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Portfolio Modeling in Environmental Decision Making

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ABSTRACT OF THE
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The number of decisions concerning environmental issues is increasing both due to legislation and public interest. Environmental decisions are typically complex and have sociopolitical, ecological and economic dimensions. Methods of multi-criteria decision analysis (MCDA) can support making such multi-objective decisions and indeed environmental applications of MCDA have attracted considerable interest among both researchers and practitioners.

Standard MCDA methods are appropriate for selecting one action out of few alternatives. However, often in environmental problems the decision objectives are best pursued by selecting a set of actions, i.e. a portfolio. A new subfield of MCDA, portfolio decision analysis (PDA), has emerged for supporting decisions where several actions are chosen.

This thesis analyzes the applicability of PDA in environmental decision making. The current state of environmental decision analysis is presented through a literature review, including a review of the most common PDA software. The thesis identifies the key phases of applying PDA in environmental problems and discusses associated challenges and possible solution approaches. Two examples illustrate the application process. The first example develops a PDA model to support the zoning of bog areas for peat extraction with the objective of minimizing environmental risks to the watercourses around the zoned areas. The second example describes how PDA can support building a sustainable and inexpensive water supply system in an urban area.

Keywords: Portfolio decision analysis, multi-criteria decision analysis, environmental decisions, decision support, robust portfolio modeling

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Antalet miljöbeslut har ökat de senaste åren på grund av både lagstiftning och ökat allmänt intresse på miljöfrågor. Kännetecknande för många miljöbeslut är att de har ett flertal intressenter och är invecklade, eftersom ekologiska, ekonomiska, miljö- och hälsomålsättningar bör beaktas samtidigt. Multikriterieanalysens (multi-criteria decision analysis, MCDA) metoder lämpar sig väl för hanteringen av situationer med flera målsättningar och de har även fått ett starkt fotfäste inom miljöbeslutsfattningen.

Multikriterieanalys är passande för situationer där en åtgärd sökes bland flera. Ofta är situationen dock sådan att man bäst når målsättningarna genom att välja flera åtgärder, dvs. en portfölj. Ett nytt område inom beslutsanalysen, portföljbeslutsanalys, har uppstått för att stödja beslut där flera åtgärder väljs.

Detta arbete analyserar hur portföljbeslutsanalys lämpar sig för miljöbeslutsfattning. I arbetet presenteras miljöbeslutsfattningens nuläge genom en litteraturöversikt, som även innefattar en recension om de mest populära dataprogrammen för portföljbeslutsanalys. Arbetet identifierar centrala skeden i portföljbeslutsprocessen och diskuterar de utmaningar som uppstår samt presenterar möjliga lösningar till dessa. Två exempel illustrerar portföljbelutsanalysens tillämpning. I det första exemplet utvecklas en portföljmodell för valet av mossar för torvupptagning, då skaderisken för vattendrag skall minimeras. Det andra exemplet beskriver hur portföljbeslutsanalys understöder konstruktionen av ett hållbart och kostnadseffektivt system för vattenförsörjning i en förort.

Nyckelord: Portföljbeslutsanalys, multikriterieanalys, miljöbeslut, beslutsstöd robust portföljmodellering

Contents

1 Introduction

1.1 Multi-criteria decision analysis in environmental applications

Decision analytic methods have gained a firm foothold in environmental decision making (Huang et al., 2011; Hobbs and Meier, 2000; Linkov and Moberg, 2011; Gregory et al., 2012). Decision analysis is used for structuring the situation and in making a decision which corresponds to the decision-makers' preferences and beliefs (Clemen, 1996). The decision making process itself, when conducted in a structured way, can produce a learning process as well as help groups with conflicting goals in reaching a consensus. Moreover, decision analysis provides analytic justification for decisions, which is often mandated by legislation.

Environmental decisions are typically complex, large and have many objectives. This has increased the popularity of using multi-criteria decision analysis (MCDA) in environmental contexts. Keeney (1980) analyzed the decision of siting energy facilities (power plants, dams, refineries) when environmental impacts, health and safety, socioeconomic effects and public attitudes are considered in addition to engineering and economic criteria. Kangas et al. (2008) offer an overview of decision support for forest management planning with the aim of ecological, economic and social sustainability. Further examples of how MCDA is used in environmental applications can be found in e.g. Linkov and Moberg (2011), Paruccini et al. (1994), Huang et al. (2011), Herath and Prato (2006) and Hobbs and Meier (2000).

1.2 Portfolio modeling in environmental decision making

Standard MCDA methods are used to evaluate a discrete set of options under multiple decision criteria. However the set of options often contains elements, that are combinations of several actions. Creating the options is itself a process of forming portfolios.

Approaching decision situations in terms of portfolios has a long history. Markowitz (1952) laid the foundations for modern portfolio theory (MPT), which aims at selecting a portfolio of financial assets with an optimal risk-return balance. A similar risk-return thinking lies behind capital budgeting models, albeit the focus is on investments inside a corporation rather than on tradable assets (Lorie and Savage, 1955). Quantitative models for project selection have been used especially in creating and managing R&D portfolios (see Roussel et al., 1991), where several goals need to be regarded simultaneously. The MPT approach of diversifying risk has also found its way to environmental decision making, e.g. Marinoni et al. (2011) analyze the future uncertainties of a set of intervention measures for improving water quality using MPT. Indeed MPT has been widely applied in environmental contexts (see, e.g., Brumelle et al., 1990; Parks, 1995; Springer, 2003; Figge, 2004; Knoke et al., 2005; Aerts et al., 2008; Sanchirico et al., 2008; Blanford, 2009; Marinoni et al., 2009; Oliver and Stasko, 2009; Xu and Tung, 2009; Schindler et al., 2010; Hoekstra, 2012; Kandulu et al., 2012; Paydar and Qureshi, 2012; Lester et al., 2013; Thibaut and Connolly, 2013; Yemshanov et al., 2013).

MPT assumes that there is a market for tradable financial assets and that the assets are continuous (i.e. can be bought in any quantity). In environmental decision making, however, the actions often warrant yes/no decisions. The new subfield of MCDA, portfolio decision analysis (PDA), deals with such decisions. Salo et al. (2011, p. 4) define PDA as a 'body of theory, methods and practice which seeks to help decision-makers make informed multiple selections from a discrete set of alternatives through mathematical modeling that accounts for relevant constraints, preferences and uncertainties.' Portfolio modeling with a multi-criteria decision analytic focus is widespread, but the terminology differs. Portfolios are also called strategies (Dall'O et al., 2013) and configurations (Mitchell et al., 2007). The problem of allocating scarce resources to a discrete set of actions is called resource allocation. The term resource allocation is used when e.g. different operations are funded from a single budget so that the result maximizes a given criterion, see e.g. Crarnes et al. (1976), Tietenberg and Lewis (2000, p. 118-136) and Cook and Proctor (2007).

There has been a lot of interest in PDA in the last years. Montibeller et al. (2009) present a framework for structuring multi-criteria portfolio decisions inside organisations. They apply the framework to two case studies, one concerning public health and the other identifying new viable public services. Keisler (2011) presents another framework for making portfolio decisions with special focus on the value of information during different stages of the decision making process. Fasolo et al. (2011) review behavioural issues arising in portfolio choice decisions and discuss ways for debiasing. Phillips and Bana e Costa (2007) describe a social process for making a portfolio decision, the decision conference. The authors illuminate the process with the help of experience from several case studies. Liesiö et al. (2007, 2008) outline the robust portfolio modeling (RPM) methodology, which enables analysis of portfolios when there is incomplete information about stakeholder preferences. Stummer and Heidenberger (2003) present an interactive way of exploring the possible portfolios in a decision situation. So far, there have been few explicit applications of PDA to environmental situations (Bryan, 2010; Convertino and Valverde Jr, 2013).

1.3 Applying portfolio decision analysis to environmental decisions

The portfolio approach has been applied implicitly when creating the options from a set of different actions in the MCDA process. This is usually done by the problem specialists or facilitators without using a model. The area is new and this thesis aspires to further demonstrate how to use PDA modelling in environmental decisions.

The process description presented in this thesis covers the essential aspects of structured environmental decision making and presents them in a step-wise manner. The stages of the process are illuminated with two examples. One concerns the selection of a set of peat bogs in Central Finland. The other is about providing water to a suburban district in Australia. Similar environmental portfolio problems arise in choosing forest protection sites (Punkka, 2006) or carbon emission mitigation strategies (Pacala and Socolow, 2004).

In summary, the research objectives of this thesis are:

- To review the software currently being used for portfolio modeling.
- To describe the process of applying multi-criteria portfolio models in environmental decisions.
- To illuminate with the help of examples how portfolio modeling can be applied.

1.4 Structure

This thesis is organized as follows: Section 2 reviews relevant literature about environmental decision making, MCDA and PDA. It also includes a review of several PDA software. Section 3 describes a process for applying portfolio models to environmental problems. Sections 4 and 5 illustrate the process description with two examples, one dealing with selecting bogs for peat extraction and the other with selecting actions for saving water in a residential area. Finally Section 6 offers the concluding remarks.

2 Literature review

2.1 Multicriteria decision analysis in environmental contexts

The use of multicriteria decision analysis in environmental contexts is increasing. Huang et al. (2011) list over 300 scientific articles published during 2000–2009 in which MCDA methods have been utilized in environmental problems. Linkov and Moberg (2011, p. 14) further note that the use of MCDA methods in environmental problems has increased both in proportional and absolute terms during the years 1990–2010. Environmental decisions are often complex and involve several stakeholders with differing priorities, which makes it hard to solve them without the aid of analysis (Kiker et al., 2005). Gregory et al. (2012) have listed common types of environmental management decisions (see Table 1).

Table 1: Common types of environmental management decisions, from Gregory et al. (2012, p. 48)

Type	What is needed	Examples
Choosing a single preferred alternative	An informed, transparent and broadly supported solution to a policy or planning problem	Developing a management plan for an endangered species or airshed
Developing a system for repeated choices	A system for efficient, consistent and defensible decisions that are likely to be repeated	Setting annual harvest levels or seasonal water allocations
Making linked choices	A way to separate decisions into higher and lower order choices, or those to be made now as opposed to later	Screening analysis followed by detailed evaluation; decisions that might be informed by investment in research
Ranking	A way to put actions or items in order of importance or preference, according to clear criteria	Prioritizing watersheds for restoration efforts; ranking projects to be funded
Routing	Grouping of actions or items into different categories, so they can be evaluated appropriately. This is often a preliminary action to more detailed assessment.	Screening out ineligible projects or proposals; identifying proposals for more detailed evaluation

Several countries have legislation that demands a careful assessment of the environmental impacts of governmental actions. In the United States for example responsible officials are required[1] to provide a detailed statement on

(i) the environmental impact of the proposed action,

(ii) any adverse environmental effects which cannot be avoided should the proposal be implemented,

(iii) alternatives to the proposed action,

(iv) the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity, and

(v) any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented.

The Decree about the Environmental Consequence Assessment Procedure by the Finnish Government[2] lists 52 types of projects in 12 different categories which are all subject to an environmental assessment procedure prior to their implementation. These projects include e.g. the building of power plants with a maximum output exceeding 300MW, constructing oil refineries and building new railroads for long-distance traffic. With an application field this large by legislation alone, it is no wonder that MCDA methods are being used extensively. The most common MCDA methods in practice are the analytical hierarchy process (AHP) and multiattribute utility (or value) theory (MAUT/MAVT) (Kiker et al., 2005; Huang et al., 2011).

2.2 Portfolio decision analysis

Portfolio decision analysis (PDA) is a 'body of theory, methods and practice which seeks to help decision-makers make informed multiple selections from a discrete set of alternatives through mathematical modeling that accounts for relevant constraints, preferences, and uncertainties'

[1]National Environmental Policy Act of 1969, http://www.usinfo.org/enus/government/branches/nepaeqia.htm

[2]Statsrådets förordning om förfarandet vid miljökonsekvensbedömning, English translation by the author (see http://www.finlex.fi/sv/laki/ajantasa/2006/20060713).

(Salo et al., 2011, p. 4). Portfolio decision analysis is sometimes called resource allocation. Although multicriteria resource allocation and portfolio decision making may sometimes have different connotations, here these terms are both used to mean a decision situation with multiple objectives and alternatives. A portfolio is *a collection of decision alternatives*. These decision alternatives are often called projects, actions, options or units of analysis. In this thesis they are denoted by the term *action*. As a decision analytic method, the aim of PDA is to find a solution that corresponds to the decision-maker's preferences. These preferences are seldom clear and the challenge is larger when several decision-makers are involved (Clemen, 1996, p. 459-502).

Phillips and Bana e Costa (2007) describe five challenges that decision-makers face when using PDA: (1) benefits are characterized by multiple conflicting objectives, (2) decision-makers have limited information about the portfolio actions, (3) the overall result suffers when resources are allocated to actions individually, (4) several people are involved in the decision and (5) those that disagree may pursue non-approved actions if they are not committed to the group decision. These challenges highlight the need for engaging people and presenting relevant information in an understandable way. PDA addresses points 1 and 3. Points 2, 4 and 5 are more related to the way how the analysis is conducted, here decision conferencing or some other social process involving multiple decision-makers is necessary. Here three possible social processes – decision conferencing, a framework for structuring multi-criteria portfolio models and interactive portfolio selection – are presented.

2.2.1 Decision conferencing

Phillips and Bana e Costa (2007) underline the importance of the social process in group decisions. The selection of a portfolio is not merely a technical challenge but a social one as well. Furthermore, when the social process is conducted effectively and in a manner that increases trust among participants, a better technical solution is obtained (Sharpe and Keelin, 1998).

The social process framework that Phillips and Bana e Costa (2007) have used in several projects is *decision conferencing* and it can be summarized in six different stages. It should be noted however, that this process description assumes a single organization with several departments and is not as such applicable in all decision situations.

First, a smaller meeting between key executives is held where the structure of the model is decided and the scope of actions assessed. Second, a kick-off meeting is organized, where responsible persons from all business units (or expertise areas) gather together and refine the proposed model. Third, the teams have individual meetings where team members share their knowledge in a bottom-up manner. The team meetings are carried out in a brainstorming fashion. The team members are encouraged to think what can possibly be done (assuming no constraints) to achieve the objectives provided in stages one and two. Fourth, senior managers gather together, review and refine the given actions. Improvement suggestions are sent back to the teams who will then refine their proposal. The fifth stage is a merge meeting with the team leaders and senior staff. Here bottom-up knowledge meets top-down requirements, the trade-offs are assessed and the solution space (i.e. different feasible portfolios) is explored. Finally, the model is evaluated, possibly refined further and implemented.

2.2.2 Structuring a multicriteria portfolio model

Montibeller et al. (2009) propose a framework for structuring multicriteria portfolio models. According to Montibeller et al. (2009) when structuring a standard MCDA-model two activities are needed: developing a hierarchy of criteria (or objectives) and defining (or identifying) a set of actions, which are possibly grouped as belonging to different areas. Structuring the criteria can be done with value-focused thinking or alternative-focused thinking. Structuring the actions/areas can be done either top-down or bottom-up. These lead to four possible ways of structuring multicriteria portfolio models. The authors note that value-focused thinking usually leads to better results, as it is based on the idea that actions are only means to achieve organizational objectives (Montibeller et al., 2009, p. 849). Alternative-focused thinking comes into question mainly when the problem and the actions are relatively well-defined. Keeney (1994a) notes that focusing on alternatives is a limited way to think through a decision situation. The values of the decision-maker should drive the process, as they are the reason why the decision is made in the first place.

Table 2: Advisability of different methods to structure a multicriteria portfolio model, from Montibeller et al. (2009).

		Structuring actions and areas	
		Top-Down	Bottom-Up
Structuring criteria	Alternative-focused thinking	Advisable when areas are pre-defined and the set of actions well-known.	Advisable when areas are not pre-defined and are used to group actions. The set of actions is well-known.
	Value-focused thinking	Advisable when areas are pre-defined but the set of actions may vary.	Advisable when areas are not pre-defined and new actions can be included during the analysis.

Montibeller et al. (2009) include two case studies in their article. The first one is a project for reducing teenage pregnancies in the UK conducted for the Teenage Pregnancy Strategy Committee (TPSC). The case study had the following stages:

1. A causal map of the issues surrounding the decision problem was created. The current funded areas were taken as a basis for the choice of areas. The actions were chosen on the basis of the projects that were currently funded. This stage resulted in nine areas with seven actions in the largest area. The initial causal map revealed some potential new areas and actions, which were added to the model.

2. The benefit criteria were structured. The initial criteria set represented objectives and thus had to be translated into measurable attributes. Six benefit criteria were identified in addition to the cost criterion.

3. A group workshop was conducted to evaluate different options and criteria weights in the portfolio model.

4. The workshop group was asked to propose a portfolio of actions which they could feasibly fund next year. This portfolio was dominated, i.e. there existed other portfolios which were better on all

measures. The facilitator proposed a set of efficient portfolios and the group chose together a solution among those.

According to the authors the members of TPSC found creating the model useful, as it forced them to give explicit statements about their beliefs and objectives. The process was however hard to manage at times due to interpersonal relations. The modeling approach also possibly prevented participants from considering TPSC's strategic objectives. This case study was an example of a top-down approach, since the decision areas were defined first and actions second.

