Abstract

Planning, design and operational decisions are made under complex circumstances of multiple objectives, conflicting interests and participation of multiple stakeholders. Selection of alternatives can be performed by means of traditional economics-based methods, such as benefit-cost analysis. Alternatively, analyses of decision problems, including water resource allocation problems, which involve trade-offs among multiple criteria, can be undertaken using multi-criteria decision analysis (MCDA). MCDA is used to assist decision makers (DMs) in prioritising or selecting one or more alternatives from a finite set of available alternatives with respect to multiple, usually conflicting, criteria.

In the majority of decision problems, MCDA is complicated by input parameters that are uncertain and evaluation methods that involve different assumptions. Consequently, one of the main difficulties in applying MCDA and analysing the resultant ranking of the alternatives is the uncertainty in the input parameter values (i.e. criteria weights (CWs) and criteria performance values (PVs)). Analysing the sensitivity of decisions to various input parameter values is, therefore, an integral requirement of the decision analysis process. However, existing sensitivity analysis methods have numerous limitations when applied to MCDA, including only incorporating the uncertainty in the CWs, only varying one input parameter at a time and only being applicable to specific MCDA techniques.

As part of this research, two novel uncertainty analysis approaches for MCDA are developed, including a distance-based method and a reliability based approach, which enable the DM to examine the robustness of the ranking of the alternatives. Both of the proposed methods require deterministic MCDA to be undertaken in the first instance to obtain an initial ranking of the alternatives. The purpose of the distance-based uncertainty analysis method is to determine the minimum modification of the input parameters that is required to alter the total values of two selected alternatives such that rank equivalence occurs. The most critical criteria for rank reversal to occur are also able to be identified based on the results of the distance-based approach. The proposed stochastic method involves defining the uncertainty in the input values using probability distributions, performing a reliability analysis by Monte Carlo Simulation and undertaking a significance analysis using the Spearman Rank Correlation Coefficient. The outcomes of the stochastic uncertainty analysis approach include a distribution of the total values of each alternative based upon the expected range of input parameter values. The uncertainty analysis methods are implemented using a software program developed as part of this
Abstract

research, which may assist in negotiating sustainable decisions while fostering a collaborative learning process between DMs, experts and the community. The two uncertainty analysis approaches overcome the limitations of the existing sensitivity analysis methods by being applicable to multiple MCDA techniques, incorporating uncertainty in all of the input parameters simultaneously, identifying the most critical criteria to the ranking of the alternatives and enabling all actors preference values to be incorporated in the analysis.

Five publications in refereed international journals have emerged from this research, which constitute the core of the thesis (i.e. PhD by Publication). The publications highlight how uncertainty in all of the input parameters can be adequately considered in the MCDA process using the proposed uncertainty analysis approaches. The methodologies presented in the publications are demonstrated using a range of case studies from the literature, which illustrate the additional information that is able to be provided to the DM by utilising these techniques. Publications 1 and 2 (Journal of Environmental Management and European Journal of Operational Research) demonstrate the benefits of the distance-based uncertainty analysis approach compared to the existing deterministic sensitivity analysis methods. In addition, the benefits of incorporating all of the input parameters in the uncertainty analysis, as opposed to only the CWs, are illustrated. The differences between global and non-global optimisation methods are also discussed. Publications 3 and 4 (Journal of Water Resources Planning and Management and Journal of Multi-Criteria Decision Analysis) present the stochastic uncertainty analysis approach and illustrate its use with two MCDA techniques (WSM and PROMETHEE). Publication 5 (Environmental Modelling & Software) introduces the software program developed as part of this research, which implements the uncertainty analysis approaches presented in the previous publications.

Despite the benefits of the approaches presented in the publications, some limitations have been identified and are discussed in the thesis. Based on these limitations, it is recommended that the focus for further research be on developing the uncertainty analysis methods proposed (and in particular the program, and extension of the program) so that it includes additional MCDA techniques and optimisation methods. More work is also required to be undertaken on the Genetic Algorithm optimisation method in the distance-based uncertainty analysis approach, in order to simplify the specification of input parameters by decision analysts and DMs.
Declaration

I, Kylie Marie Hyde, declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work, except as acknowledged in the text, and that the material has not been submitted, either in whole or in part, for a degree at this or any other university.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

Signed: .................................................................

