Operational Research, 199(3):846-856.

Montibeller, G. and von Winterfeldt, D. (2015). Cognitive and motivational biases in decision and risk analysis. Risk Analysis, 35(7):1230-1251.

Morton, A., Keisler, J. M., and Salo, A. (2016). Multicriteria portfolio decision analysis for project selection. In Greco, S., Ehrgott, M., Figueira, J.R. (Eds.), Multiple Criteria Decision Analysis, 1269-1298. Springer.

Pacala, S. and Socolow, R. (2004). Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science, 305(5686):968–972.

Paydar, Z. and Qureshi, M. E. (2012). Irrigation water management in uncertain conditions - application of modern portfolio theory. Agricultural Water Management, 115:47–54.

Phillips, L. D. and Bana e Costa, C. A. (2007). Transparent prioritisation, budgeting and resource allocation with multi-criteria decision analysis and decision conferencing. Annals of Operations Research, 154(1):51– 68.

Possingham, H., Ball, I., and Andelman, S. (2000). Mathematical methods for identifying representative reserve networks. In Ferson, S., Burgman, M. (Eds.), Quantitative methods for conservation biology, 291–306. Springer.

Pöyhönen, M., Vrolijk, H., and Hämäläinen, R. P. (2001). Behavioral and procedural consequences of structural variation in value trees. European Journal of Operational Research, 134(1):216–227.

Prato, T. and Herath, G. (2007). Multiple-criteria decision analysis for integrated catchment management. Ecological Economics, 63(2):627–632.

Salo, A., Keisler, J. M., and Morton, A. (Eds.). (2011). Portfolio Decision Analysis. Springer.

Salo, A. and Hämäläinen, R. P. (1995). Preference programming through approximate ratio comparisons. European Journal of Operational Research, 82(3):458–475.

Selart, M. and Johansen, S. T. (2011). Understanding the role of value-focused thinking in idea management. Creativity and Innovation Management, 20(3):196–206.

Sharpe, W. F. (1964). Capital asset prices: A theory of market equilibrium under conditions of risk. The Journal of Finance, 19(3):425–442.

Siebert, J. and Keeney, R. L. (2015). Creating more and better alternatives for decisions using objectives. Operations Research, 63(5):1144–1158.

Slotte, S. and Hämäläinen, R. P. (2015). Decision Structuring Dialogue. EURO Journal on Decision Processes, 3(1): 141-159.

Stummer, C. and Heidenberger, K. (2003). Interactive R&D portfolio analysis with project interdependencies and time profiles of multiple objectives. IEEE Transaction on Engineering Management, 50(2):175– 183.

Stummer, C., Kiesling, E., and Gutjahr, W. J. (2009). A multicriteria decision support system for competence-driven project portfolio selection. International Journal of Information Technology & Decision Making, 8(2):379–401.

Toppila, A., Liesiö, J., and Salo, A. (2011). A resource allocation model for R&D investments: A case study in telecommunication standardization. In Salo, A., Keisler, J. M., Morton, A. (Eds.), Portfolio Decision Analysis, pages 241–258. Springer.

Vilkkumaa, E., Salo, A., and Liesiö, J. (2014). Multicriteria portfolio modeling for the development of shared action agendas. Group Decision and Negotiation, 23(1):49–70.

Voinov, A. and Bousquet, F. (2010). Modelling with stakeholders. Environmental Modelling & Software, 25(11):1268–1281.

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., Ramu, P. (2016). Modelling with stakeholders–next generation. Environmental Modelling & Software, 77:196-220.

van der Honert, R.C. (2016). Improving decision making about natural disaster mitigation funding in Australia – A Framework. Resources, 5(3): 28.

von Nitzsch, R. and Weber, M. (1993). The effect of attribute ranges on weights in multiattribute utility measurements. Management Science, 39(8):937–943.

von Winterfeldt, D. and Edwards, W. (1986). Decision Analysis and Behavioral Research. Cambridge University Press.

Zheng, P. Q. and Hobbs, B. F. (2013). Multiobjective portfolio analysis of dam removals addressing dam safety, fish populations, and cost. Journal of Water Resources Planning and Management, 139(1):65–75.