The second case study was about developing and evaluating new income generation actions for the public institution Library Learning and Culture (LLC) in the UK. It was conducted in the following manner:

1. A group workshop was held to identify evaluation criteria and develop ideas for new services (actions). The evaluation criteria were elicited and structured first using a causal map. LLC's objectives were separated into 'strategic' (or 'fundamental') objectives and so-called 'means-objectives', i.e. those objectives that were only a vehicle to achieve the strategic ones.

2. The means-objectives were utilized to brainstorm new actions. The most interesting actions were chosen by the facilitator and managers.

3. The performance of the different actions with regard to the criteria were assessed in meetings. Criteria weights were elicited.

4. Different portfolios were explored in the last workshop and a common solution was agreed upon.

The authors deemed it especially beneficial not to predefine the action-areas based on the library's subdivisions, as this reduced the potential of conflict and encouraged the participants to consider organizational priorities. This was a bottom-up approach, first actions were defined/generated and then grouped into areas.

2.2.3 Interactive portfolio selection

Stummer and Heidenberger (2003) propose a way of interactively selecting a satisfying portfolio among the efficient portfolios. Once the set of efficient portfolios is calculated the procedure starts with an arbitrarily selected initial portfolio. The portfolio is represented by its value and resource objective levels. The decision-maker then sets aspiration levels (lower and upper bounds) on objectives and moves to a better portfolio. This better portfolio can be used as the initial portfolio in another interactive portfolio selection, it can be saved and the procedure started all over again with a different initial portfolio or the current portfolio can be accepted as a satisfying solution. The interactive portfolio selection procedure encourages portfolio level thinking instead of considering actions separately. What is more, it does not necessitate the elicitation of weights, which is time-consuming and susceptible to biases (Hämäläinen and Alaja, 2008).

2.2.4 Robust portfolio modeling (RPM)

RPM is a decision support methodology for analyzing multiple criteria portfolio problems presented by Liesiö et al. (2007, 2008). With RPM portfolio problems with incomplete ordinal preference statements can be analyzed. Such a statement is, e.g. 'lowering costs is more important than lowering air pollution'. When evaluating such statements one has to keep in mind the criterion intervals. The correct evaluation question is 'Would you prefer an increase in "costs" from the worst level to the best level to a similar increase under "air pollution"?' rather than 'Would you deem "costs" or "air pollution" as more important?' (Keeney, 1994b, p. 797-798). According to Lindstedt et al. (2008) RPM gives structure to a complex decision problem, helps the communication between decision-makers and provides a transparent decision recommendation.

2.3 Software for multicriteria resource allocation

Lourenço et al. (2008) and Jalonen (2007) have listed software used in portfolio decision making. Here Equity, HiPriority and RPM-Decisions are reviewed more closely. All of them use a linear-additive value model for evaluating actions. An action j is characterized by a vector $x^j =$

$(x_1^j, ..., x_n^j)$, containing the action's attribute consequences for all n attributes. Each attribute i receives a weight w_i, which represents the importance of the change $x_i^0 \rightarrow x_i^*$ in comparison to the same change in other attributes. Here x_i^0 is the least desired attribute consequence and x_i^* the most desired attribute consequence among all actions. The attribute consequences are converted to values with functions $v_i : x_i^j \rightarrow [0, 1]$. The value of an action is

$$v(x^j) = \sum_{i=1}^{n} w_i v_i(x_i^j), \tag{1}$$

where the w_i are weights of individual attributes. The problem these software are solving is

$$\max_{z_j} \sum_{j=1}^{m} z_j v(x^j)$$
$$z_j \in \{0, 1\}, j = 1, ..., m.$$

This is the basic formulation, which can be modified with different interactions between actions and with resource constraints.

Computer software allows the decision-maker to explore different 'what if'-scenarios and do sensitivity analysis with different values. The interactivity and speed of execution are the main advantages of decision software. These software are however not especially user-friendly. Data import is tedious in both Equity and HiPriority, merely getting started can take several hours. Most software are thus best applied in the presence of a decision analyst, who can also help in choosing the right software.

2.3.1 Equity

Equity is a commercial software package developed by London School of Economics and currently offered by Catalyze Ltd[3]. In Equity, actions are organized by areas, e.g. geographical areas or business units. Each area can have either *cumulative* actions if many actions can be chosen from one area or *mutually exclusive* actions if only one action from the area can be chosen. A base level -action is first included (usually 'do

[3] http://www.catalyze.co.uk/index.php/software/equity3/

nothing'). All the actions are given costs and benefit scores. Multi-criteria benefits are supported, but in the end the user needs to provide precise weights, which are used to compute a single overall benefit for each action (see Equation (1)).

The program's user interface works fairly well. The user can easily include and exclude actions in a portfolio and see immediately how this affects the portfolio plot. When the selected portfolio is not optimal, i.e. a larger benefit or a smaller cost could be achieved without worsening the other attribute, Equity proposes better portfolios (see Figure 1).

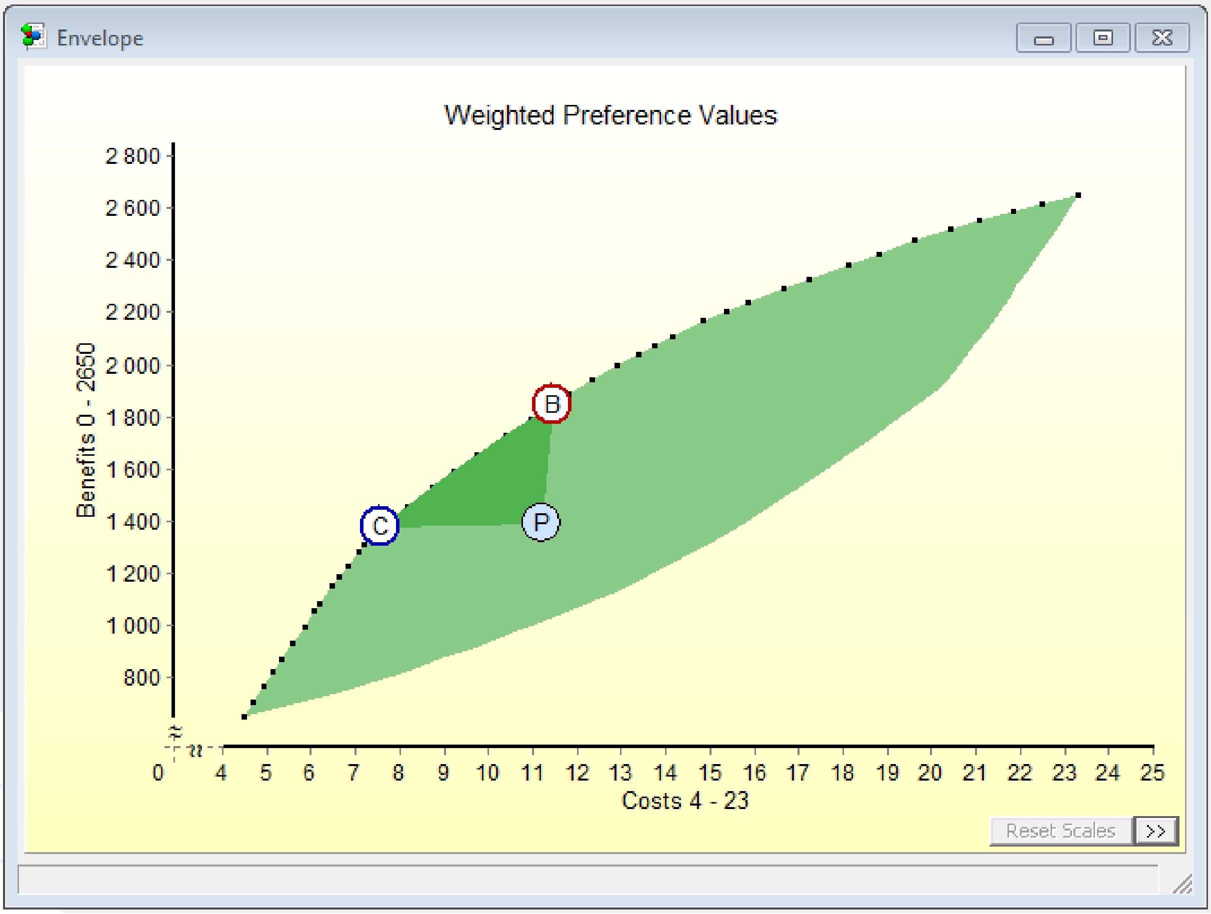

Figure 1: Equity's portfolio window, where portfolios are showed on a cost-benefit plot. The currently selected portfolio selection is denoted by the letter P. The software suggests a portfolio C which is cheaper than P (and has the same benefit) and a portfolio B which has a larger benefit than P (and the same cost).

Equity finds efficient portfolios by using benefit-to-cost ratios. A steeper slope translates to a more favorable cost-benefit ratio. The user can explore the solution space by choosing a portfolio she likes or by simply mapping the current portfolio on the cost-benefit plot. If this portfolio is not efficient, the software subsequently proposes two portfolios – one portfolio cheaper and another with a larger benefit than the user-chosen portfolio. According to the developers, the end result is usually a balance between the current portfolio and the two better ones.

Equity has been utilized by Phillips and Bana e Costa (2007) to choose a portfolio of R&D actions for a pharmaceutical company. The actions were grouped in five therapeutical areas with 6-14 actions per area. For ten years the portfolio of R&D actions has been reviewed annually using Equity. Phillips (2011) used Equity to help the Royal Navy in deciding which combination of capabilities should be chosen for a new navy destroyer. According to the author the combination of technical system modelling with stakeholder-engaging group processes saved 2 years of design work. In the case studies by Montibeller et al. (2009) presented in Section 2.2.2, Equity was also used for analysis.

A standard one-year license for Equity costs 1 850 £ (2 115 €), but it is available also as a free 20-day trial version. Importing large amounts of data to Equity is tedious. In principle it supports data formatted as comma separated values (.csv), but in practice this way of importing data is dysfunctional.

2.3.2 HiPriority

HiPriority is a software package developed by Quartzstar Software Ltd[4]. Similar to Equity, it supports actions to be grouped into categories. HiPriority enables several types of interdependencies between actions. It is possible to define one-way exclusions (action A is included in the portfolio only if action B is), two-way exclusions (A is included only if B is included and vice versa) or exclusion sets (either actions A, B and C are all in the portfolio or none of them is). HiPriority utilizes a cost-benefit approach. The benefits are aggregated to a single value by using weights.

One significant advantage of HiPriority is the user-friendly solution presentation shown in Figure 2. In the upper right corner of Figure 2 the portfolios are plotted on a cost-benefit plot. The Pareto-optimal portfolios (called 'Golden frontier portfolios' in HiPriority) are denoted

[4] http://www.quartzstar.com/

by yellow circles. By clicking on one of the circles the user sees in the upper left corner which actions are included in that particular portfolio, namely the ones marked with a star. In the lower left corner the details for the selected portfolio's actions are shown. In the lower pictures actions are ordered according to their benefit-to-cost ratio. Uncertainty of information is not supported, the costs, benefits and weights are all taken as exact values. Sensitivity analysis is somewhat hard to do. In the solution window neither the scores nor the weights can be changed, but the user needs to go back to the data grid (choose 'Data Grid' under 'Process') and change them. On the other hand, the actions can be rearranged according to their cost-benefit ratio, which allows the user to fairly quickly see how a certain change affects results.

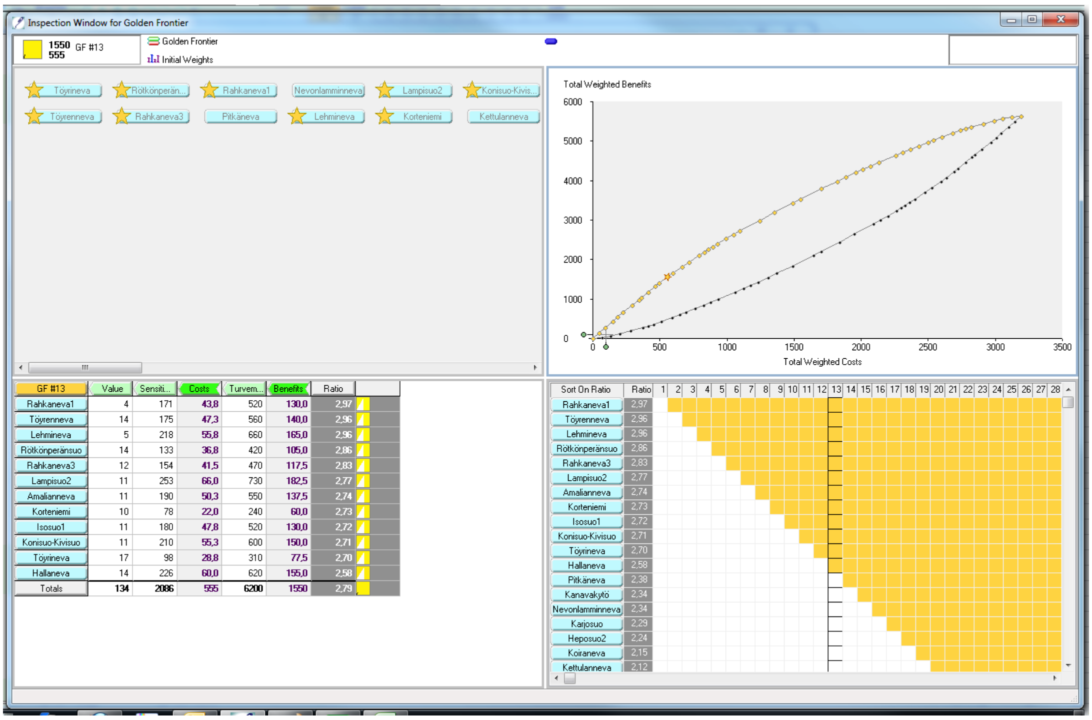

Figure 2: The solution window in HiPriority. A portfolio is selected by clicking one of the yellow circles in the upper right subplot. The selected portfolio is denoted by a star. Similarly the actions included in the selected portfolio are denoted by a star in the upper left subplot. In the lower left subplot actions' attribute consequences and their cost-benefit ratios are presented for the selected portfolio. The lower right subplot presents cost-benefit ratios for all actions and ranks actions according to it. Note the similarity of the upper right subplot with Equity's solution window in Figure 1.

First-time users may run into trouble when attempting to input costs, as HiPriority rounds everything to the nearest integer. Also any cost greater than 100 is treated as 100. To sum up, any values input to HiPriority should be transformed to the interval $[0, 100]$ and rounded up to the nearest integer. It is possible to import values as an Excel sheet to HiPriority by choosing 'Import' under 'File'. HiPriority is available as charityware, i.e. free to download but users are encouraged to make donations.

2.3.3 RPM-Decisions

RPM-Decisions is a software developed by the Robust Portfolio Modeling group[5] at the Systems Analysis Laboratory at Aalto University.

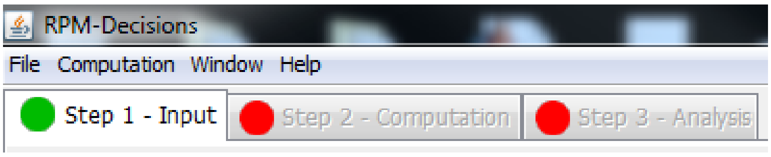

Figure 3: The stages of analysis in RPM-Decisions. The green circles denote accomplished and red circles unaccomplished stages.

In RPM-Decisions the analysis is split up in three stages, which are visible as tabs in the software toolbar (see Figure 3). The first stage is to input relevant data. It is possible to copy data from an Excel sheet, but attention should be paid to the decimal separator – in RPM-Decisions it is a dot (.). There are five different input categories: criterion scores, feasibility constraints, value tree, criterion scores (lower bounds) and weight constraints. The number of actions that RPM-Decisions can analyze is not limited.

Action interactions can be included using the 'feasibility constraints' input option. The input wizard (see Figure 4) offers logical, positioning or synergy constraints. The logical constraint means that an action is included in the portfolio only if certain other actions are also in it. This could be the case e.g. for several stages of a project which need to be conducted in a certain order. With the positioning option the user can constrain the number of actions chosen in a group to be at most, at least or exactly a specific number. The groups are formed by clicking on

[5] http://rpm.aalto.fi/rpm-personnel.html

actions in the constraint wizard window. Action synergies are modeled as an extra action C, which is included in the portfolio if actions A and B also are (C being the synergy benefit). After all necessary action criteria scores and interactions are input, the user can proceed to the next stage, computation.