Dated: .................................................................
Acknowledgements

The balance of personal life with doctoral research is a complex multi-criteria decision analysis problem. A doctoral candidate is forced to trade-off recreation time against time spent with a computer and a ceiling high stack of journal papers.

(Hajkowicz, 2000)

I wish to thank my supervisors, Associate Professor Holger Maier and Dr Chris Colby for their encouragement, guidance and support over the four year period it has taken to complete this study. This thesis would not have been completed without the enthusiasm and dedication of Associate Professor Holger Maier.

I would also like to acknowledge the role of the Australian Research Council, the Department for Water, Land, Biodiversity and Conservation, and the Department of Trade and Economic Development in providing funding for this project. This funding enabled two overseas trips to be undertaken, including attendance at an international summer school on MCDA in Montreal, Canada and two international conferences in Whistler, Canada and Coimbra, Portugal.

Particular thanks must also be given to directors and staff of Australian Water Environments who enabled me to work part-time for the first two and a half years of my PhD and the Environment Protection Authority who allowed me to take time off during the last nine months of the PhD so that it could be completed.

I would like to extend my best wishes to my fellow postgraduate students for their support and understanding. In particular, Michael Leonard and Rob May for their assistance with programming in Visual Basic for Applications and especially to Michael Leonard for provision of his genetic algorithm code.

Finally, I would like to thank my family, friends and partner, Michael, for their understanding, great patience and encouragement to complete.
Publications

The following publications and conference presentations have arisen from this research:

**Journal Papers:**


**Conference Papers:**


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<tr>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHP</td>
<td>Analytic Hierarchy Process</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>BCA</td>
<td>Benefit Cost Analysis</td>
</tr>
<tr>
<td>CAM</td>
<td>Conflict Analysis Model</td>
</tr>
<tr>
<td>CGT</td>
<td>Cooperative Game Theory</td>
</tr>
<tr>
<td>CP</td>
<td>Compromise Programming</td>
</tr>
<tr>
<td>CTP</td>
<td>Composite Programming</td>
</tr>
<tr>
<td>CWs</td>
<td>Criteria Weights</td>
</tr>
<tr>
<td>DEA</td>
<td>Data Envelope Analysis</td>
</tr>
<tr>
<td>DISID</td>
<td>Displaced Ideal</td>
</tr>
<tr>
<td>DIVAPIME</td>
<td>Determination d'Intervalles de Variation pour les Parametres d'Importance des Methodes Electre</td>
</tr>
<tr>
<td>DM</td>
<td>Decision Maker</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision Support System</td>
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<tr>
<td>DST</td>
<td>Dempster-Shafer Theory</td>
</tr>
<tr>
<td>EF</td>
<td>Ecological Footprint</td>
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<tr>
<td>EIA</td>
<td>Environmental Impact Assessment</td>
</tr>
<tr>
<td>EIS</td>
<td>Environmental Impact Statement</td>
</tr>
<tr>
<td>ELECTRE</td>
<td>Elimination and Choice Translating Reality (Elimination Et Choix Tradusiant la Réalité)</td>
</tr>
<tr>
<td>ESAP</td>
<td>Evaluation and Sensitivity Analysis Program</td>
</tr>
<tr>
<td>EVI</td>
<td>Expected Value of Information</td>
</tr>
<tr>
<td>EVPI</td>
<td>Expected Value of Perfect Information</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>GAIA</td>
<td>Graphical Analysis for Interactive Assistance</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
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<tr>
<td>GP</td>
<td>Goal Programming</td>
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<tr>
<td>GRAPA</td>
<td>Graphical Point Allocation</td>
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<td>GRG2</td>
<td>Generalised Reduced Gradient Nonlinear Optimisation Method</td>
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<td>GRS</td>
<td>Graphical Rating Scale</td>
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<tr>
<td>HDT</td>
<td>Hasse Diagram Technique</td>
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<td>HIPRE</td>
<td>Hierarchical Preference Analysis Software</td>
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<td>Measuring Attractiveness by a Categorical Based Evaluation Technique</td>
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<td>MAS</td>
<td>Multi-Agent Systems</td>
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<td>MADM</td>
<td>Multiple Attribute Decision Making or Modelling</td>
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<td>MCQA</td>
<td>Multi-Criterion Q Analysis</td>
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<tr>
<td>MCS</td>
<td>Monte Carlo Simulation</td>
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<tr>
<td>MDI</td>
<td>Minimum Discrimination Information</td>
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<tr>
<td>MESA</td>
<td>Matrix for the Evaluation of Sustainability Achievement</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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</tr>
<tr>
<td>MEW</td>
<td>Multiplicative Exponent Weighting</td>
</tr>
<tr>
<td>MODM</td>
<td>Multi-Objective Decision Making</td>
</tr>
<tr>
<td>MODS</td>
<td>Multi-Objective Decision Support</td>
</tr>
<tr>
<td>NA</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>NAIADE</td>
<td>Novel Approach for Imprecise Assessment and Decision Evaluations</td>
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<tr>
<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>PC</td>
<td>Preference Cones</td>
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<td>PROBE</td>
<td>Preference Robustness Evaluation</td>
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<tr>
<td>PROMETHEE</td>
<td>Preference Ranking Organisation METHod for Enrichment Evaluations</td>
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<tr>
<td>PROTR</td>
<td>Probabilistic Trade-off Development Method</td>
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<td>PVs</td>
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<td>PW</td>
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<td>SAW</td>
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<tr>
<td>STEM</td>
<td>Step Method</td>
</tr>
<tr>
<td>SWT</td>
<td>Surrogate Worth Trade-Off</td>
</tr>
<tr>
<td>TBL</td>
<td>Triple Bottom Line</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Technique for Order Preference by Similarity to an Ideal Solution</td>
</tr>
<tr>
<td>UNK</td>
<td>Unknown</td>
</tr>
<tr>
<td>UTA</td>
<td>Utility Additive</td>
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</tbody>
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Glossary of Selected Acronyms and Notation