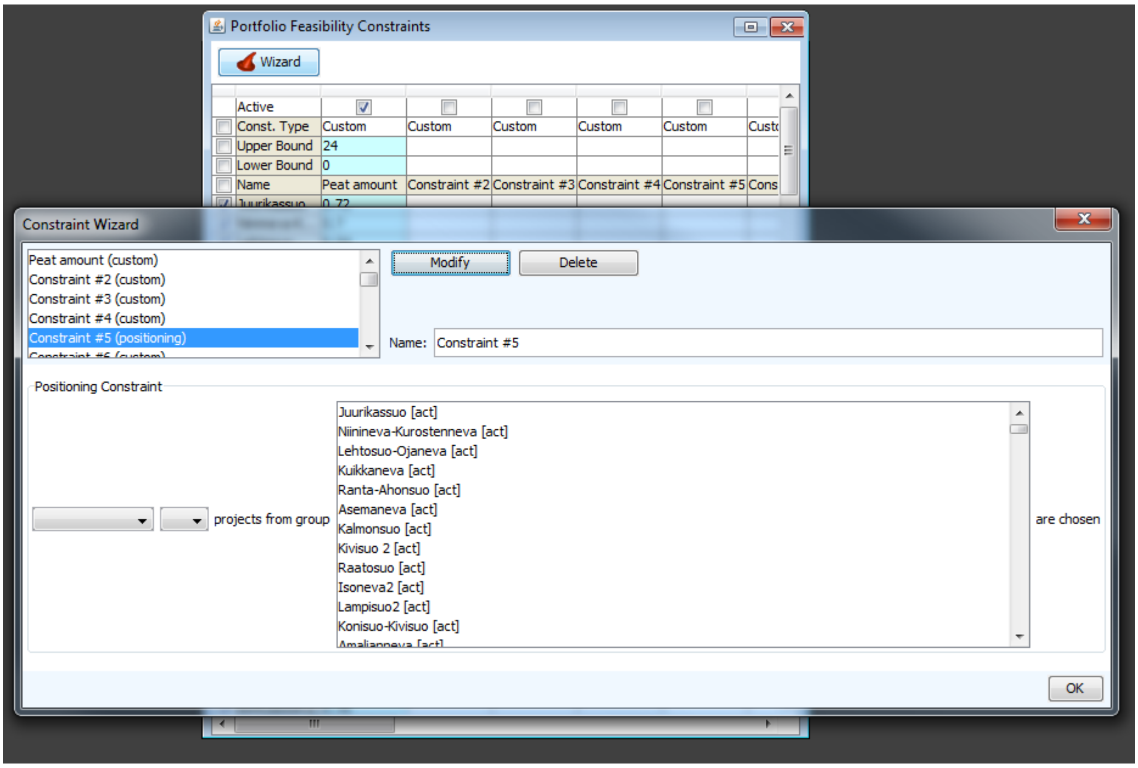

Figure 4: The constraints window in RPM-Decisions. Portfolio constraints and action interactions are input here.

There are two options for computation, ‘Fast solve’ and ‘Exact solve’. ‘Fast solve’ provides a selection of efficient portfolios whereas ‘Exact solve’ computes all of them. When the number of actions is large ($\gg$5) the number of portfolios becomes so high that ‘Fast solve’, with the box ‘only potentially optimal non-dominated portfolios’ ticked for faster computing, is recommended. RPM-Decisions displays the number of portfolios found during the computation. When the number is sufficient, the user can stop computation and proceed to the final stage, analysis. In addition to the program’s native solver the user can do the computation with XPress[6] or CPLEX[7] solver.

[6]XPress Optimization suite
[7]IBM ILOG CPLEX Optimization Studio

The analysis window has six tabs: Core Indices, Project Bar Chart, Project Scatter Plot, Portfolio Scatter Plot, Value Tree and Portfolio Screening. The Core Indices tab displays the core index of each action (see Equation (6) for definition). Project Bar Chart shows the possible values of each action. Project Scatter Plot provides scatter plots for visualizing the actions, see Figure 5 for an example. Portfolio Scatter Plot provides scatter plots for visualizing portfolios. From the portfolio scatter plots one can see on a quick glance which value combinations are possible. By right-clicking on the plot the user can zoom in and out. The Value Tree tab shows the value model, i.e. if there is a criterion hierarchy one can view it here.

Portfolio Screening is perhaps the most useful tool for analysis. Here the user can input constraints on any objective. The results on other tabs are then recomputed with those constraints active. Constraints can be removed by right-clicking on the Portfolio Screening window and choosing 'Remove constraint'. The results of the computation can also be exported to Matlab (under 'Numerical data' choose 'Export to Matlab').

Salo et al. (2006) have used RPM-Decisions for evaluating research-based business ideas. There were 61 actions that were evaluated on 7 attributes (e.g. capital investments and cash flow). The efficient portfolios were calculated using the software and the actions were partitioned in core (core index 1), borderline (core index between 0 and 1) and exterior actions (core index 0). The core indices indicate the share of non-dominated portfolios where the action is present. Korpiaho (2007) searched for the most promising R&D project proposals using RPM-Decisions. The author evaluated 26 actions based on six experts' assessment about their value. Vilkkumaa et al. (2009) describe a case study concerning the selection of a national wood product research agenda. The case study includes 59 actions, of which about a third were included in the final portfolio. These actions were evaluated by 15-20 experts with regard to 3 criteria. It is possible to try out the software as a Java applet[8], but the entire software is available per request only.

[8] http://rpm.aalto.fi/rpm-software.html

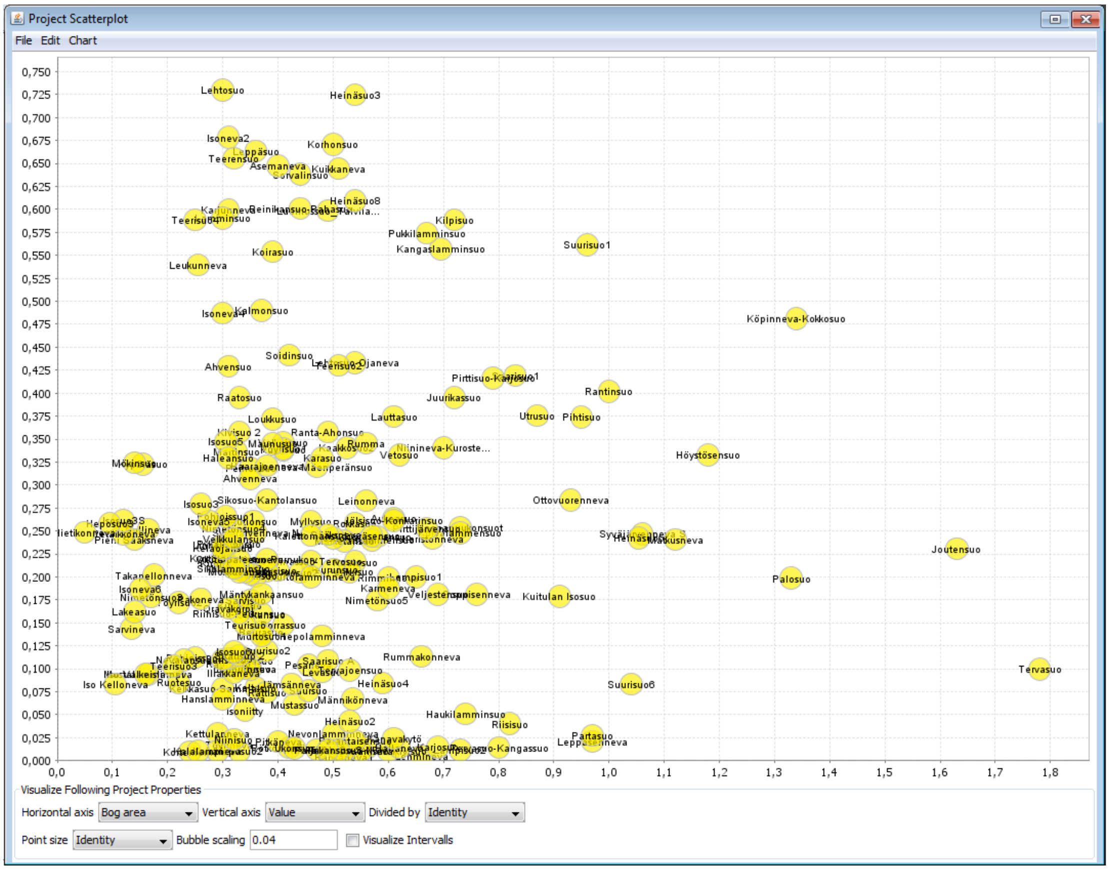

Figure 5: An example of a scatter plot generated with RPM-Decisions. Here the actions are visualized on a Bog area - Water system value plot.

2.4 Portfolio decision quality

Decisions and outcomes are fundamentally different, a good outcome is not per se evidence of a good decision. The intention of good decisions is to maximize the likelihood of good outcomes (Matheson and Matheson, 1998). The concept of decision quality describes both the quality of the analysis and the commitment to action (McNamee and Celona, 2001, p. 6). A decision quality of 100 % is defined as the level where further analysis would not be motivated due to its cost. Matheson and Matheson (1998, p. 17-34) view decision quality as a chain, where the quality is determined by its weakest link. The links are framing, actions, information, values, reasoning and commitment to action. An illustration of those is found in Figure 6. The weakest of these links should be the focus of attention, as it provides the most cost-effective way of improving the decision quality.

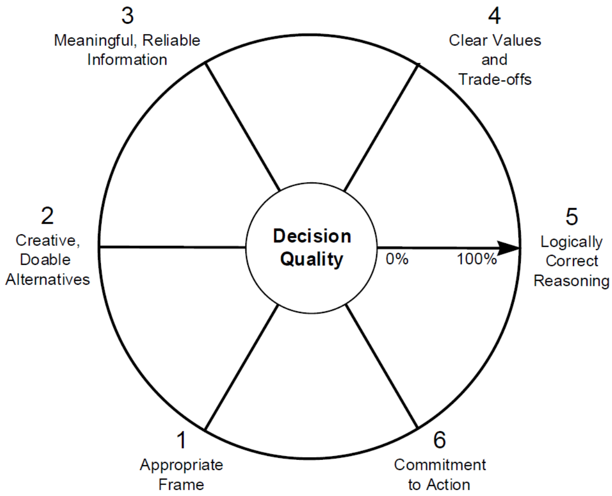

Figure 6: The six dimensions of decision quality, from McNamee and Celona (2001, p. 255).

Keisler (2011) extends the decision quality framework into portfolio decisions. The first of the six decision quality dimensions, framing, usually refers to what is to be decided, why and by whom. In portfolio decisions a natural first step is to determine what the actions are. There is extra cost in considering actions as a portfolio rather than as a series of individual actions. (Keisler, 2004). Therefore, in order to consider a set of actions as a portfolio, the extra cost should be offset by a greater benefit. This benefit could arise from modeling the interdependencies between actions.

Keisler (2011) deems high-quality actions to be such that they can be evaluated correctly, their analysis is worthwhile and they cover the solution space well. In other words a high-quality action needs to be *well-specified*, *feasible* and *creative*.

In addition to accurate information about individual actions, it is of great importance to have information about action interdependencies. As Keisler (2011, p. 36) notes, '[...] synergies and dissynergies, dynamic dependencies/sequencing, and correlations may all make the value of the portfolio differ from the value of its components considered in isolation.' Due to action interdependencies, an action ranking alone is not sufficient for determining a preferred portfolio.

Decision-makers seek the most preferred actions, but this is not always straightforward. When there are multiple stakeholders, it is often impossible to find one single solution which all could agree upon. This is in part due to different preferences and in part due to the process of constructing the preferences. Even constructing the preferences for a single decision-maker - in technical terms assessing a value function - is susceptible to biases and path-dependency (Payne et al., 1999). Some decision dimensions, such as fish population size or water level in a lake, may have a preferred level, meaning that deviations to both directions are undesired. Others may have diminishing marginal returns: an extra km^2 of nature reserve is much more valuable if the reserve is 2 km^2 large than if its size is 1 000 km^2. Taking into account and modeling such interdependencies correctly is very important when assessing the values and trade-offs.

The logic element of decision quality means the assurance that information, values and actions are properly combined. In other words, the combination should identify the course of action most consistent with the decision-maker's preferences. McNamee and Celona (2001, p. 260) note that most problems do not require complex logic once the problem is well understood. If the reasoning is clear, one should be able to describe the problem to an intelligent outsider.

McNamee and Celona (2001, p. 261) underline the importance of involving key implementers in the decision making process. Their commitment increases greatly once they understand the framing, actions, information, values and logic used to arrive at the decision.

3 Applying portfolio decision analysis in environmental problems

This section outlines how PDA is applied in environmental problems. There are four main stages:

1. Framing, structuring and learning the problem together with decision-makers
   (a) Identification of stakeholders
   (b) Designing the participation process
   (c) Generating value and resource objectives
   (d) Generating actions
   (e) Defining attributes
2. Structuring the portfolio model
   (a) Defining portfolio actions
   (b) Defining logical interdependencies between actions
   (c) Gathering data on actions' attribute-specific consequences
3. Structuring the value model
   (a) Preference elicitation
4. Analyzing portfolios
   (a) Setting consequence targets and resource constraints
   (b) Solving the set of efficient portfolios
   (c) Sensitivity analysis

The first stage consists of framing, structuring and learning the problem. Framing consists of figuring out what is to be decided and why. In this stage it is important to find out who the decision-makers and interest groups are, as there are certainly a multitude of those in any environmental decision. Another topic that needs to be addressed is the participation process. This process is needed for information gathering, value judgements and interactive solution exploration. Alternatives for the process include workshops, meetings, web-participation (in the form of forums, fill-in forms, social media etc.) and door-to-door polls. The decision-makers generate value and resource objectives taking into account the input from all stakeholders. Actions are generated with the aim of achieving these objectives. Attributes (measurement scales) are defined in order to measure how different actions contribute.

The second stage consists of gathering data on actions, deciding how they are modeled mathematically and defining logical dependencies between them. The necessary data on each action is its resource consumption and attribute consequences. Actions can be modeled mathematically as binary yes/no decisions, as being continuous on an interval or as having a small number of stages. Logical interdependencies arise e.g. in a situation where a project consists of several actions that need to be conducted sequentially. Including the last action of a sequential decision in a portfolio does not make sense unless the previous actions are included as well.

The third stage is structuring the value model. This involves scoring each attribute level and deciding which value objectives matter more than others in the decision. Another question addressed at this stage is how the actions' attribute consequences map to an overall portfolio value. The purpose is to make an informed decision about which portfolios are more beneficial from the decision-maker's viewpoint.

The fourth stage is analyzing portfolios. Since value judgements, resource consumptions and attribute levels often involve uncertainty, sensitivity analysis must be carried out meticulously. Efficient portfolios are then calculated for different resource constraints and performance targets.

3.1 Framing, structuring and learning the problem together with decision-makers

3.1.1 Identification of stakeholders

The beginning of an environmental decision process is to identify the stakeholders. Stakeholders are all the persons, groups and organizations who are or can be affected by the decision. Stakeholders are separated into decision-makers and interest groups. Decision-makers are the persons and/or organizations with the power and responsibility to make the decision. Interest groups are all others with an interest in the outcome.

Usually problems large enough to warrant serious decision analytic thinking involve multiple stakeholders. Environmental problems mainly fall into this category (Kiker et al., 2005). There can be a legal requirement for a single authority (e.g. a governmental agency) to make the decision, but that does not mean that other groups should be neglected in the process. Midgley and Reynolds (2001, p. 13) identify four broad stakeholder groups in environmental decisions: operations research practitioners, the public sector, corporations and non-governmental organizations.

3.1.2 Designing the participation process

There are several ways of engaging stakeholders, e.g. web-based forums, discussion groups or door-to-door opinion polls. For smaller groups workshops, meetings, brainstorming sessions and decision conferences can be added to the list. Facilitating, or in some cases moderating, the participation process is important. Especially in web participation, there is a risk that a vocal minority dominates the discussion. The process needs not be consensus-seeking, as the value judgements of different groups most probably differ from each other, but rather driven towards a common understanding of the situation (Kiker et al., 2005).

Whatever the participation process, it is important that all stakeholders get to voice their views and contribute to achieving an understanding of the situation. Incorporating all who are affected by the decision makes it easier to carry the decision through. A broader range of participants (and points of view) also makes more probable that viable actions and value objectives are not neglected.

3.1.3 Generating value and resource objectives

In PDA objectives can be separated into value and resource objectives. Value objectives define issues that decision-makers care about in the decision situation. Resource objectives denote what is limiting all feasible solutions. Usually there are 2–15 value objectives and 1–2 resource objectives. Examples of value objectives in an environmental decision are ‘increase fish abundance’ and ‘improve soil condition’. A typical resource objective is ‘minimize cost’.

There are several techniques for generating value objectives. One option is to have a session with all stakeholders and ask the participants to write down what they want to achieve with the decision. Some guiding questions (inspired by Keeney, 1994b) for object generation are:

- What do you want to achieve with this decision? Why is that important?
- What would be a perfect action, a terrible action and a reasonable action? What is good about each?
- What environmental, social, economic, health or safety objectives are important?
- Why is that objective important? How can you achieve it? What do you mean by that objective?

In PDA it is necessary to also define the resource objectives at this stage. One way of finding out the resource objectives is by listing or thinking up different actions and asking yourself ‘Can we implement all actions?’. The answer is going to be e.g. ‘No we cannot, because we do not have enough employees for that’. Other possible reasons could be ‘no, because we do not have money’ or ‘no, because that would eradicate too many sites of ecological value’. Next imagine that this limitation is wiped out of the way and ask again ‘Can we conduct all actions?’. The process is repeated as many times as necessary, but usually only one or two of the resource objectives are relevant for the decision. Resource objectives are not necessarily constraints, since there are no preferred or required levels for resource objectives (as in the decision conference approach by Phillips and Bana e Costa, 2007). Constraints are defined later in the process (see Section 3.4.1).

Even though different stakeholders have differing values, they should develop a common understanding about the objectives. Some stakeholders may have an indifferent attitude with regard to some objectives. This is fine, as long as they do not advocate changing the direction of desired change in that objective. The importance or weight of the objectives will be dealt with later. This also leaves the possibility of assigning a 'not at all important' for some objectives.

3.1.4 Generating actions

In order to achieve the objectives some actions need to be implemented. It is in everyone's interest that the set of actions is diverse. If good actions are not considered, they will not be chosen and the decision will be poorly aligned with the objectives.

A value-focused way of generating actions is to consider each value objective and think how it could be achieved (Keeney, 1994b). Which action would generate as much value as possible along each objective? If there is a predetermined set of actions the stakeholders can think about how each action could be made better. The Nominal Group Technique (Delbecq et al., 1975) is one way of generating actions and also makes sure that all participants are heard.

Sometimes decision-makers have a clear idea of what the actions to be analyzed are (e.g. whether to extract peat from a pre-defined set of bogs or not). Even in such cases it may still be fruitful to explore *what else* could be included in a portfolio. It is possible that some low-cost opportunities exist which provide a substantial amount of value in some objective. Such an action could be one that mitigates the harmful effects of the original actions. In the case of a diminished fish stock due to peat extraction, it might be possible to generate an action 'plant fish' to increase fish abundance.

In all situations with several decision-makers there are some shared interests, wherefore it is important to aim at generating actions for mutual gain (Fisher and Ury, 1981; Susskind et al., 1999). It is easier to split a larger pie than a smaller one. Even when there is only a single decision-maker, it is in his interest to invent several actions that are as versatile as possible.

3.1.5 Defining attributes

Attributes measure how well different actions meet the value and resource objectives. Typical attribute scales in an environmental problem could be cost in euros, expected number of bird deaths, size of a polluted area (in square kilometers) or number of jobs lost. The purpose of attributes is to measure how well the objectives are achieved. Some objectives suggest an obvious attribute. Minimum cost is measured in euros, maximum habitat as geographic area. Others may not be as easily measured, e.g. resident happiness or landscape quality.

For objectives with no natural scale, there are two approaches for constructing the measurement scale (Clemen, 1996, p. 78–79). The first alternative is to use a different scale as a proxy. A proxy scale measures something which has a high correlation with the objective. When the objective is resident happiness, one could consider residents' distance to nearest nature reserve and water color in residential area as proxy scales. Resident happiness is obviously not dependent only on those attributes. However other attributes such as street maintenance frequency or number of public transport connections are redundant if actions do not affect them.

The second alternative for attributes with no natural scale is to construct one. This means defining a number of levels explicitly for an attribute from best to worst. An example of a constructed scale is presented in Table 3.

Table 3: An example of a constructed attribute scale measuring the environmental impact of nuclear waste strategies, from Edwards et al. (2007, p. 120).

Attribute level	**Representative environmental impact**
0	No impact
1	Impact to historical or archeological site of major significance; no aesthetic or biological impact
2	Major aesthetic impact or disruption of an endangered species habitat; no archeological or historical impact
3	Major aesthetic impact or disruption of an endangered species habitat, plus impact to historical or archeological site of major significance
4	Major aesthetic impact and disruption of an endangered species habitat, no archeological or historical impact
5	Major aesthetic impact and disruption of an endangered species habitat, plus impact to historical or archeological site of major significance

Good attributes should be unambiguous, comprehensive, direct, operational and understandable (Keeney, 2007, p. 120–125). Cost in euros is an unambiguous attribute, but cost measured as either high, medium or low is not. The latter attribute scale is highly subjective and situation-dependent. Even if medium cost is clearly defined as e.g. 10–20 thousand euros, it is obvious that 11 thousand euros is preferred to 18 thousand. For some actions, it may be hard to define exact attribute consequences. Uncertainties can be presented e.g. as intervals, probability distributions or verbal descriptions.

An attribute is comprehensive if it covers the whole range of consequences and the implicit value judgements are appropriate for the decision problem. As an example of an attribute covering only a part of the consequences consider measuring 'bird deaths' when the objective is 'maximize bird population health'. Birth defects or diseases are not captured by the attribute 'bird deaths'. A second attribute 'non-fatal detrimental effects on birds (number of birds affected)' could be added in order to capture all consequences. The attribute 'bird deaths' also contains an implicit value judgement, namely that all bird deaths are equal. This may be correct, but it can also be the case that minimizing deaths of fertile birds is more important than minimizing deaths of older birds[9].

An attribute should directly measure its underlying objective. The attribute 'non-fatal detrimental effects on birds (number of birds affected)' is an example of a direct attribute. 'Water pH value in nesting area' on the other hand is not a direct attribute, because it may or may not have an effect on bird population health.

Operationality of an attribute means in short: is it practical? It should be possible to obtain the required information in the given budget and timetable, either from existing data, mathematical models or expert judgements. An operational attribute also enables decision-makers to make informed value tradeoffs. This is closely related to the understandability of an attribute.

For an attribute to support the making of an informed choice it should be understandable to all decision-makers. An attribute such as 'uranium concentration in tap water (μg/l)' is problematic. Most people have no idea whether a uranium concentration of 1 μg/l is fatally toxic or irrelevantly small. This makes trade-offs involving this attribute uninformed, since it is unclear how much money or other resources should be used

[9] This example is from Keeney (2007, p. 122–123), somewhat modified.

to lower uranium concentration. A better attribute could be 'uranium concentration in tap water (% of daily supply limit)'. The facilitators could also inform decision-makers about the health effects of uranium at different concentration levels.

3.2 Structuring the portfolio model

3.2.1 Defining portfolio actions

After the actions $j \in J = \{1, \ldots, m\}$ and the attributes $i \in I = \{1, \ldots, n\}$ are identified, the mathematical model is constructed, beginning with the definition of portfolio actions. For each action j there is a corresponding decision variable $z_j \in \{0, 1\}$, i.e. each action either is in the portfolio or outside of it.

Some actions can be carried out to a certain degree, e.g. there may be three different funding levels for an action: no funding (0€), medium funding (5000€) or full funding (10 000€). This can be treated as a situation with three different actions, out of which maximally one is chosen. Suppose that the indices of these three actions are in the set $J' \subset J$. The fact that the actions J' are all different versions of the same action imposes a constraint

$$\sum_{j \in J'} z_j \leq 1. \tag{2}$$

The funding in the above example may naturally also be given as an interval such as [0 €, 10 000€]. In such cases the action is split up in as many different actions as are deemed necessary. A fine-grained partition leads to a better solution, but on the other hand computation becomes tedious when there is a large number of actions.

3.2.2 Defining logical interdependencies between actions

Logical interdependencies are requirements of the type 'only one action out of A, B and C can be selected' (see Equation (2)), 'at least one of A, B and C must be selected', 'B can be selected only if A is selected' and so on. Such requirements arise naturally in many decision situations. For example in a case where an action has two possible outcomes, a bad and a good one, only one of those outcomes can be realized. Hence it makes sense to only include either one of those in the portfolio. In some cases one of the options must be selected, e.g. 'at least one of A, B and C must be selected'. This imposes the constraint

$$z_A + z_B + z_C \geq 1.$$

One possibility is that a project consists of several actions that must be conducted sequentially. Conducting the last one is impossible if the previous ones are not conducted. For example the constraint 'B can be selected only if A is selected' corresponds to

$$z_B \leq z_A.$$

3.2.3 Gathering data on actions' attribute-specific consequences

Each action is described by a consequence vector $x^j = (x_1^j, \ldots, x_n^j)^T$, where x_i^j is the consequence of action j with regard to attribute i. These consequences form the basis of portfolio value assessment and it is important to gather accurate data on them.

Some attribute-specific consequences are easily available ('peat bog area'), while others need to be measured ('pH value in water system'). Sometimes data must be assessed from the stakeholders through questionnaires ('recreational value of water system'). Attributes for which data-gathering proves too tedious, a redefinition or construction of a different attribute scale can be necessary.

3.3 Structuring the value model

In a standard MCDA process the value model is built to capture the decision-maker's preferences among the possible multiattribute action consequence vectors and then used to identify the most preferred action, see, e.g. Keeney and Raiffa (1976). In situations with multiple decision-makers the value model also often combines the individual preferences into a group preference. This enables analysis of which actions are most preferred from the viewpoint of the group of decision-makers. In PDA the value model must capture – in addition to the multiattribute and group preferences – preferences among possible action combinations, i.e. combinations of possible multiattribute consequence vectors.

Perhaps the most widely used model to calculate portfolio value is the linear-additive value model (Golabi et al., 1981). The linear-additive value model aggregates the actions' attribute-specific consequences into an overall action value and then aggregates these action values into a portfolio value. The value of an action is

$$v(x^j) = \sum_{i=1}^{n} w_i v_i(x_i^j),$$

where the w_i are attribute weights and $v_i(x_i^j)$ is the value of attribute i's consequence for action j. The value of a portfolio is

$$V(z) = \sum_{j=1}^{m} z_j v(x^j) + (1 - z_j) v(x^{j0}),$$

where $v(x^{j0})$ is the value of not choosing action j and $z_j \in \{0, 1\}$.

The additive-linear value model assumes that the attributes i are preference-independent and that an action's contribution to the portfolio value does not depend on what other actions are included in the portfolio (Golabi et al., 1981). For an example of preference-dependence between attributes consider the recreational value of a lake, measured with attributes 'aesthetic value' and 'visitors per year'. If a value model simply added up those two effects, it would not account for the fact that aesthetics has no value if there are no visitors. Also the value of aesthetics rises with the number of visitors, hence more attention should be paid to the aesthetics of a popular site than that of a rarely visited one. In order to preserve the additivity assumption, the attributes could be combined into a single, new constructed attribute 'expected aesthetic value for people' with some number of well-defined attribute levels (an example of a constructed attribute is found in Table 3).

For an example of preference-dependent actions consider a situation of saving water in a residential area where drought is an issue. An action leads to 5% water savings, costs 10 M$ and causes 30 MT greenhouse gas emissions. In the additive-linear model this action brings the same value increase when added to a portfolio (20%, 100M$, 200MT) and a portfolio (80%, 10M$, 0MT). This underlying assumption may not hold e.g. in the case where a small amount of water can be supplied from existing sources but for larger amounts new sources need to be found. The value of increasing water savings by 5 percentage units is larger when the overall savings are 20% than when they are 80%.

When the preference assumptions of the additive-linear value model are relaxed the portfolio value can be calculated with a multilinear portfolio value function (Liesiö, 2014). The multilinear portfolio value function can be used to capture preference dependencies between actions and attributes, thus making it possible to model, for instance, non-constant attribute-specific portfolio value. In some it is also possible to use heuristic approaches in which additional terms are added to the additive-linear portfolio value model to capture dependencies between actions or attributes, see e.g. Grushka-Cockayne et al. (2008). Often, consequences on some attributes (e.g. money or manpower) can be aggregated and evaluated at the portfolio level. In such cases a non-linear attribute-specific value function can be directly applied on the portfolio level (Argyris et al., 2011). Another approach is to use additional constraints to limit the portfolios' attribute-specific consequence to an interval where the assumption of constant marginal value serves as a reasonable approximation (Kleinmuntz, 2007).

A more complicated value model leads to challenges in preference elicitation, as also in standard MCDA. In PDA a non-linear portfolio value results in additional challenges in the identification of the most preferred portfolio, since it requires solving a non-linear integer optimization problem.

3.3.1 Preference elicitation

Elicitation of the decision-maker's preferences refers to the process of estimating the numerical values for the parameters in the chosen portfolio value model. For instance, preference elicitation for the additive-linear portfolio value model consists of two phases, scoring and weighting (Golabi et al., 1981).

The customary practice is to give the most preferred attribute consequence a score of 1 and for the least preferred consequence a score 0. Let's denote the least preferred consequence of attribute i with $\underline{x}_i$ and the most preferred consequence with $\overline{x}_i$. The corresponding scores are $v_i(\underline{x}_i) = 0$ and $v_i(\overline{x}_i) = 1$. The form of the scoring function is usually chosen to be either linear, convex or concave. These scoring functions are illustrated in Figure 7. A linear scoring function means that each unit of increase in the attribute consequence increases value with the same amount. A convex scoring function corresponds to a situation where an additional attribute consequence unit contributes more value the higher the attribute level. A concave scoring function is the opposite, an additional unit contributes less value the higher the attribute level.

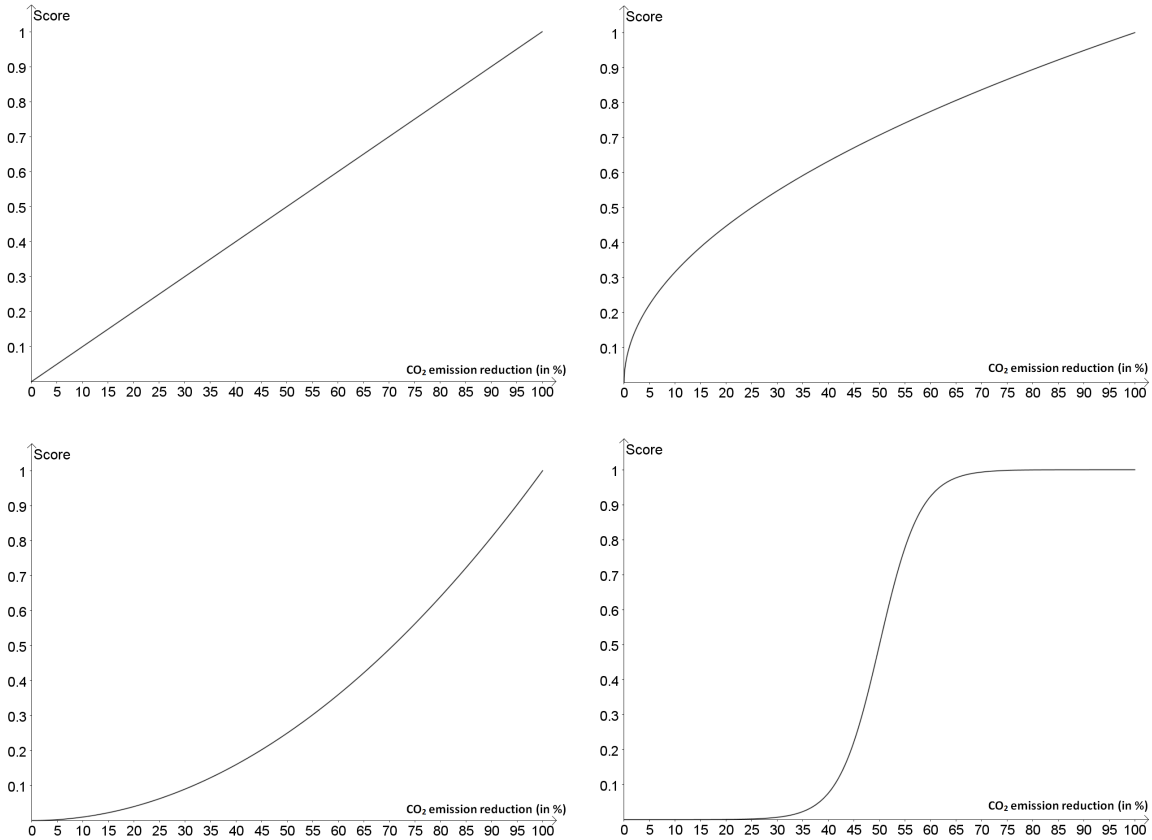

Figure 7: Functions for scoring CO_2 emission reductions. In these figures the least desired consequence is $\underline{x}_i = 0\%$ and the most desired $\overline{x}_i = 100\%$. Upper left is a linear, upper right a concave, lower left a convex and lower right a sigmoid scoring function.

The weight of an attribute in the model is dependent on how much change is possible in that attribute. Consider a simple case with two attributes, cost and bird deaths. Suppose that there are two possible portfolios represented by $x =$ (150€, 20 000 bird deaths) and $y =$ (50€, 10 000 bird deaths). In this case the attribute 'bird deaths' should receive a higher weight than cost, assuming that 10 000 less bird deaths is preferred to 100€ savings.

One method of eliciting weights is to present all consequence intervals and ask the following question: 'In which attribute would the change from the worst portfolio performance level $\underline{x}_i$ to the best level $\overline{x}_i$ be most important?' The attribute which is deemed most important gets a weight of 100. Next the second most important attribute is identified in a similar manner and given a weight between 0 and 100, reflecting its importance compared to the most important attribute. This method is applied until all attributes have weights. Finally all the acquired weights are divided by their sum in order to make weights add up to 1. This results in a weight vector $w = (w_1, \ldots, w_n)$.

The weights w can be elicited together for all the stakeholders at the same time or separately for each stakeholder. In the former case, a complete compromise is probably not found, as the values are different. But if there is only a small number (2-4) of stakeholders, they may agree on most of the weights, leaving only a handful open to speculation. Methods exist for dealing with incomplete information, but the results become less precise the more general the information about weights.

3.4 Analyzing portfolios

After preference elicitation the value model is completely specified and hence it can be combined with the portfolio model to produce decision recommendations, i.e., portfolios that satisfy logical interdependency constraints and perform well with regard to the decision objectives. It is beneficial, especially in multi-stakeholder settings, to organize a workshop where the results are presented and sensitivity analysis, constraint setting and different what-if analyses can be done interactively (Stummer and Heidenberger, 2003).

For small portfolio models (less than 50 actions) interactive computation of action recommendations in the workshop is possible for all the software reviewed in Section 2.3. In RPM-Decisions, however, when the feasible sets of weights and scores are large, and there are many interdependencies between actions, solving even a small portfolio problem can take several minutes. For larger models the necessary computations need to be done beforehand. This often means that the results are computed for several combinations of the key model parameters (resource constraints, weights).