**VAS**  Visual Analogue Scale  
**VBA**  Visual Basic for Applications  
**VIP**  Variable Interdependent Parameters  

**WA**  Weighted Average  
**WLAM**  Weighted Linear Assignment Method  
**WPM**  Weighted Product Method  
**WSM**  Weighted Sum Method  

**ZAPROS**  Closed Procedures Near Reference Situations (abbreviation of Russian words)  
**Z-W**  Zionts-Wallenius  

**Notation**

- $d_2 \text{ or } L_2$: Euclidean distance  
- $d_1 \text{ or } L_1$: Manhattan distance  
- $d_k$: Kullback-Leibler distance  
- $\text{LL}_{x/l}$ and $\text{UL}_{x/l}$: lower and upper limits, respectively, of the PVs of each criterion for the initially lower ranked alternative  
- $\text{LL}_{x/h}$ and $\text{UL}_{x/h}$: lower and upper limits, respectively, of the PVs of each criterion for the initially higher ranked alternative  
- $\text{LL}_w$ and $\text{UL}_w$: lower and upper limits, respectively, of each of the CWs  
- $M$: total number of criteria  
- $p$: preference threshold  
- $q$: indifference threshold  
- $V(a_i)_{opt}$: modified total value of the initially lower ranked alternative obtained using the optimised parameters  
- $V(a_i)_{opt}$: modified total value of the initially higher ranked alternative obtained using the optimised parameters  
- $w_{mi}$: initial CW of criterion $m$  
- $w_{mo}$: optimised CW of criterion $m$
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>$X_{mnli}$</td>
<td>initial PV of criterion $m$ of initially lower ranked alternative $n$</td>
</tr>
<tr>
<td>$X_{mnlo}$</td>
<td>optimised PV of criterion $m$ of initially lower ranked alternative $n$</td>
</tr>
<tr>
<td>$X_{mnhi}$</td>
<td>initial PV of criterion $m$ of initially higher ranked alternative $n$</td>
</tr>
<tr>
<td>$X_{mnh}\theta$</td>
<td>optimised PV of criterion $m$ of initially higher ranked alternative $n$</td>
</tr>
<tr>
<td>$\Pi(a,b)$</td>
<td>outranking degree of every alternative $a$ over alternative $b$</td>
</tr>
<tr>
<td>$\phi^+$</td>
<td>leaving flow</td>
</tr>
<tr>
<td>$\phi^-$</td>
<td>entering flow</td>
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</tbody>
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