3.4.1 Setting consequence targets and resource constraints

The value model can be augmented by setting target levels for some objectives. Targets are statements like 'at least 5 000 hectares of peat bogs for extraction' or 'more than 10 000 bird nesting sites preserved'. Let us assume that attribute i measures the number of bird nesting sites. Then the latter statement means a requirement

$$\sum_{j=1}^{m} z_j x_i^j \geq 10000. \tag{3}$$

The resource constraints need to be set together with the targets. A resource constraint is a level for an attribute which may not be exceeded. There are essentially two types of resources. The first one needs to be minimized regardless of the attribute level, meaning that the less we consume of the resource the better. Financial resources usually fall into this category, since they can be easily allocated elsewhere. The second type of resource is such that the consumption should not exceed a certain level, but below that level there are no consumption preferences. This could be the case with the workforce of a company. With a permanent staff of ten persons, a company can allocate around 370 hours per week to different projects. However the amount of hours that different projects consume does not matter, as long as it does not exceed 370 hours weekly.

Assume the budget is 30 000 € and that attribute i measures each action's cost. This statement translates then into

$$\sum_{j=1}^{m} z_j x_i^j \leq 30000. \tag{4}$$

As can be seen from Equations (3) and (4), targets and constraints are two sides of the same coin. The distinction between them concerns only the direction of desired change, and they could theoretically both be called constraints. The distinction is nonetheless worth preserving for the sake of clarity.

With several stakeholders, there are certainly differing opinions about the constraints and targets. One way of solving this is to choose the strictest target and constraint along each objective. E.g. in a case where one stakeholder desires to preserve at least 100 bird nesting sites and another stakeholder 10 000, the latter one is adopted as a target, because the former one is included in it. This approach has an apparent downside; it may result in no feasible solutions. Another strategy is to negotiate common targets and constraints.

3.4.2 Solving the set of efficient portfolios

As previously noted, in most cases it is not possible to study each possible portfolio individually due to the large number of portfolios. Portfolios need to be pruned somehow. For a single decision-maker with exact weights and actions' consequences, the solution is acquired by maximizing portfolio value

$$\begin{aligned} &\max\ V(z) \\ &\sum_{j=1}^{m} z_j x_i^j \leq r_i,\ i = 1, \ldots, n \\ &z \in \{0,1\}^m, \end{aligned} \tag{5}$$

where the $r_1, \ldots, r_n$ are resource constraints. In the more common case – with either several decision-makers, imperfect information about weights or both – the above optimization problem does not have a single optimal solution.

In such cases PDA models are often used to produce a set of efficient portfolios (also called non-dominated or Pareto-optimal portfolios, see e.g. Liesiö et al., 2007, 2008; Stummer and Heidenberger, 2003). For instance Liesiö et al. (2008) use the following definition: portfolio z is *efficient* if there is no feasible portfolio z' that

i) consumes less (or an equal amount) of each resource and

ii) has a greater value for all feasible weights.

Solving the set of efficient portfolios is computationally more demanding than solving a single optimal portfolio (cf. problem (5)). However, there are many reasonable efficient exact and approximate algorithms available (Liesiö et al., 2008; Mild et al., 2013) of which some have been implemented into software (e.g. RPM-Decisions).

An action's core index indicates the proportion of efficient portfolios where that action is present, i.e.,

$$CI(z_j) = \frac{|\{z \in P_E | z_j = 1\}|}{|P_E|}, \tag{6}$$

where P_E is the set of efficient portfolios and $|\{\cdot\}|$ denotes the number of portfolios in the set $\{\cdot\}$. An action which is present in all efficient portfolios has the core index 1 and is called a core action. An action which is present in no efficient portfolio has the core index 0 and is called an exterior action. The actions present in only a part of the efficient portfolios, i.e. core index in the interval $(0, 1)$, are called borderline actions.

The core indices provide a straightforward decision recommendation: select core actions, discard exterior actions and analyze the borderline actions further. One way to narrow down the search space is by introducing additional constraints on the weights w.

3.4.3 Sensitivity analysis

In PDA also standard sensitivity analysis can be used as an alternative for computing the entire set of efficient portfolios. Sensitivity analysis of resource constraints and consequence targets has two main purposes:

- To find out if more value can be generated by a marginal increase in a resource constraint.
- To find out if a resource constraint can be tightened (and thus resources spared for other uses) without a significant loss of value.

Both purposes are formulated in rather subjective terms. There are no definite answers to what constitutes a 'marginal increase' or a 'significant loss of value', these are up to the decision-makers to decide. Surveying different 'what-if' -scenarios enables decision-makers to negotiate a common solution and to make informed trade-offs.

In economics, the term 'shadow price' is used to denote the increase of value, which is achieved by relaxing a constraint. This is one way of reporting the sensitivity of constraints. One has to bear in mind that the decision variables are usually binary and not continuous. This has the consequence that an increase in a resource constraint brings no value, unless it results in a new action being selected. One workaround is to report how much each constraint needs to be increased for the next action to be selected and how much the overall value increases as a result.

Sensitivity analysis of the value model provides information about the consequences of the decision-makers' value statements. It also allows informed trade-offs by finding out if substantial amounts of value can be generated along one objective by bargaining on the value of another objective. Decision-makers may want to reconsider their weight statements after the results are presented.

Often decision-makers and stakeholders have a solution in mind before the analysis has even started. This solution may become a 'pet action' (or portfolio) which they want to conduct no matter what. At the sensitivity analysis stage it is advisable to inform them about the consequences of those actions, i.e., what the overall result is when pet actions are forced into the portfolio compared to the case when all actions are treated equally.

4 Illustrative example: Minimizing the environmental risk of peat production

In this Section an example of portfolio modeling is presented. The example, although fictional, is based on the MCDA analysis by Marttunen et al. (2011), who developed an MCDA model to capture the environmental risks arising from extracting peat from bogs for energy production. The model was then used for prioritizing zoning of bogs for energy production.

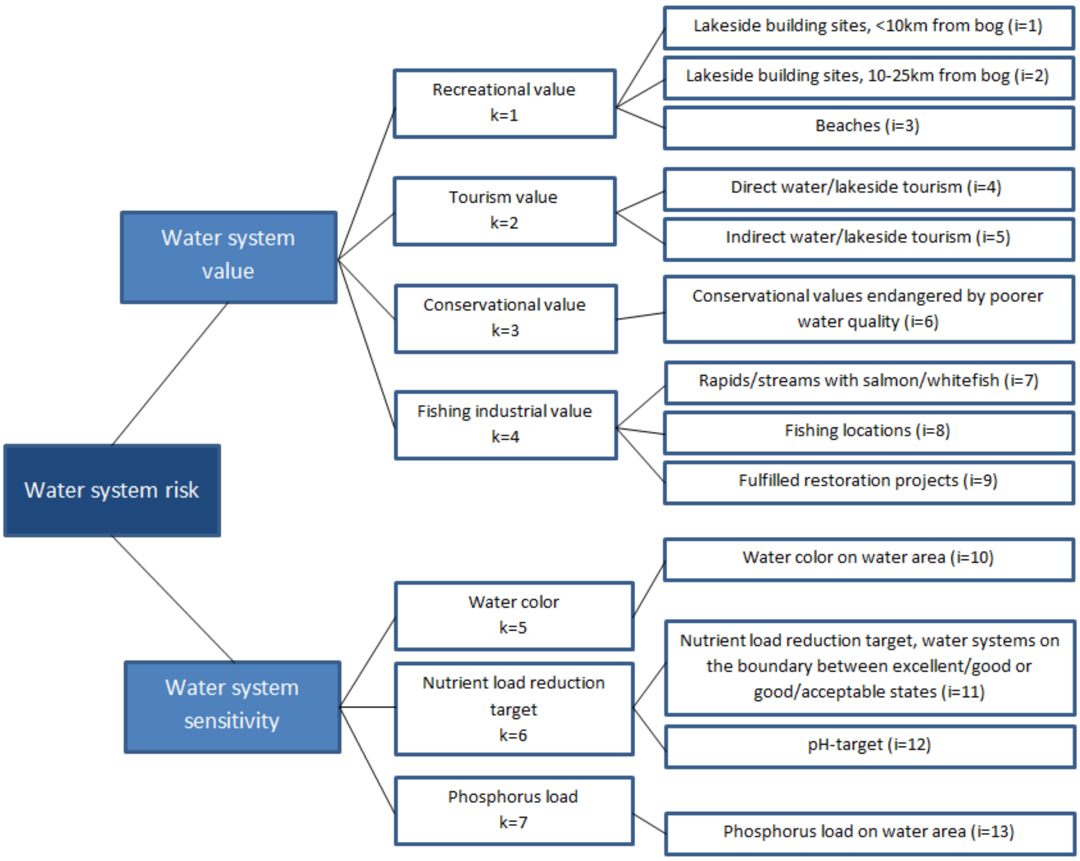

Figure 8: Value tree for the selection of peat bogs in Central Finland. The value objective 'water system risk' consists of two main level criteria which are measured with altogether 13 attributes.

4.1 Problem framing

The problem framing starts with assessing what is to be decided. In the peat bog selection problem, the municipal coalition needs to decide which bogs are zoned for peat extraction. This is done in order to meet the increased demand for peat due to the construction of a new power plant.

Peat extraction poses some risk to water systems. This harm is quantified with altogether 13 attributes (see Figure 8), which fall under two main categories, water system value and water system sensitivity.

The extraction of peat from potential bogs, altogether 206, are a natural choice as actions. The decision-makers can also include actions that are aimed at mitigating the risks peat production poses on water systems. Fish planting and new beaches are examples of such actions.

4.2 Structuring the portfolio model

Structuring the portfolio model involves deciding whether the actions are modeled with binary or continuous decision variables. The zoning areas are already pre-defined and they are either included in the plan or not, so they are modeled with binary decision variables.

Attribute consequences for each of the 13 attributes in Figure 8 and the bog area are gathered for all actions. Some consequences are easily available from existing sources, e.g. 'lakeside building sites'. For other attributes input from decision-makers or interest-holders is necessary.

4.3 Structuring the value model

A value model is a model for incorporating the decision-makers' preferences. It defines how the actions' attribute-specific consequences map to an overall portfolio value.

For the sake of simplicity only the two main level attributes, water system value and water system sensitivity, from Figure 8 are used. Action j is represented by the vector (x_V^j, x_S^j). Assuming an additive-linear value model, the portfolio value to be minimized is

$$V(z) = \sum_{j=1}^{206} z_j (w_V v_V(x_V^j) + w_S v_S(x_S^j)),$$

where $v_V(\cdot)$ and $v_S(\cdot)$ are the attribute-specific scoring functions for water system value and water system sensitivity. The minimization is done for different peat requirements $P(z) \geq P$, where

$$P(z) = \sum_{j=1}^{206} z_j x_P^j$$

and x_P^j is the amount of peat on bog j.

4.4 Analyzing portfolios

Equity Of the software reviewed in Section 2.3 let us first take a look on Equity. Equity proposes two alternatives to the current (initial) portfolio. One alternative cheaper than the current one but with the same benefit and the other alternative providing more benefit for the same cost. Inside Equity actions are grouped inside areas, which represent for instance different business units or geographical areas. The areas can be either cumulative or exclusive. From an exclusive area only one action can be chosen, whereas a cumulative area has no such limitation.

In this case the actions are grouped into areas according to the bogs' drainage basin. Furthermore the areas are treated as cumulative, so choosing one peat bog does not exclude choosing others from the same drainage basin. The peat bogs are described with three variables: water system value (V), water system sensitivity (S) and peat amount (P). An initial portfolio is chosen, with one bog from each drainage basin. Figure 9 shows alternatives for the current selection when different parameters w_V and w_S are chosen.

HiPriority The cost objectives, water system value and water system sensitivity, are summed up to a single cost for each action. HiPriority then ranks actions according to their benefit-to-cost ratio

$$\frac{x_P^j}{w_S v_S(x_S^j) + w_V v_V(x_S^j)}$$

in a descending order. I.e., bogs with a higher ratio produce a large amount of peat for the water system risk they inflict. Sensitivity analysis is done by exploring different 'what if' -scenarios by changing the weights w_S and w_V in the data grid input window (see Figure 10).

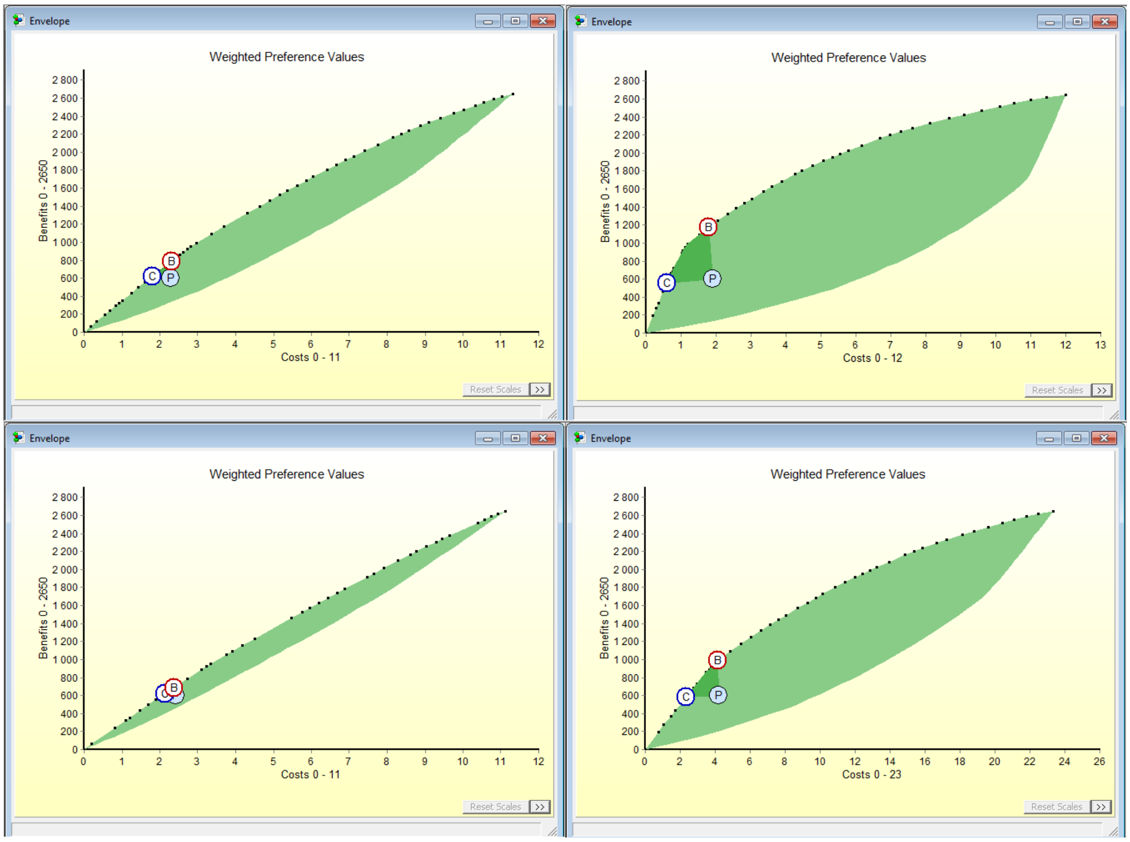

Figure 9: What if -analysis in Equity for different values of the cost parameters water system value w_V and water system sensitivity w_S. The portfolios (green area) are shown on a cost-benefit plot, with the cost $V(z)$ on the x-axis and the benefit $P(z)$ on the y-axis. The subplots correspond to values $(w_V, w_S) = (0.25, 0.75); (0.75, 0.25); (0.1, 0.9); (0.5, 0.5)$. All subplots have three circles; P, C and B. P is the current portfolio, C is a cheaper alternative to the current portfolio with the same benefit and B provides more benefit than the current portfolio with the same cost.

RPM-Decisions The data is input on the 'Criterion scores' sheet under 'Step 1 - Input' (see Figure 3) and can be easily copied there from Excel. RPM-Decisions solves efficient portfolios for the problem

$$\min \; V(z) = w_V \sum_{j=1}^{206} z_j v_V(x_V^j) + w_S \sum_{j=1}^{206} z_j v_S(x_S^j) - w_P \sum_{j=1}^{206} z_j v_P(x_P^j)$$

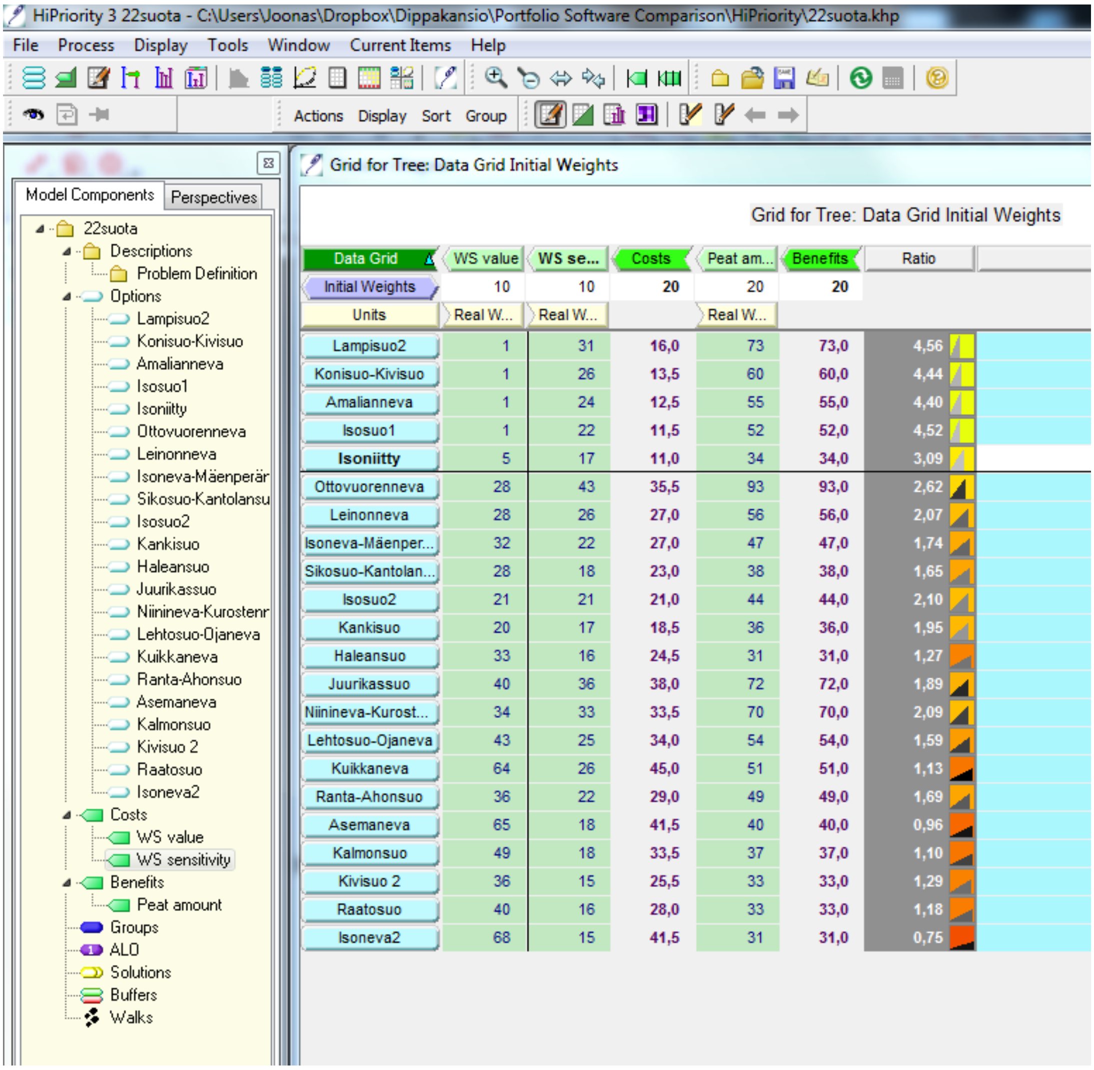

Figure 10: The data grid input window in HiPriority with data for 22 of the 206 actions analyzed in the example. Weights for the cost and benefit objectives are input on the second row in the table ('Initial Weights'). The benefit-to-cost ratios are presented in the rightmost column.

with weight restrictions

$$w_S + w_V + w_P = 1$$
$$w_S, w_V, w_P \in [0, 1].$$

In other words the model maximizes peat and minimized the water system risk, which consists of water system value and water system sensitivity. The results are computed using the option 'Only potentially optimal ND-portfolios' under 'Fast solve', since this speeds up the computation considerably. There are several options for analyzing the portfolios. ‘Core indices’ displays the core indices for all actions, i.e. the share of efficient portfolios that include the action (see Figure 11). The core indices provide a clear decision recommendation: choose core actions, discard exterior actions and analyze the borderline actions further (Liesiö et al., 2007, p. 1497). In this case there are no core projects (these would be displayed in green in the software) or exterior projects (red), the smallest core index 0.0019 belongs to ‘Hietikonneva’.

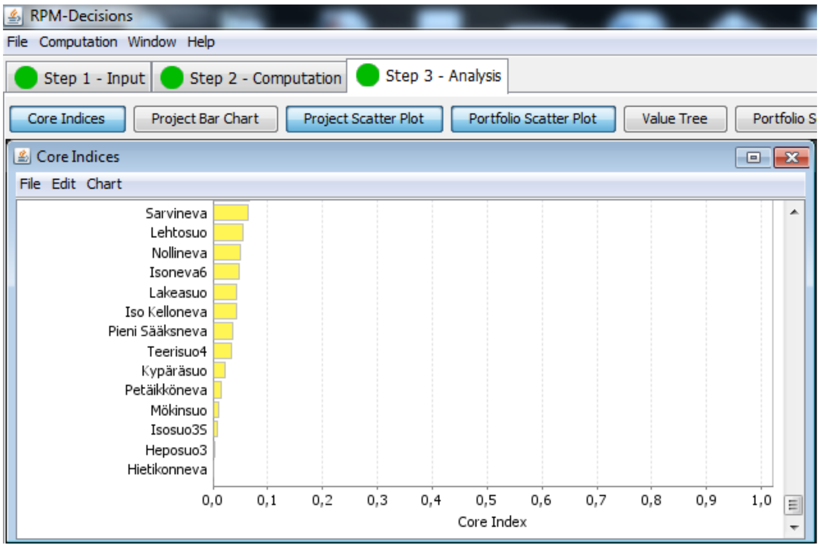

Figure 11: The actions’ core indices in the peat bog selection problem presented in RPM-Decisions.

Since all actions are borderline actions and this provide little guidance in portfolio selection, some constraints are necessary. The ‘Portfolio screening’ window offers a way to interactively set constraints and see how these affect the results. E.g. constraining the peat bog area to exceed 60km^2 is done by clicking on ‘Bog area’ in the screening window, dragging the lower constraint to 60 and upper constraint the total area of all bogs, 98.18 (see Figure 12). After this the user can proceed to view the new core indices when the constraint is in effect. Now approximately 2/5 of the actions are core actions and the rest borderline actions. By further constraining the risk to water system value to 1/3 of the total value the number of borderline actions is reduced to 10% of all actions.

One possibility to search through the portfolio space is to visualize the portfolios on a ‘bog area - water system value’ -plot. From this plot one can see which constraints are possible and which result in no feasible portfolios. An example of such a plot is presented in Figure 13.

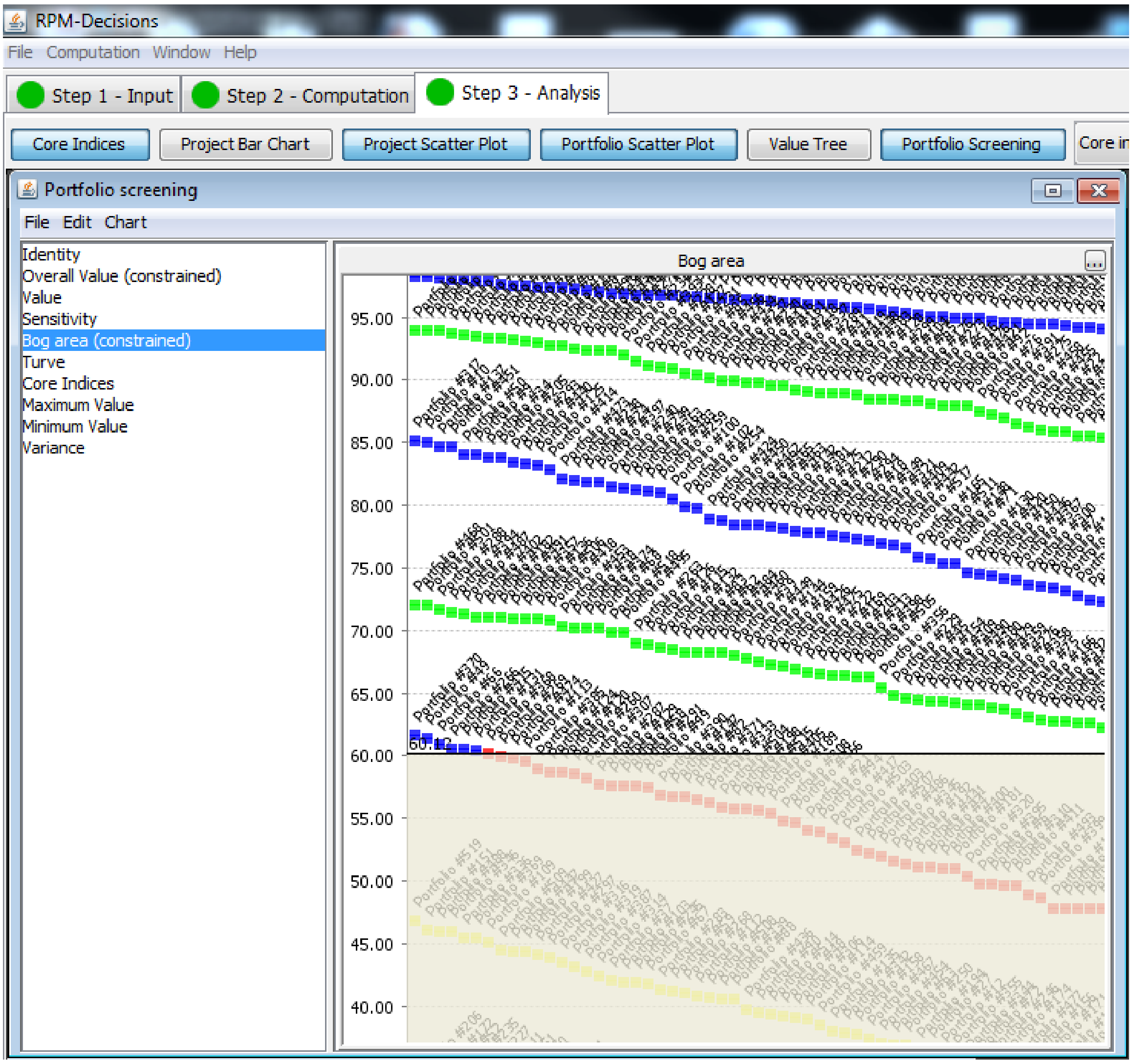

Figure 12: The portfolio screening window in RPM-Decisions. The admissible portfolios are green or blue and the portfolios which do not meet the constraint are red or yellow.

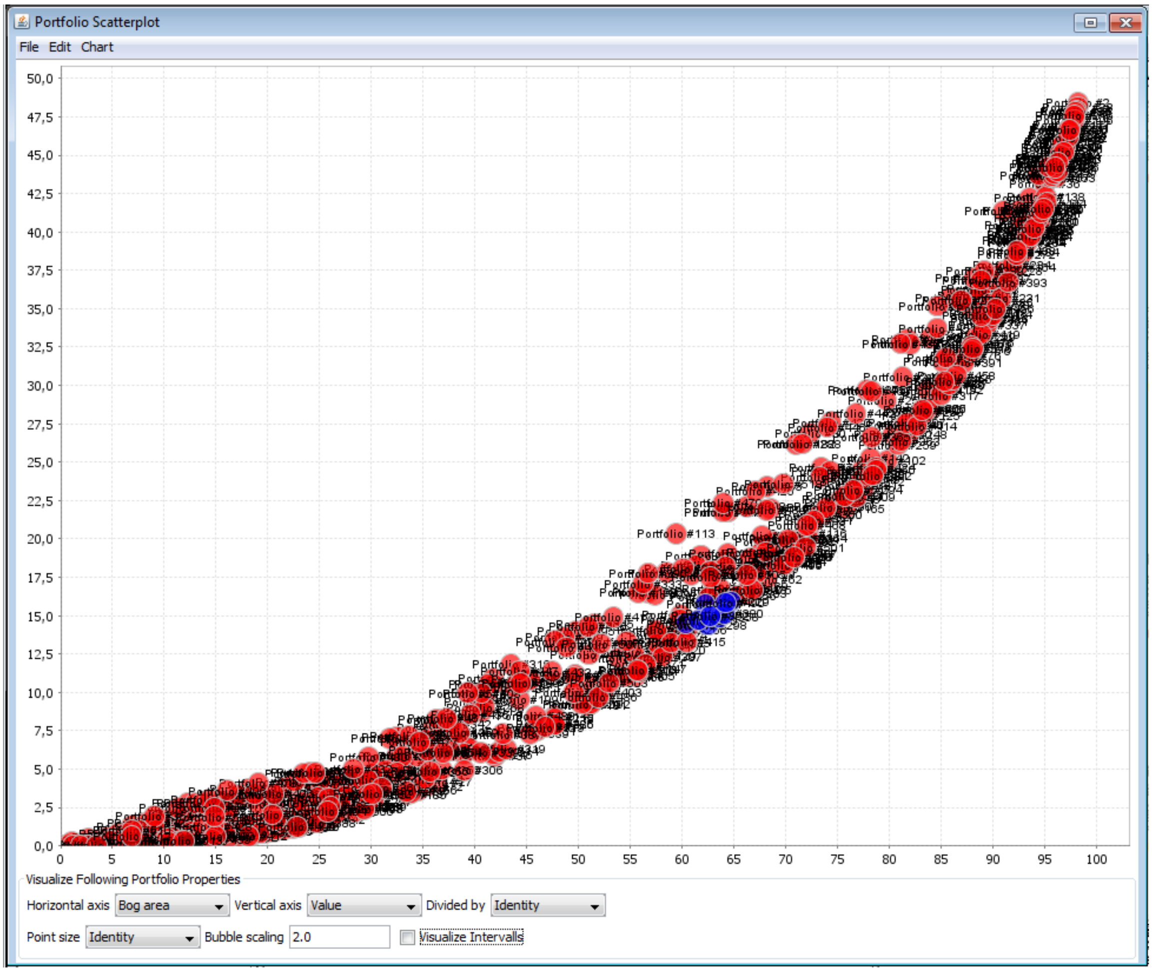

Figure 13: Portfolio plot in RPM-Decisions. The horizontal axis represents the total area of peat bogs in a portfolio in km^2. The vertical axis is the total portfolio water system value. Feasible portfolios within the current constraints are represented in blue, unfeasible portfolios in red.

4.5 Discussion

The additive-linear value model is not entirely adequate in this case. Peat bogs with a shared drainage basin are interconnected. The water system value of a drainage basin may be entirely spoiled after a certain amount of peat has been extracted and in this case additional extraction poses no increase in risk. This suggests that the value model inside a drainage basin can be non-linear for water system value. The peat bogs are divided onto $k = 1, ..., 105$ drainage basins. The indices of the bogs on drainage basin k are found in the set J_k. The value model inside a single drainage basin is chosen to be piece-wise linear for water system value. The water system value for a portfolio z is

$$V_V(z) = \sum_{k=1}^{105} \widetilde{v}_V(\sum_{j \in J_k} z_j x_V^j), \tag{7}$$

where $\widetilde{v}_V$ is the drainage basin specific value function given by

$$\widetilde{v}_V(\sum_{j \in J_k} z_j x_V^j) = \min\{1, \sum_{j \in J_k} z_j v_V(x_V^j)\}. \tag{8}$$

That is, up to a water system value 1 the value function is linear, after that the drainage basin is considered ‘spoiled’ and additional bogs do not increase the water system value. For the water system sensitivity the values for different bogs are simply summed up,

$$V_S(z) = \sum_{j=1}^{206} z_j v_S(x_S^j). \tag{9}$$

The value of a portfolio is

$$V(z) = w_V V_V(z) + w_S V_S(z). \tag{10}$$

Using the value functions defined in Equations (7)-(10) the optimal portfolios are calculated for weights $(w_V, w_S) = (0.01, 0.99)$, $(0.02, 0.98), ..., (0.99, 0.01)$ and zoning area requirements $P = 1000$, $2000, ..., 9000$ hectares. This results in $99 \cdot 9 = 891$ portfolios. For the scores $v_S(\cdot)$ and $v_V(\cdot)$ the values from Marttunen et al. (2011) are used. For each zoning area requirement the portfolios fulfilling the requirement are studied closer. These are (roughly) the efficient portfolios, as defined in Section 3.4.2, for the information set $S_w = \{(w_V, w_S) | w_V + w_S = 1, \ \ w_V, w_S \in (0,1)\}$. Each bog is present in none, some or all of the efficient portfolios. The share of portfolios where the bog is present is the core index of the portfolio (see Equation (6)). The core bogs (core index 1) are in the optimal portfolio for all weights in S_w and the exterior bogs (core index 0) are present in none of the optimal portfolios. The bogs for which the core index is between 0 and 1 (borderline bogs) are present in some of the optimal portfolios but not all. The core indices for all 206 bogs and zoning area requirements are presented in Appendix A.

5 Illustrative example: Building a sustainable urban water system

Mitchell et al. (2007) present a case study on cost analysis of options and alternative configurations for sustainable urban water in the 'Bridgewater' region, referred to as 'Steve's story'. The aim is to meet the water demand in an urban area while considering ecological impacts.

5.1 Problem framing

The task is to make water supply meet demand in the new development Bridgewater Downs for the next 50 years in a cost-effective manner. Water is scarce in the area, and it is hence important to have plans how to reduce demand of potable water. Water savings are the single value objective in this case. Cost is one of the resource objectives. Externalities are (positive or negative) effects of a decision on otherwise uninvolved parties, who do not have a say in the matter. The externalities include greenhouse gas (GHG) emissions, biodiversity impacts on local ecosystems and perceived public health risk. Of these only GHG emission reductions are quantified as a resource objective. The other externalities are incorporated in the analysis by considering only actions that meet certain externality constraints (see Mitchell et al., 2007, p. 36-37).

The actions and their effects are presented in Table 4. The cost of each action consists of several subcategories; some of the costs are annually reoccurring whereas others are one-time costs. The subcategories are specified in Table 5 and the total cost of each action in Table 4. When estimating the total cost a discount rate of 7% is used. Many of the costs are dependent on the number of households and commercial lots. The development is empty on the outset, but will reach a final size of 8 000 households and 125 commercial lots. The growth rate is 330 households and 5 commercial lots annually. In addition to the costs, the water savings and GHG emissions are estimated for each action.

Table 4: Actions' consequences and interdependencies in Section 5's example, data from Mitchell et al. (2007, p. 48).

Action	Description	Water savings (%)	Cost (millions of 2006 $)	Avoided GHG emissions over 50 years (in MT)	Mutually exclusive with
a	Efficiency for new residential + new commercial customers	13	1.15	108	-
b	4500 l raintanks for all new residential toilet + garden water use	20	17.03	-36	f
c	Small scale recycling for new residential toilet + garden water uses	19	22.51	-14.5	e
d	Aquifer storage + recovery (ASR) for irrigation of public open space (includes a large wetland for stormwater capture + treatment)	19	3.02	-14.5	e
e	Large scale dual reticulation from upgrade of existing sewage treatment plant to all new residential toilet + garden water uses + public open space irrigation	40	22.51	-45	c, d
f	3000 l rain tanks for all new residential hot water	18	13.12	-31	b

Table 5: Cost factors associated with different actions, data from Mitchell et al. (2007, p. 52).

Cost description	Cost	Unit	Part of action
Efficient fixtures (4.5/3L Toilet) fixtures	100	\$/hh	a
Efficient appliances	200	\$/lot	a
4.5kL raintank installed	3 500	\$/hh	b
Raintank pump operating expenditure	0.3	\$/kL	b,f
Raintank inspection and maintenance	50	\$/hh/yr	b,f
Raintank pump replacement every 15yrs	500	\$/hh	b,f
STEP and small bore sewer	5 000	\$/hh	c
2ML/day wastewater treatment plant	$1.75{\cdot}10^6$	\$	c
Small bore system including WWTPO&M	375	\$/hh	c
STEP pump opex	25	\$/hh	c
150 ML/yr ASR site - bores and pumps	200 000	\$/site	d
Wetland for stormwater capture	$1{\cdot}10^6$	\$	d
ASR site - bores and pumps	0.1	\$/kL	d
Dual reticulation	2 000	\$/hh	e
Dual reticulation mains	1 000	\$/hh	e
Upgrade STP to recycled water class A	$8{\cdot}10^6$	\$	e
Upgrade STP to recycled water class A	200	\$/ML	e
3.0kL raintank installed	2 500	\$/hh	f

5.2 Structuring the portfolio model

For the sake of simplicity the decision variables are assumed to be binary in this analysis, i.e. the actions are either carried out completely or not at all. For most actions this is a valid assumption. Consider action c, which includes 'upgrade of existing sewage treatment plant'. The plant either is upgraded or not. For other actions, the assumption does not hold. Raintanks can be built for any range of households between 0 and 8 000. Binary actions do however provide a sufficient approximation and hence raintanks are also modeled as binary in this example.

The six possible actions are not independent. Consider the raintanks in action b and f. A single household does not collect enough rainwater for two tanks (Mitchell et al., 2007, p. 51). Actions b and f can hence be considered mutually exclusive. Actions c and d meet the same demand as action e, hence action e is mutually exclusive with actions c and d. Without any interdependencies there would be $2^6 = 64$ portfolios. Taking the interdependencies into account, 30 portfolios can be constructed from the six actions a,b,. . . ,f. These portfolios are listed in Table 6.

Table 6: Portfolios in Section 5's example. The efficient portfolios are bolded.

	a	b	c	d	e	f	Water savings (x_S)	Cost (x_C)	Avoided GHG (x_G)
Portfolio 1	✓	✓	✓	✓	-	-	71	43.7	43
Portfolio 2	✓	✓	✓	-	-	-	52	40.7	57.5
Portfolio 3	✓	✓	-	✓	-	-	52	21.2	57.5
Portfolio 4	✓	✓	-	-	✓	-	73	40.7	27
Portfolio 5	✓	✓	-	-	-	-	33	18.2	72
Portfolio 6	✓	-	✓	✓	-	✓	69	39.8	48
Portfolio 7	✓	-	✓	✓	-	-	51	26.7	79
Portfolio 8	✓	-	✓	-	-	✓	50	36.8	62.5
Portfolio 9	✓	-	✓	-	-	-	32	23.7	93.5
Portfolio 10	✓	-	-	✓	-	✓	50	17.3	62.5
Portfolio 11	✓	-	-	✓	-	-	32	4.2	93.5
Portfolio 12	✓	-	-	-	✓	✓	71	36.8	32
Portfolio 13	✓	-	-	-	✓	-	53	23.7	63
Portfolio 14	✓	-	-	-	-	✓	31	14.3	77
Portfolio 15	✓	-	-	-	-	-	13	1.2	108
Portfolio 16	-	✓	✓	✓	-	-	58	42.6	-65
Portfolio 17	-	✓	✓	-	-	-	39	39.6	-50.5
Portfolio 18	-	✓	-	✓	-	-	39	20.1	-50.5
Portfolio 19	-	✓	-	-	✓	-	60	39.6	-81
Portfolio 20	-	✓	-	-	-	-	20	17.0	-36
Portfolio 21	-	-	✓	✓	-	✓	56	38.7	-60
Portfolio 22	-	-	✓	✓	-	-	38	25.5	-29
Portfolio 23	-	-	✓	-	-	✓	37	35.6	-45.5
Portfolio 24	-	-	✓	-	-	-	19	22.5	-14.5
Portfolio 25	-	-	-	✓	-	✓	37	16.1	-45.5
Portfolio 26	-	-	-	✓	-	-	19	3.0	-14.5
Portfolio 27	-	-	-	-	✓	✓	58	35.6	-76
Portfolio 28	-	-	-	-	✓	-	40	22.5	-45
Portfolio 29	-	-	-	-	-	✓	18	13.1	-31
Portfolio 30	-	-	-	-	-	-	0	0.0	0

5.3 Structuring the value model

There are two value objectives (water savings and GHG emission reductions) and one resource objective (cost). Since the attribute consequences for each portfolio are known, value functions are applied directly on the portfolio consequences. The attributes are preference-independent, i.e. the consequence of one attribute does not affect the desirability of the other attributes. The value of a portfolio x is thus the sum of the attributes' values,

$$V(x) = w_S V_S(x_S) + w_C V_C(x_C) + w_G V_G(x_G),$$

where $V_S(x_S)$ is the value of portfolio x with regard to attribute 'water savings'. $V_C(x_C)$ and $V_G(x_G)$ are values of portfolio x w.r.t costs and avoided GHG emissions respectively. w_S, w_C and w_G are the attribute weights, $w_S + w_C + w_G = 1$.

5.3.1 Attribute-specific value functions

Water savings range from 0% to 73%, avoided GHG emissions from -81MT to 108MT and costs from 0M$ to 43.7M$. The possibility of doing nothing (not choosing a single action) is included here as a baseline, hence a water saving of 0% and a cost of 0$ is possible. Each portfolio is given scores with regard to the attributes. The least desired attribute level receives score 0 and the most desired level score 1. It is assumed that an increase of one unit in an attribute has the same value for each attribute level, i.e. the marginal value is constant. This results in linear scoring functions, as presented below

$$V_S(x_S) = \frac{x_S}{73}, x_S \in [0, 73]$$
$$V_C(x_C) = \frac{43.7 - x_C}{43.7}, x_C \in [0, 43.7]$$
$$V_G(x_G) = \frac{x_G + 81}{189}, x_G \in [-81, 108]$$

E.g. portfolio 15 with attribute consequences $x_S = 13\%$, $x_C = 1.15M\$$ and $x_G = 108MT$ receives scores $V_S(13) = 0.18$, $V_C(1.15) = 0.97$ and $V_G(108) = 1$.

The weights w_S, w_C and w_G can be assessed by asking elicitation questions such as 'Is the rise in water savings from 0% to 73% more valuable than the fall in costs from 43.7M$ to 0$?'. The answer 'yes' implies that $w_S > w_C$.

5.4 Analyzing portfolios

The interesting portfolios are the efficient ones, presented in boldface text in Table 6. The dominated portfolios x' are screened out, since there is a portfolio x such that $V(x) \geq V(x')$ for all weights in the set $S_w = \{w_S, w_C, w_G \in \mathbb{R}^3_+ | w_S + w_C + w_G = 1\}$. The efficient portfolios were computed with RPM-Decisions. Concentrating on the efficient portfolios enables the decision-makers to reduce the number of analyzed portfolios without needing to answer a single elicitation question, i.e. one of the efficient portfolios will be the choice for *any weights* in S_w.

There are 15 efficient portfolios (compare to the original five configurations in Mitchell et al., 2007, p. 48). The core indices (presented in Figure 14, see Section 3.4.2 for definition) reveal that all actions are present in some – but not all – of the efficient portfolios.

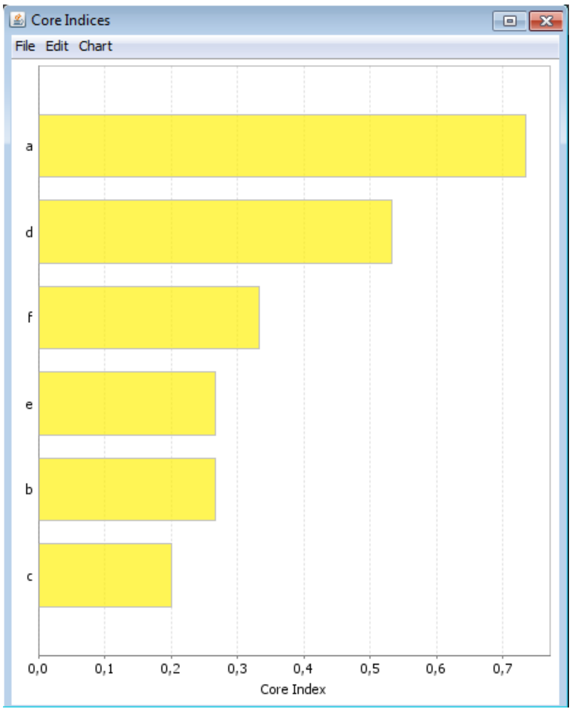

Figure 14: Core indices for all actions.

Figures 15 and 16 illustrate the cost, water savings and avoided GHG emissions of all efficient portfolios. Consider, for instance, the portfolio marked with an arrow. There are other portfolios which provide more avoided GHG emissions with less cost. However, this portfolio has greater water savings than all others with the same cost .

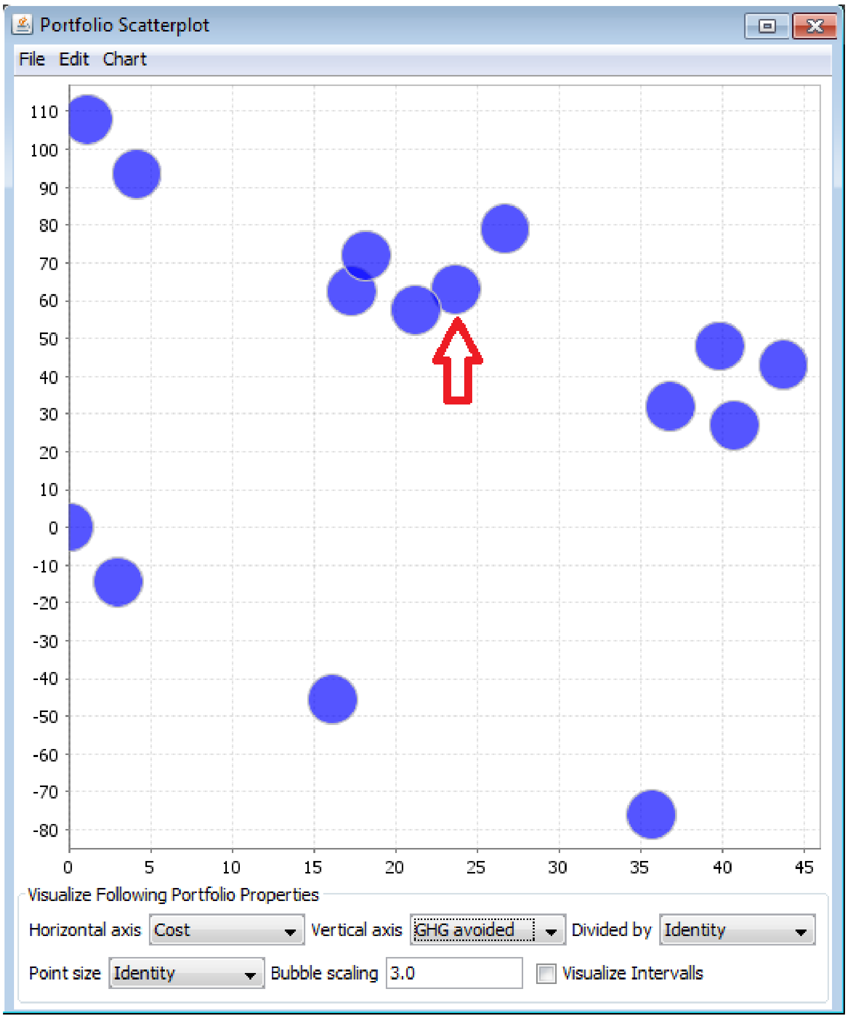

Figure 15: Portfolio scatter plot generated with RPM-Decisions. The x-axis shows cost and the y-axis avoided GHG emissions.

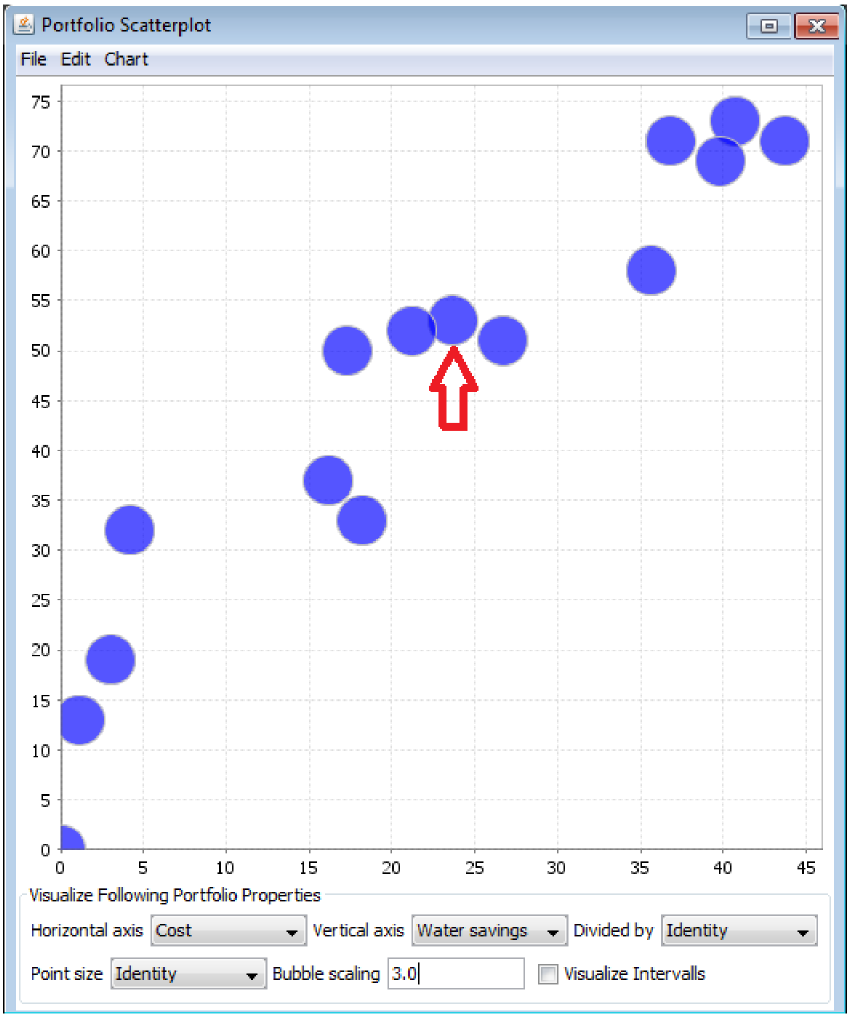

Figure 16: Portfolio scatter plot generated with RPM-Decisions. The x-axis shows cost and the y-axis water savings.

6 Conclusions

This thesis illustrates the possibilities of portfolio modeling in environmental decision making. Currently multi-criteria decision analytic (MCDA) methods are being used extensively to analyze environmental decisions. The options that are evaluated with MCDA models often consist of several actions, hence making the decision a portfolio decision. A new subfield of MCDA, portfolio decision analysis (PDA), has emerged in the last ten years. PDA has attracted a lot of interest from practitioners in other fields, but there have been few explicit applications to environmental situations.

The use of PDA in environmental problems is demonstrated with the help of two examples. The first example surveys the zoning of peat bog areas for extraction in Central Finland, while minimizing the risk to water systems in the region. The portfolio approach enables analyzing which combinations of actions (i.e. portfolios) provide most peat with a certain level of risk to water systems. The risk to water systems is measured with two main attributes, ‘water system value’ and ‘water system sensitivity’. With the help of PDA it is possible to analyze the problem and identify preferred actions without specifying exact preference weights for the attributes.

The second example analyzes which actions to undertake in order to provide water to a suburban area in a sustainable manner for the next 25 years. In the original case study by Mitchell et al. (2007) five options are analyzed. These were created in a heuristic manner as combinations of six actions. PDA enables identifying all 30 feasible portfolios. Out of these 15 are efficient, i.e. no other feasible portfolio performs better on all three objectives; cost, water savings and avoided greenhouse gas emissions. A larger set of options makes it possible to reach a decision which is better aligned with the objectives.

This thesis suggests several avenues for further research. First, a framework to facilitate the application of PDA to environmental problems does not currently exist. Such a framework should be developed to lower the threshold of applying PDA. Second, environmental problems often have inherent non-linearities. For instance the water quality of an untouched lake can be severely worsened due to a small nutrient increase, while an equal additional nutrient increase can have only a marginal effect on water quality. Methods to deal with these non-linearities exist (see e.g. Chen and Huang, 2001), but they are not often implemented in the off-the-shelf software. Third, while methods for group decision making in PDA have been developed (see, e.g., Vilkkumaa et al., 2009), these methods' application to practice is not yet widespread. Since environmental decisions often involve multiple stakeholders, this avenue of research should be pursued further.

A Core indices for the 206 actions in Section 4's example

Table 7: The core indices of peat bogs for different zoning area requirements. (1/6)

	Zoning area requirement (in hectares)								
Bog name	1000	2000	3000	4000	5000	6000	7000	8000	9000
Töyrineva	0.22	1	1	1	1	1	1	1	1
Töyrenneva	1	1	1	1	1	1	1	1	1
Rötkönperänsuo	0.99	1	1	1	1	1	1	1	1
Rahkaneva3	0.99	1	1	1	1	1	1	1	1
Rahkaneva1	1	1	1	1	1	1	1	1	1
Pitkäneva	0	0.64	0.98	1	1	1	1	1	1
Nevonlamminneva	0	0.96	1	1	1	1	1	1	1
Lehmineva	1	1	1	1	1	1	1	1	1
Lampisuo2	1	1	1	1	1	1	1	1	1
Korteniemi	0.04	0.57	0.9	1	1	1	1	1	1
Konisuo-Kivisuo	0.99	1	1	1	1	1	1	1	1
Kettulanneva	0	0.1	0.57	0.75	1	1	1	1	1
Keltasuo	0	0.56	1	1	1	1	1	1	1
Kanavakytö	0.43	0.98	1	1	1	1	1	1	1
Isosuo1	0.85	1	1	1	1	1	1	1	1
Hallaneva	0.86	1	1	1	1	1	1	1	1
Amalianneva	0.96	1	1	1	1	1	1	1	1
Rättisuo	0	0	0.61	1	1	1	1	1	1
Ruotesuo	0	0	0	0	0.01	0.32	1	1	1
Kurkisuo4	0	0	0	0.73	1	1	1	1	1
Karjosuo	0.53	0.91	1	1	1	1	1	1	1
Isoniitty	0	0	0.1	0.3	0.41	0.48	0.72	1	1
Heposuo2	0	0.25	0.47	0.66	0.79	0.99	1	1	1
Parantaisensuo	0	0.34	0.71	0.82	1	1	1	1	1
Töyrisuo2	0	0	0	0	0	0	0	0.02	1
Peurasuo	0	0	0	0.7	1	1	1	1	1
Mustassuo	0	0	0.24	0.45	0.59	0.75	1	1	1
Koiraneva	0	0.17	0.32	0.52	0.57	0.7	0.94	1	1
Kalalampi	0	0.11	0.25	0.39	0.46	0.52	0.63	0.85	1
Illakkaneva	0	0	0	0.03	0.21	0.32	0.51	0.95	1
Ukonsuo	0	0.23	0.4	0.58	0.72	0.88	1	1	1
Mustalamminneva	0	0	0	0	0	0	0	0.23	0.71
Iso Valkeislampi	0	0	0	0	0	0	0	0.2	0.63
Rautasuo	0	0	0	0	0.9	1	1	1	1
Pohjoissuo2	0	0	0	0	0	0.07	0.43	1	1

Table 8: The core indices of peat bogs for different zoning area requirements. (2/6)

	Zoning area requirement (in hectares)								
Bog name	1000	2000	3000	4000	5000	6000	7000	8000	9000
Kelkkasuo-S.suo	0	0	0	0.13	0.3	0.39	0.77	1	1
Syväjärvenneva S	0.54	0.72	0.95	1	1	1	1	1	1
Syväjärvenneva N	0	0	0.18	0.34	0.44	0.54	0.72	0.99	1
Soppisenneva	0	0.52	0.88	1	1	1	1	1	1
Pesaneva	0	0	0.11	0.84	1	1	1	1	1
Kunnarsuo	0	0	0	0	0	0.21	0.41	0.92	1
Honkasuo	0	0	0	0.04	0.6	1	1	1	1
Hietikonneva	0	0	0	0	0	0	0	0	0
Haapapuukonsuot	0.14	0.43	0.68	0.93	1	1	1	1	1
Kortesuo	0	0	0	0.21	0.63	1	1	1	1
Tervasuo-K.suo	0.15	0.48	0.77	0.89	1	1	1	1	1
Takapellonneva	0	0	0	0	0	0	0	0	0.01
Porrassuo	0	0	0	0	0.85	1	1	1	1
Partasuo	0.17	0.65	0.97	1	1	1	1	1	1
Heinäsuo5	0.45	0.67	0.94	1	1	1	1	1	1
Suurisuo5	0	0	0	0	0.06	0.27	0.44	1	1
Murtosuo1	0	0	0	0	0.07	0.31	0.77	1	1
Louhuinneva	0	0	0	0.07	0.27	0.38	0.83	1	1
Kirvessuo	0	0	0	0	0	0	0.71	1	1
Karhusuo2	0	0	0	0	0	0	0.22	1	1
Iso Sääksneva	0	0	0	0	0	0.47	1	1	1
Suurisuo3	0	0	0	0	0.12	0.3	0.55	1	1
Rummakonneva	0	0	0.95	1	1	1	1	1	1
Rokkasuo	0	0	0.23	0.55	0.75	0.96	1	1	1
Nevalansuo	0	0	0	0	0	0	0.12	0.37	0.97
Kankisuo	0	0	0	0	0	0	0.22	1	1
Isosuo2	0	0	0	0	0	0.37	1	1	1
Haukilamminsuo	0	0.32	0.76	0.92	1	1	1	1	1
Hepolamminneva	0	0	0	0.13	0.48	0.78	1	1	1
Suurisuo2	0	0	0	0	0.31	0.54	1	1	1
Saikansuo	0	0	0	0	0	0.12	0.36	1	1
Riihisuo-Peurunsuo	0	0	0	0	0	0	0.13	0.59	1
Myllysuo	0	0	0	0.17	0.53	0.67	0.91	1	1
Leppäsenneva	0.31	0.72	1	1	1	1	1	1	1
Suursuo	0	0	0.07	0.3	0.41	0.52	0.81	1	1
Saarisuo A	0	0	0	0.26	0.43	0.59	0.99	1	1
Peurunsuo	0	0	0	0	0	0.6	1	1	1
Niinisuo	0	0.06	0.19	0.27	0.33	0.38	0.49	0.68	0.91
Leinonneva	0	0	0	0.43	0.62	0.84	1	1	1

Table 9: The core indices of peat bogs for different zoning area requirements. (3/6)

	Zoning area requirement (in hectares)								
Bog name	1000	2000	3000	4000	5000	6000	7000	8000	9000
Sikosuo-K.suo	0	0	0	0	0.09	0.4	0.62	1	1
Sarvineva	0	0	0	0	0	0	0	0	0
Raatesuo	0	0	0	0	0	0	0.01	1	1
Pirttisuo1	0	0	0	0	0	0	0	0.46	1
Penkkisuo	0	0	0	0	0.13	1	1	1	1
Olkitaipaleenneva	0	0	0	0	0	0	0	0.14	1
Moskuvansuo	0	0	0	0	0	0	0	0.34	1
Hirsisuo	0	0	0	0	0	0	0.09	1	1
Paljakansuo-S	0.01	0.17	0.32	0.45	0.55	0.65	0.86	1	1
Paljakansuo-N	0.03	0.18	0.35	0.52	0.57	0.69	0.91	1	1
Heinäsuo4	0	0	0.13	0.31	0.4	0.47	0.67	1	1
Heinäsuo2	0	0.07	0.23	0.35	0.44	0.51	0.64	0.91	1
Tervasuo	0.41	1	1	1	1	1	1	1	1
Tervajoensuo	0	0	0.05	0.23	0.33	0.4	0.58	0.85	1
Teerisuo3	0	0	0	0	0	0	0.03	0.13	0.3
Saarisuo 2	0	0	0	0	0.09	0.22	0.38	0.75	1
Riisisuo	0	0.44	0.8	1	1	1	1	1	1
Ottovuorenneva	0	0.33	0.74	1	1	1	1	1	1
Männikönneva	0	0	0.14	0.28	0.36	0.41	0.56	0.8	1
Mannissuo-P.suo	0	0	0	0	0	0	0	0.82	1
Leväsuo	0	0	0.04	0.33	0.47	0.62	1	1	1
Kelaojansuo	0	0	0	0	0	0	0	0	1
Jämsänneva	0	0	0.03	0.2	0.33	0.4	0.58	0.96	1
Isosuo6	0	0	0	0	0.04	0.19	0.34	0.72	1
Iso Kelloneva	0	0	0	0	0	0	0	0	0.06
Hanslamminneva	0	0	0	0.06	0.12	0.16	0.2	0.31	0.52
Teurisuo	0	0	0	0	0	0.06	0.18	0.53	1
Suurisuo6	0	0.66	1	1	1	1	1	1	1
Sikolamminsuo	0	0	0	0	0	0	0	0.06	0.81
Saarisuo1	0.15	0.3	0.52	0.69	0.8	0.93	1	1	1
Petäikköneva	0	0	0	0	0	0	0	0	0
Pirttijärvensuo	0	0	0	0.7	1	1	1	1	1
Nimetönsuo4	0	0	0	0	0.28	0.71	0.96	1	1
Kyntöläisneva	0	0	0	0	0	0	0.21	0.67	1
Rimminneva	0	0	0.15	0.93	1	1	1	1	1
Pahkasuo	0	0	0	0	0	0	0	0.68	1
Sarvisuo 1	0	0	0	0	0	0	0.07	0.36	1
Pykälistönsuo	0	0	0	0	0.19	0.6	0.78	0.99	1
Nimetönsuo5	0	0	0	0.11	0.53	1	1	1	1

Table 10: The core indices of peat bogs for different zoning area requirements. (4/6)

	Zoning area requirement (in hectares)								
Bog name	1000	2000	3000	4000	5000	6000	7000	8000	9000
Nimetönsuo3	0	0	0	0	0	0	0	0	0
Marketansuo	0	0	0	0	0.66	1	1	1	1
Kuvaslammensuo	0	0	0	0	0.7	1	1	1	1
Korvalammensuo	0	0	0	0.8	1	1	1	1	1
Karistonneva	0	0	0	0.73	1	1	1	1	1
Isosuo4	0	0	0	0	0.57	1	1	1	1
Vehmassuo-T.suo	0	0	0	0	0	0	1	1	1
Rautosuo	0	0	0	0	0.29	1	1	1	1
Palosuo	0	0.77	1	1	1	1	1	1	1
Ranta-Ahonsuo	0	0	0.01	0.11	0.47	0.62	1	1	1
Pieni Joensuo	0	0	0	0	0.62	1	1	1	1
Oravakorpi	0	0	0	0	0	0	0.01	0.27	0.68
Nollineva	0	0	0	0	0	0	0	0	0
Linnasensuo	0	0	0	0	0	0	0	0.2	1
Lauttasuo	0	0.02	0.24	0.47	0.57	0.69	0.82	1	1
Kuitulan Isosuo	0	0	0.38	0.79	1	1	1	1	1
Kivisuo 2	0	0	0	0	0.38	0.62	0.99	1	1
Kalettomansuo	0	0	0	0	0	0.08	0.95	1	1
Sorvalinsuo	0	0	0	0	0	0	0.09	0.19	0.47
Pukkilamminsuo	0	0	0	0	0.17	0.31	0.43	0.64	1
Pieni Sääksneva	0	0	0	0	0	0	0	0	0
Perhonsuo	0	0	0	0	0	0	0.14	0.4	1
Pakoneva	0	0	0	0	0	0	0	0.01	0.43
Matkusneva	0	0.09	1	1	1	1	1	1	1
Lakeasuo	0	0	0	0	0	0	0	0	0
Köpinneva-K.suo	0.01	0.34	0.63	0.87	1	1	1	1	1
Korhonsuo	0	0	0	0	0	0.06	0.19	0.3	0.59
Koirasuo	0	0	0	0	0	0	0.06	0.15	0.43
Isoneva2	0	0	0	0	0	0.19	0.72	0.99	1
Asemaneva	0	0	0	0	0.45	0.62	0.99	1	1
Isosuo5	0	0	0	0	0	0	0.15	0.32	0.68
Mäntykankaansuo	0	0	0	0	0	0	0.04	0.18	0.41
Isoneva-M.suo	0	0	0	0	0.26	0.41	0.62	1	1
Ruokosuo	0	0	0	0	0	0.07	0.28	0.56	1
Raatosuo	0	0	0	0	0	0.19	0.75	1	1
Lehtosuo	0	0	0	0	0	0	0	0	0.04
Juurikassuo	0	0	0	0.1	0.49	0.66	1	1	1
Joutensuo	0.41	0.9	1	1	1	1	1	1	1
Pohjoissuo1	0	0	0	0	0	0	0	0.23	1

Table 11: The core indices of peat bogs for different zoning area requirements. (5/6)

	Zoning area requirement (in hectares)								
Bog name	1000	2000	3000	4000	5000	6000	7000	8000	9000
Niinineva-K.neva	0	0	0.23	0.55	0.71	0.94	1	1	1
Martinsuo	0	0	0	0	0	0	0.04	0.25	0.87
Jälsisuo-K.suo	0	0	0	0	0	0.95	1	1	1
Reinikansuo-P.suo	0	0	0	0	0.1	0.29	0.42	0.69	1
Luomussuo-T.neva	0	0	0	0	0.1	0.3	0.42	0.72	1
Kilpisuo	0	0	0.09	0.18	0.36	0.44	0.56	0.82	1
Karjunneva	0	0	0	0	0	0.12	0.41	0.66	1
Karasuo	0	0	0	0	0	0	0.12	0.95	1
Kaakkosuo2	0	0	0	0	0.19	0.4	0.66	1	1
Isoneva6	0	0	0	0	0	0	0	0	0
Veljestensuo	0	0	0	0.63	0.97	1	1	1	1
Lampisuo1	0	0	0	0.07	0.48	0.93	1	1	1
Heposuo3	0	0	0	0	0	0	0	0	0
Haleansuo	0	0	0	0	0	0	0	0	0.22
Autionsuo	0	0	0	0	0	0	0	0	1
Lehtosuo-Ojaneva	0	0	0	0.08	0.47	0.62	1	1	1
Karmeneva	0	0	0	0	0.3	0.46	1	1	1
Kalmonsuo	0	0	0	0	0	0.27	0.84	1	1
Höystösensuo	0	0	0.77	1	1	1	1	1	1
Ahvensuo	0	0	0	0	0	0	0	0	0.19
Murtolamminneva	0	0	0	0	0	0.07	0.23	0.63	1
Leväsensuo	0	0	0	0	0	0.06	0.18	0.44	0.94
Isosuo3S	0	0	0	0	0	0	0	0	0
Isosuo3	0	0	0	0	0	0	0	0	0
Aukeasuo	0	0	0	0	0	1	1	1	1
Ahvenneva	0	0	0	0	0	0	0	0.32	1
Valkeissuo	0	0	0	0	0	0	0.17	0.46	1
Pihtisuo	0	0	0.39	0.74	0.99	1	1	1	1
Leppäsuo	0	0	0	0	0	0	0	0.04	0.22
Kuikkaneva	0	0	0	0	0.24	0.6	0.96	1	1
Velkkulansuo	0	0	0	0	0	0	0	0	0.33
Vetosuo	0	0	0	0	0	0	0.49	1	1
Töyrisuo1	0	0	0	0	0	0	0	0	1
Mökinsuo	0	0	0	0	0	0	0	0	0
Lamminsuo	0	0	0	0	0	0	0	0	0.06
Kypäräsuo	0	0	0	0	0	0	0	0	0
Teerensuo	0	0	0	0	0	0	0	0	0
Pirttisuo-Karjosuo	0	0	0.01	0.37	0.59	0.78	1	1	1
Maunusuo	0	0	0	0	0	0	0	0	0.52

Table 12: The core indices of peat bogs for different zoning area requirements. (6/6)

	Zoning area requirement (in hectares)								
Bog name	1000	2000	3000	4000	5000	6000	7000	8000	9000
Loukkusuo	0	0	0	0	0	0	0	0.09	1
Isoneva5	0	0	0	0	0	0	0	0	0.07
Utrusuo	0	0	0	0	0	0.89	1	1	1
Teerisuo4	0	0	0	0	0	0	0	0	0
Teerisuo2	0	0	0	0	0	0	0	0	0.67
Suurisuo1	0	0	0.03	0.21	0.52	0.59	0.85	1	1
Soidinsuo	0	0	0	0	0	0	0.01	0.22	0.79
Rumma	0	0	0	0	0	0	0	0.18	0.72
Rantinsuo	0	0	0	0.65	0.93	1	1	1	1
Leukunneva	0	0	0	0	0	0	0	0	0.03
Kangaslamminsuo	0	0	0	0	0.13	0.32	0.46	0.8	1
Isoneva4	0	0	0	0	0	0	0	0	0.13
Heinäsuo8	0	0	0	0	0	0	0	0	0.44
Heinäsuo3	0	0	0	0	0	0	0	0.01	0.32
Haarajoenneva	0	0	0	0	0	0	0	0	0.21

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